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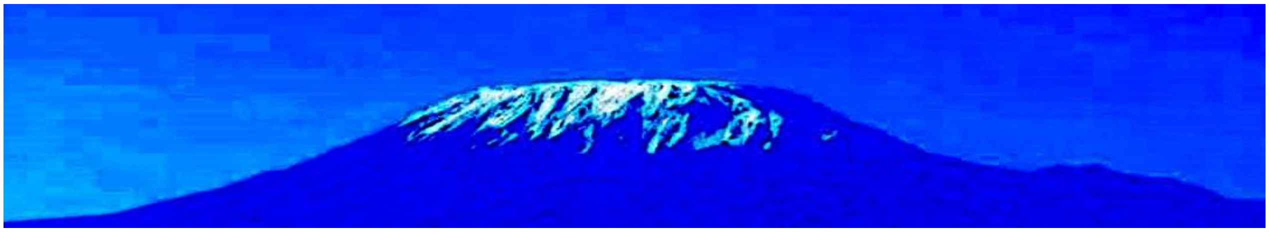

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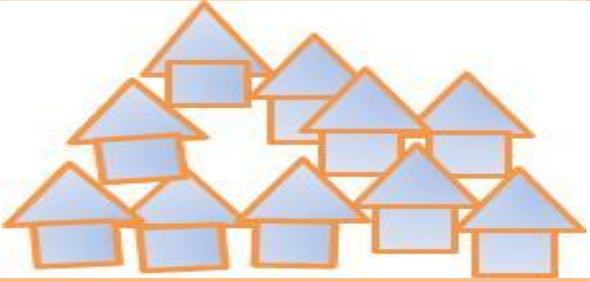

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Shrinking Waters of Lake Rukwa Basin, Tanzania: Remote Sensing Insights and Implications for Catchment Management (1994–2024)

Sixbert Joachim Msambichaka[1]

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Abstract

Lake Rukwa, one of Tanzania's most important endorheic lakes, has shrunk dramatically over the past three decades due to climate variability, sedimentation, and human-induced land use change. This study applied multi-temporal remote sensing using Landsat imagery from 1994, 2004, 2014, and 2024, supported by Sentinel-2 and Google Earth Pro validation. The Normalized Difference Water Index (NDWI) was used to delineate lake surface area, while the Normalized Difference Turbidity Index (NDTI) served as a proxy for sedimentation at major river inflows. Land use and land cover (LULC) changes were classified with a Random Forest algorithm.

Results reveal a net loss of about 65,000 hectares of lake surface area, with the sharpest decline between 2004 and 2014 at –0.68 percent per year. Extensive deforestation, estimated at 700,000 hectares, and cropland expansion exceeding 500,000 hectares have intensified soil erosion and sediment inflows. Rising NDTI values in rivers such as the Songwe (0.08 to 0.24) confirm worsening turbidity. These pressures have accelerated sediment accumulation, reduced water depth, and destabilized the lake's hydrological balance.

The findings highlight human-driven catchment degradation as the dominant driver of Lake Rukwa's decline. Mitigation requires basin-level reforestation, erosion control, and sustainable water abstraction, supported by integrated monitoring and adaptive management strategies..

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[1] The Mwalimu Nyerere Memorial Academy (MNMA)
Corresponding Author: msambichakasix@gmail.com; phone:0756288529/0714805672

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1.0. Introduction

Across the world, inland lakes are shrinking at alarming rates due to a combination of climatic variability, sedimentation, and intensified human activities. These lakes not only regulate hydrological cycles but also sustain biodiversity, livelihoods, and regional economies (Schäfer et al., 2016; Fischer et al., 2020). In sub-Saharan Africa, this trend has become particularly severe, with studies reporting dramatic surface water losses in lakes such as Chad, Malombe, and Abaya largely driven by deforestation, agricultural expansion, and increasing evaporation rates (UNEP-GRID, 2015; Makwinja et al., 2021a; Mulu et al., 2024). These cases demonstrate how unsustainable land use practices and climatic stress jointly reshape freshwater ecosystems, threatening both ecological integrity and community resilience.

Lake Rukwa, located in the southwestern highlands of Tanzania within the East African Rift System, offers a critical local manifestation of these global patterns. Despite being smaller and less studied than its neighboring lakes Tanganyika and Nyasa, Lake Rukwa plays a vital ecological and socioeconomic role. It supports fisheries, livestock grazing, irrigation, and wetland habitats that sustain wildlife and human livelihoods across Rukwa, Songwe, Mbeya, and Katavi regions (Ogutu-Ohwayo et al., 2016; Gao et al., 2018). Over the past three decades, however, the lake has experienced a pronounced reduction in surface area, attributed to sediment inflows from degraded catchments, deforestation, and changing rainfall regimes (Valimba, 2019; Habib et al., 2020; Maro et al., 2021). Despite its importance, few studies have conducted multi-decadal, integrated analyses linking land use dynamics, sedimentation, and hydrological changes.

This knowledge gap persists even as Tanzania continues to advance policies aimed at safeguarding its freshwater systems. The National Water Policy (URT, 2002) and the Integrated Water Resources Management (IWRM) Strategy (URT, 2010) emphasize sustainable catchment protection and efficient water use. Yet, their implementation has been hindered by limited spatial data, weak coordination among water authorities, and inadequate linkage between land use planning and basin-scale governance (Mwakalila, 2005; Elisa et al., 2021). Consequently, evidence-based studies like the present one are crucial to inform adaptive management of vulnerable inland basins such as Lake Rukwa.

Accordingly, this study applies multi-temporal remote sensing and GIS approaches to examine the changes in Lake Rukwa's surface area and sediment dynamics between 1994 and 2024. Using the Normalized Difference Water Index (NDWI) to map surface water extent, the Normalized Difference Turbidity Index (NDTI) as a sedimentation proxy, and Random Forest classification for land use/land cover (LULC) analysis, the research evaluates how catchment degradation and land use transformations have contributed to the lake's continued shrinkage. Beyond quantifying spatial and temporal trends, the study explores the causal linkages among deforestation, agricultural expansion, and sediment deposition to provide actionable insights for sustainable catchment management.

2.0. Literature Review

2.1. Remote Sensing Approaches to Lake Monitoring

Remote sensing has become an indispensable tool for assessing long-term changes in inland lakes, providing consistent spatial and temporal coverage across large and often inaccessible regions. Spectral indices such as the Normalized Difference Water Index (NDWI) and the Modified NDWI (MNDWI) have proven effective in delineating surface water bodies by exploiting the optical contrast between water and land (McFeeters, 1996; Pekel et al., 2016). Similarly, indices like the Normalized Difference Turbidity Index (NDTI) have been used to infer sedimentation and turbidity patterns in surface waters (Lacaux et al., 2007; Islam et al., 2020). Recent applications using Google Earth Engine (GEE) have enhanced the efficiency and reproducibility of these analyses by enabling automated processing of multi-decadal image archives (Kazemi Garajeh et al., 2024; Nkwasa et al., 2024).

Studies across Asia, North America, and Africa demonstrate the value of remote sensing for understanding lake dynamics under climate and land use pressures (Zhang et al., 2015; Bao et al., 2024; Liu et al., 2024). In Africa, high-resolution temporal analyses have captured dramatic declines in lake extent, notably in Lake Chad, which has lost over 90% of its surface area since the 1960s due to a combination of rainfall variability and human abstraction (UNEP-GRID, 2015). Similarly, Lake Malombe in Malawi and Lake Abaya in Ethiopia have exhibited comparable shrinkage linked to deforestation, sediment inflows, and irrigation expansion (Makwinja et al., 2021a; Mulu et al., 2024). These studies underscore the power of remotely sensed indices to quantify spatiotemporal variations in water and sedimentation, even in the absence of field data.

However, several methodological limitations remain. NDWI and NDTI values can be affected by vegetation cover, shallow water depth, and sensor-specific spectral differences, which complicate cross-year comparison (Du et al., 2016; Yagmur et al., 2021). Moreover, the lack of ground-truth turbidity or sediment concentration data often constrains calibration and validation (Islam et al., 2020). Therefore, while these indices are robust for trend analysis, they must be interpreted alongside complementary evidence from hydrological and land use datasets. This integrated approach is particularly relevant for closed-basin systems like Lake Rukwa, where surface reflectance patterns are tightly coupled with sediment inflows from surrounding catchments.

2.2. Catchment Degradation and Land Use Change

Catchment degradation is one of the principal drivers of lake shrinkage across East Africa. Deforestation, agricultural expansion, and overgrazing accelerate soil erosion, increasing sediment transport into downstream basins (Majule & Mwalyosi, 2005; FAO, 2018). In Tanzania, the conversion of forest and grassland into cropland has intensified particularly in upland regions such as the Mbeya Highlands and Ufipa Plateau, where steep slopes and fragile soils amplify erosion risks (Valimba, 2019; Maro et al., 2021). Sediment carried by the Songwe, Luiche, and Rungwa rivers eventually deposits in Lake Rukwa, leading to reduced depth and shrinking surface area (Habib et al., 2020; Lameck et al., 2024).

Comparable processes have been observed in other African catchments. In the Gilgel Gibe basin of Ethiopia, land use and land cover (LULC) transformations have been shown to alter runoff and sedimentation, triggering lake infilling and hydrological imbalance (Tilahun et al., 2024). Likewise, studies in Lake Malombe reveal that extensive forest clearing and cropland expansion resulted in increased turbidity and reduced ecosystem service values (Makwinja et al., 2021a, 2021b). Such evidence supports the hypothesis that human-induced LULC changes, rather than climatic factors alone, are now the dominant agents of hydrological transformation in many African inland lakes.

In the context of Lake Rukwa, recent assessments indicate that catchment-level degradation coupled with water abstraction for irrigation has significantly disrupted the basin’s natural hydrology (Elisa et al., 2010; 2021). While rainfall variability contributes to short-term fluctuations, the long-term shrinkage trend corresponds closely with patterns of deforestation and cropland intensification detected through satellite imagery. These findings underscore the importance of managing terrestrial processes alongside hydrological interventions to sustain lake ecosystems.

2.3. Policy and Management Gaps

Despite clear evidence of degradation, effective lake management in Tanzania remains constrained by institutional and policy fragmentation. The National Water Policy (URT, 2002) and Integrated Water Resources Management (IWRM) Strategy (URT, 2010) provide a strong policy foundation emphasizing sustainable water use, reforestation, and catchment restoration. However, the translation of these frameworks into action has been inconsistent. Local water user associations often operate with limited technical capacity, while enforcement of land use regulations is weak (Mwakalila, 2005). Moreover, environmental governance tends to focus on water quantity rather than sediment quality or land use drivers.

Globally, integrated lake management approaches have shown that coupling remote sensing with participatory watershed planning can enhance decision-making (Archambault, 2024; Cheng et al., 2023). In the Tanzanian context, adopting such approaches could help bridge the gap between scientific monitoring and policy response. For instance, remote sensing data could inform the identification of erosion hotspots and guide targeted reforestation or soil conservation initiatives under the supervision of the Lake Rukwa Basin Water Board (2022). Furthermore, embedding socio-economic considerations such as livelihoods, tenure systems, and institutional incentives into catchment management would align with the Socio-Ecological Systems (SES) perspective that underpins this study (Ostrom, 2009).

Generally, the literature points to three critical insights: (1) remote sensing provides a robust foundation for multi-decadal lake monitoring but requires careful calibration; (2) land use change is the predominant driver of sedimentation and lake shrinkage in the Lake Rukwa Basin; and (3) despite the existence of policy frameworks, implementation gaps and weak data integration hinder effective response. These gaps justify the present study's focus on combining remote sensing analysis with management-oriented interpretation to support sustainable basin governance.

2.4. Theoretical Framework

Understanding the shrinkage of Lake Rukwa requires a conceptual lens that captures the intertwined relationships between human activities, environmental processes, and policy responses. This study adopts the Socio-Ecological Systems (SES) framework and the Pressure-State-Response (PSR) model to interpret these interactions. Together, they provide a complementary structure for linking causal drivers, observed environmental changes, and management strategies.

2.5. The Socio-Ecological Systems (SES) Framework

The SES framework views ecosystems and human societies as interconnected, co-evolving systems where feedback loops determine overall resilience (Ostrom, 2009). Within this perspective, the Lake Rukwa Basin functions as a coupled system in which anthropogenic land use practices such as deforestation, cropland expansion, and water abstraction interact with ecological processes like sediment transport, rainfall variability, and evaporation to influence the lake's hydrological balance.

In this study, "social subsystems" refer to land use and livelihood activities across the catchment, while "ecological subsystems" encompass the lake's hydrology, sediment load, and water quality. Changes in one subsystem directly affect the other: for instance, increased cultivation on steep slopes raises erosion and sediment delivery, which in turn reduces water storage capacity and affects fisheries and irrigation livelihoods. The SES framework thus provides a dynamic foundation for analyzing how these feedback mechanisms drive the observed contraction of Lake Rukwa's surface area.

Operationally guided by the SES framework, this research selected variables to holistically interpret the socio-environmental processes shaping the basin by connecting human pressures, ecological responses, and system feedbacks: human pressures were represented through LULC changes derived from Random Forest classification, ecological responses were assessed via NDWI-based surface area extraction and NDTI-derived sedimentation patterns, and system feedbacks were examined by correlating LULC transformations with turbidity trends to identify cause-effect linkages between land degradation and hydrological decline.

2.6. The Pressure State Response (PSR) Model

Complementing the SES approach, the PSR model (OECD, 1993) provides a structured framework to organize environmental information and assess policy implications, which in this study is applied by defining anthropogenic activities and climatic drivers like deforestation and rainfall variability as the Pressures; the measured changes in the lake's surface area and sediment load as the State; and potential management interventions such as reforestation and integrated water governance as the Responses. By mapping satellite-derived changes to this PSR framework, the study directly connects environmental degradation to its underlying causes to identify mitigation strategies, a structure that aligns with Tanzania's IWRM Strategy (URT, 2010) and its emphasis on adaptive management through continuous monitoring and policy feedback.

2.7. Integrating SES and PSR for Lake Rukwa Analysis

By integrating the SES and PSR frameworks, this study ensures that remote sensing outputs are interpreted not as mere descriptive data but as critical indicators of systemic pressures and responses, thereby strengthening the analytical and practical relevance of the research; for instance, NDWI-based shrinkage trends represent the degrading "state" of the system, LULC changes and rising NDTI values embody the anthropogenic "pressures," and recommended actions like catchment restoration correspond to the necessary "responses," a dual approach that conceptually bridges the gap between environmental monitoring and management by positioning satellite-derived evidence as empirical proof of both SES feedback loops and the sequential PSR stages, thus directly linking geospatial evidence to socio-ecological interpretation and actionable policy decisions.

Generally, the theoretical foundation of this study lies at the intersection of socio-ecological theory, environmental assessment models, and remote sensing science. The SES framework contextualizes the dynamic human-environment interactions within the Lake Rukwa Basin, while the PSR model structures these insights into actionable pathways for policy and management. Together, they provide an integrated basis for analyzing how human pressures translate into environmental change and how informed responses can enhance the resilience of Tanzania's inland lake ecosystems.

3.0. Context and Methods

3.1. Study Area Context

The Lake Rukwa Basin lies in southwestern Tanzania between latitudes 7°S–9°S and longitudes 31°E–34°E, spanning the administrative regions of Rukwa, Songwe, Mbeya, Katavi, and Tabora. The basin forms part of the Western Branch of the East African Rift System, characterized by fault-bounded plateaus and escarpments that channel runoff into the lake. Lake Rukwa itself is endorheic, receiving inflows primarily from the Songwe, Luiche, Kavu, and Rungwa rivers.

The surrounding highlands, particularly the Mbeya Highlands and Ufipa Plateau, exhibit steep slopes and highly erodible soils, making them susceptible to sediment generation (Majule & Mwalyosi, 2005; FAO, 2018). Average annual rainfall ranges from 800 to 1,200 mm, while evaporation exceeds 2,000 mm/year, producing a negative water balance that heightens sensitivity to both climatic fluctuations and anthropogenic disturbance (Habib et al., 2020).

Dominant land uses include mixed smallholder agriculture, livestock grazing, and timber extraction activities that contribute to extensive deforestation and soil erosion. These processes collectively make the Lake Rukwa Basin an ideal natural laboratory for studying the interactions between land use, sedimentation, and hydrological change.

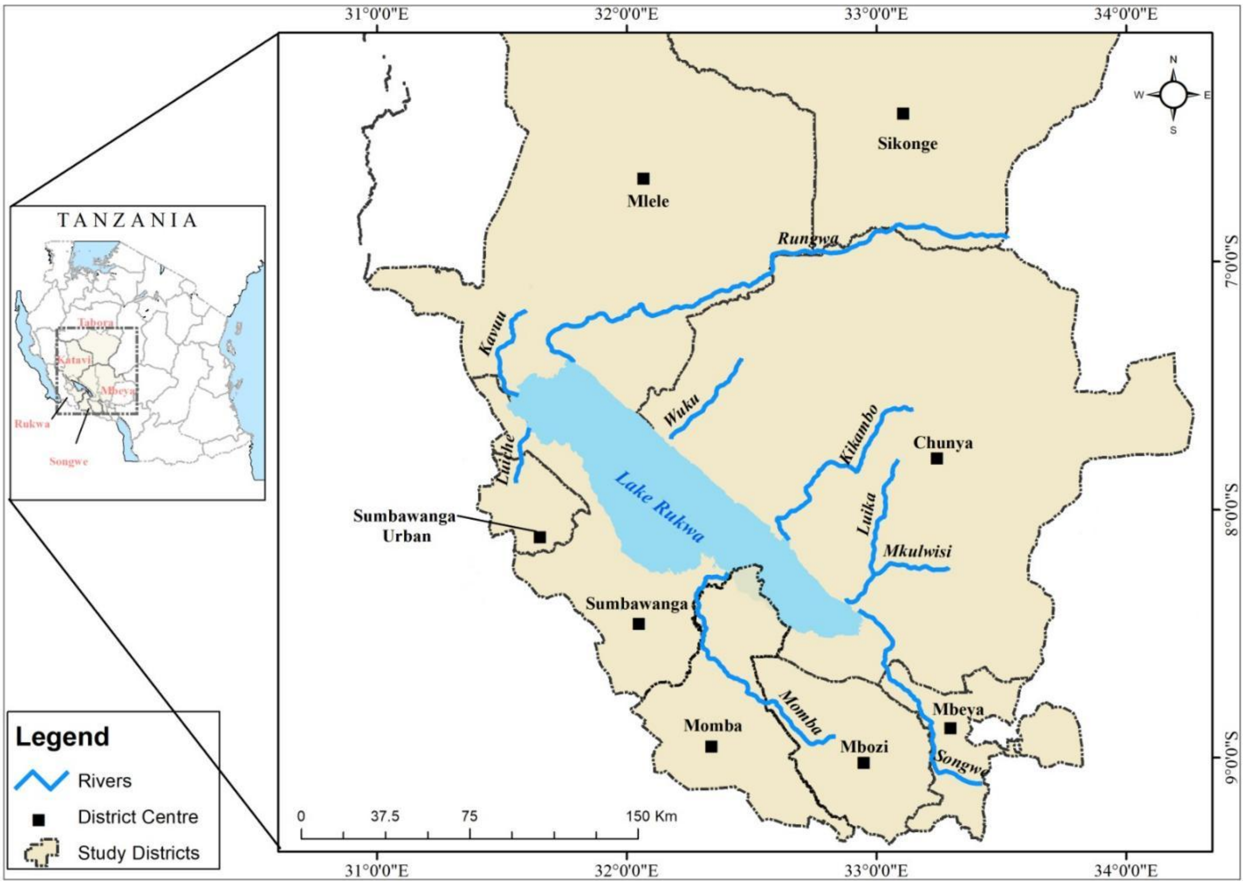

Figure 1: Location of the Study Areas
Source: UDSM Department of Geography (2025)

3.2. Data Sources and Year Selection

Remote Sensing Datasets

The study utilized multi-temporal satellite imagery from Landsat 5 TM (1994), Landsat 7 ETM+ (2004), and Landsat 8 OLI/TIRS (2014 and 2024), all accessed via the Google Earth Engine (GEE) platform and selected based on having less than 20% cloud cover, being from dry season months (April–September) to minimize seasonal fluctuations, and the availability of near-anniversary scenes to ensure inter-year consistency, while Sentinel-2 MSI imagery and high-resolution Google Earth Pro scenes were additionally used to enhance validation through visual cross-checking and accuracy assessment.

3.3. Justification for Year Selection

The four study years; 1994, 2004, 2014, and 2024 were strategically selected to capture distinct socio-environmental and climatic periods, establishing a 1994 baseline before major agricultural expansion, a 2004 snapshot following post-ENSO variability and early irrigation intensification, a 2014 benchmark coinciding with rapid deforestation linked to population growth, and a 2024 endpoint representing the most recent conditions under contemporary land management and climate stress, thereby enabling a comprehensive 30-year comparative analysis that captures decadal-scale dynamics aligned with major land policy and climatic milestones to ensure both environmental and temporal representativeness.

3.4. Image Preprocessing

The preprocessing steps were essential to ensure that the satellite imagery used in this study was of high quality and suitable (Yi et al., 2018) for accurately detecting surface area changes in Lake

Rukwa. All images were processed within the Google Earth Engine platform using standardized surface reflectance products, undergoing key preprocessing steps that included geometric correction for accurate co-registration, radiometric calibration to convert digital numbers to top-of-atmosphere reflectance, cloud and shadow masking via the Fmask algorithm, topographic correction using a DEM-based model to minimize illumination effects in sloped terrain, and atmospheric correction using GEE's built-in Landsat Surface Reflectance Collection to ensure inter-year comparability, with final image quality verified through reflectance histograms and visual inspection to confirm uniform illumination and the absence of residual cloud artifacts.

3.5. Lake Surface Area Extraction

The surface area of Lake Rukwa was delineated using the Normalized Difference Water Index (NDWI), a widely used spectral index for mapping open water bodies in optical remote sensing imagery (Shinde et al., 2024; Vasanthi et al., 2024). Processing was performed in Google Earth Engine (GEE), which enabled efficient multi-temporal analysis of Landsat imagery for the study years (1994, 2004, 2014, 2024). The Landsat green and near-infrared (NIR) bands corresponded to bands 2 and 4 for TM/ETM+, and bands 3 and 5 for OLI/TIRS sensors. The NDWI was calculated using the equation 1

$$NDWI = \frac{Green\ Band - NIR\ Band}{Green\ Band + NIR\ Band} \text{……………………………………..Equation 1}$$

A threshold value of 0.3 was applied to classify pixels as water (>0.3) or non-water (≤0.3). This value was selected following the original approach by McFeeters (1996) and supported by other studies on African inland water bodies (e.g., Rokni et al., 2014; Du et al., 2016), which showed that NDWI thresholds in the range of 0.25–0.35 effectively distinguish open water from surrounding vegetation and bare soil in medium-resolution imagery. For this study, the threshold was further validated through iterative visual inspection and comparison with high-resolution Google Earth Pro imagery to minimize misclassification in shallow or vegetated shoreline areas. This combination of literature-based selection and site-specific empirical verification ensured both methodological consistency and local accuracy. The NDWI-derived water masks for each study year were exported to ArcGIS for surface area computation and change detection. NDWI was applied solely for lake area delineation.

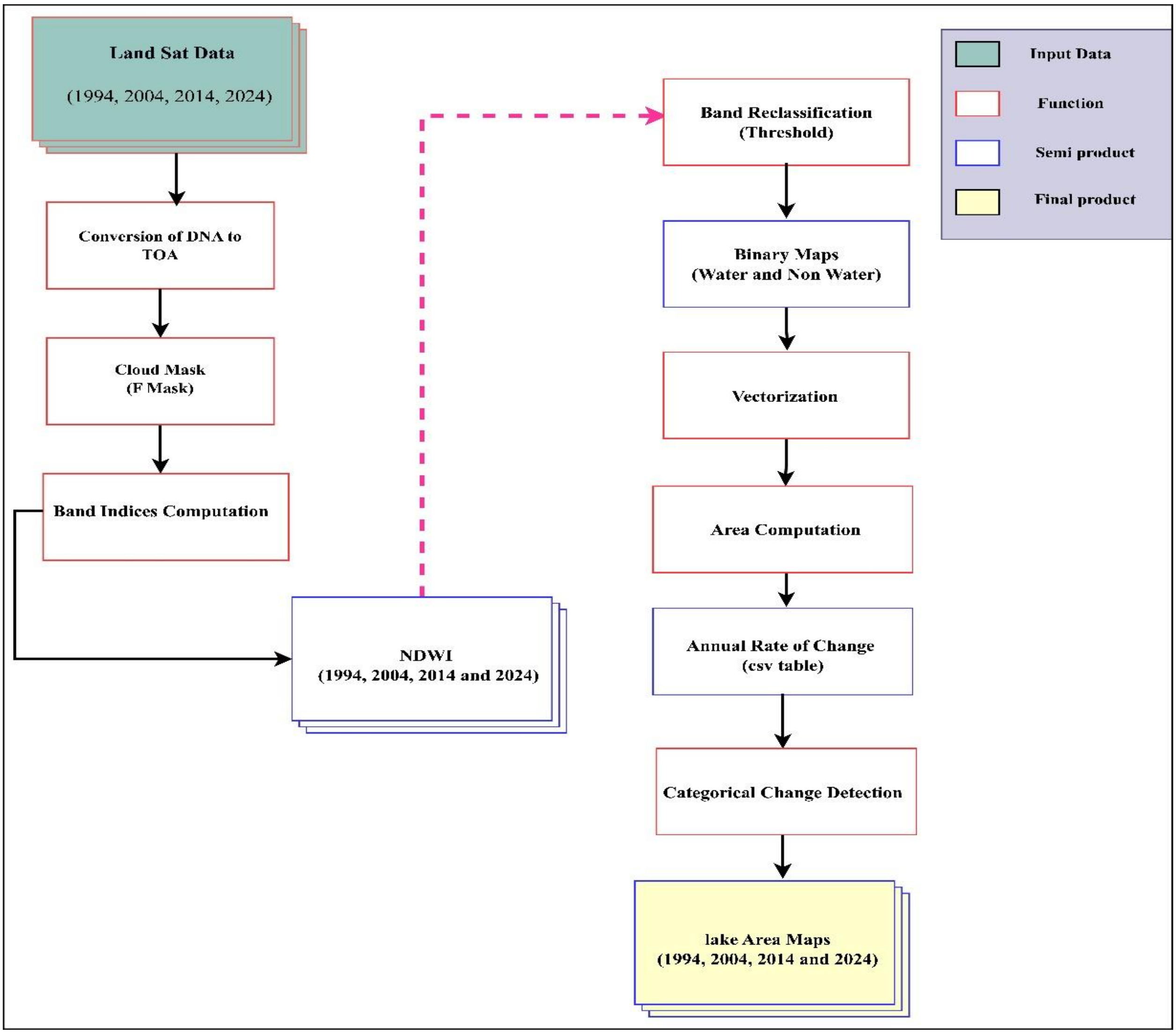

Figure 2: Data preprocessing and analysis for remote sensing sedimentation extraction

3.6. Land Use/Land Cover (LULC) Change Analysis

To assess potential catchment-scale drivers of sedimentation, LULC maps were generated for each study year using a supervised classification approach with the Random Forest (RF) algorithm in GEE. The classification scheme included five classes: water, vegetation, cropland, bare land, and built-up areas. Training samples for each class were derived from high-resolution Google Earth imagery and existing land cover datasets. Accuracy assessment was performed using a stratified random sampling approach, with confusion matrices and overall accuracy/Kappa coefficients calculated for each year to ensure classification reliability (Congalton, 1991). The LULC change maps were then analyzed to identify patterns of deforestation, agricultural expansion, and bare land increase in the lake’s catchment, which could contribute to sediment delivery

3.7. Sedimentation Proxy (NDTI)

Direct measurement of sedimentation in Lake Rukwa was not feasible due to the absence of bathymetric surveys and long-term in-situ suspended sediment concentration data. To overcome this limitation, the study adopted remote sensing-based sedimentation proxies that have been widely applied in similar fluvial environments (Blaisdell et al., 2016; Islam et al., 2020). The study employed the Normalized Difference Turbidity Index (NDTI), a spectral index widely used to detect variations in surface water turbidity from satellite imagery (Lacaux et al., 2007; Islam et al., 2020). NDTI exploits the difference in reflectance between the red and green bands, where turbid water typically exhibits higher red reflectance due to suspended sediments. The index was computed in Google Earth Engine (GEE) for the selected study years (1994, 2004, 2014, and 2024) using the following formula:

$$NDTI = \frac{Red - Green}{Red + Green} \text{………………………………………………Equation 2}$$

For Landsat 5 TM and Landsat 7 ETM+, the red and green bands corresponded to bands 3 and 2, respectively, while for Landsat 8 OLI/TIRS they corresponded to bands 4 and 3. Pre-processed surface reflectance data were used to minimize atmospheric effects. In this study, NDTI values were calculated specifically for major river inflow zones into Lake Rukwa, identified from high-resolution imagery and hydrological datasets. For each year, NDTI maps were generated, and values were extracted for buffered zones around the Songwe, Kalambo, and Lupa river mouths. The outputs were then exported to ArcGIS for spatial overlay with lake shoreline data and subsequent analysis

3.8. Change Detection and Statistical Analysis

Change detection was performed by overlaying NDWI-derived water polygons from each study year in **ArcGIS**. Net gains and losses in surface area were computed, and annual rates of change were derived using the formula:

$$\text{Rate} = \frac{(A_2 - A_1)}{A_1 \times n} \times 100$$

where A_1 and A_2 represent lake areas at times t_1 and t_2, and n is the number of years between observations.

LULC transitions were analyzed through transition matrices, quantifying conversions such as forest-to-cropland or shrubland-to-bare land. To explore linkages between catchment change and sedimentation, Pearson correlation and spatial regression analyses were conducted between LULC categories and mean NDTI values across sub-basins.

Spatial clustering of high NDTI zones was further assessed using Moran’s I to identify sedimentation hotspots within the basin.

3.9. Validation, Limitations, and Reproducibility

Validation was conducted through a multi-tiered approach involving visual inspection using Sentinel-2 and Google Earth imagery for shoreline verification, quantitative accuracy assessment via confusion matrices and Kappa statistics for each classification year, and cross-sensor turbidity validation to ensure consistency between Landsat and Sentinel datasets, which helped mitigate recognized limitations such as the absence of in-situ sediment data, potential spectral confusion in vegetated shorelines, and classification uncertainty in mixed land covers through the use of dynamic NDWI thresholds and multi-sensor validation, with all preprocessing and analysis scripts executed within GEE and ArcGIS Pro following a reproducible workflow documented for future studies.

4.0. Results

Lake Area Dynamics

Analysis of NDWI-derived maps revealed a consistent contraction in Lake Rukwa’s surface area over the past three decades (Figure 3). The total surface area declined from approximately 598,220 ha in 1994 to 532,943 ha in 2024, indicating a net loss of 65,277 ha (Table 1).

The period between 2004 and 2014 recorded the most rapid decline, with an annual reduction rate of –0.68% per year (≈3,933 ha/year). This phase corresponds with intensified agricultural expansion and catchment clearing observed in the LULC analysis. The subsequent decade (2014–2024) exhibited a slower decline (–0.12% per year), suggesting temporary stabilization, possibly due to short-term rainfall recovery or localized reforestation programs.

Spatially, shrinkage was most pronounced along the northern and eastern margins, particularly near the inflow zones of the Songwe and Luiche rivers. These shallow shoreline areas are more sensitive to sediment accumulation and reduced inflow. The southern and central portions of the lake remained relatively stable, reflecting greater depth and lower sediment deposition rates

As demonstrated by a bathymetric survey that shows a depth decline from 9.5 meters to 3.4 meters over a ten-year period, this sediment deposition lowers Lake Rukwa's effective depth, making shallow areas more susceptible to drying out during times of low water inflow (NASA Earth Observatory, 2019; Gwalema & Malata, 2018). Additionally, changes in land use within the lake's catchment area, such as deforestation, agriculture, and urbanization, increase soil erosion, further contributing to sedimentation.

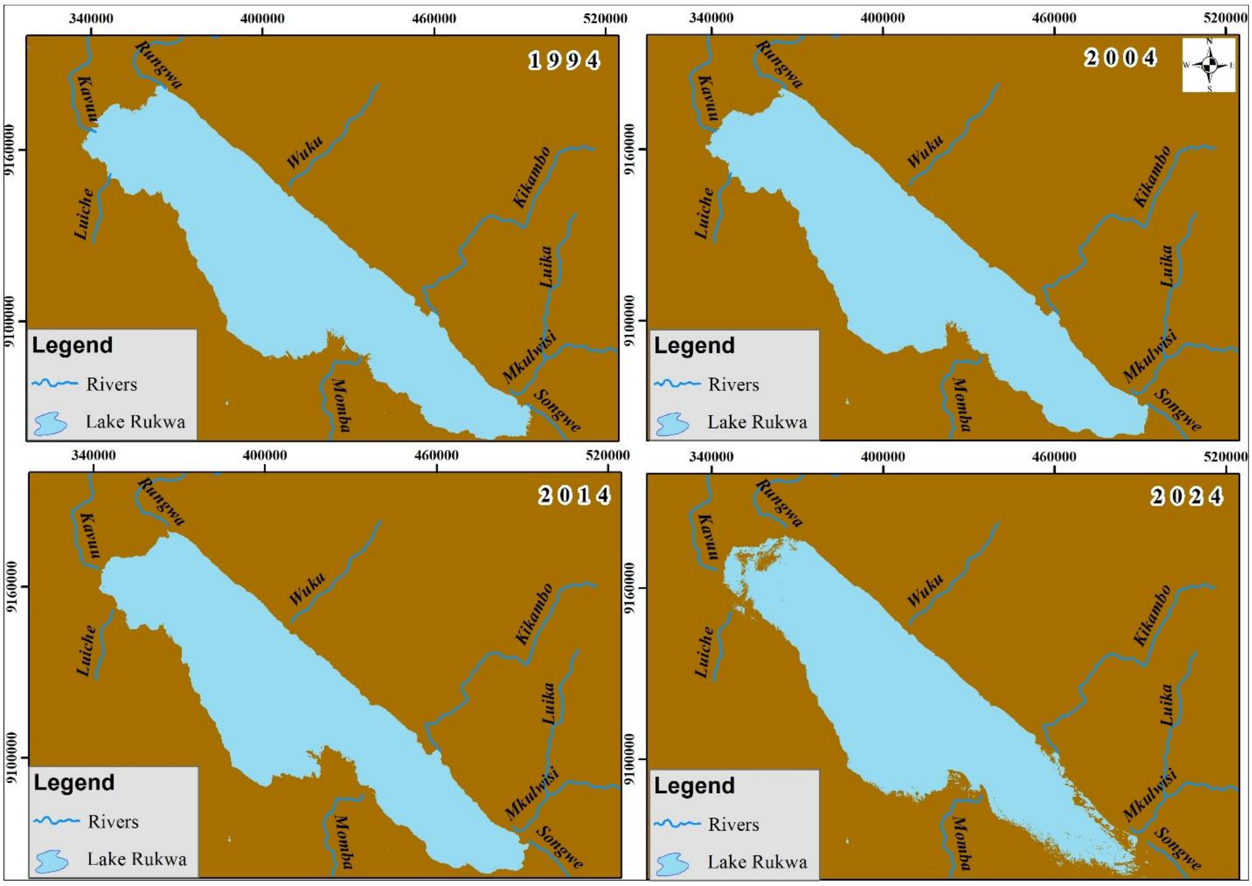

Figure 3. Distribution of Lake Rukwa Area from 1994 to 2024

Observed Trends in Lake Rukwa

Furthermore, figure 4 depicts observed trends of lake Rukwa from 1994 to 2024, with overall changes indicting decreasing in lake area. In 1994, the lake had an area of 598,220.55 Ha, which marks the highest value in the dataset. The surface area decreased by 2004, with the area recorded at 578,686.86 Ha. This reduction represents a loss of 19,533.69 Ha. By 2014, the lake's surface area further shrank to 539,351.73 Ha, a decrease of 39,335.13 Ha from 2004. Finally, in 2024, the lake area dropped to 532,943.28 Ha, reflecting a further reduction of 6,408.45 Ha.

The graph clearly shows a gradual yet steady contraction in the lake's area over the years. This continuous decline suggests an ongoing process of environmental change, likely due to factors such as reduced inflow from rivers and sedimentation.
The trend of shrinkage over time aligns with the broader environmental observations that suggest lake area reductions in many parts of the world due to natural and anthropogenic pressures. Understanding the specific drivers of these changes in Lake Rukwa will be essential for informing management strategies aimed at halting or reversing the decline in its surface area.

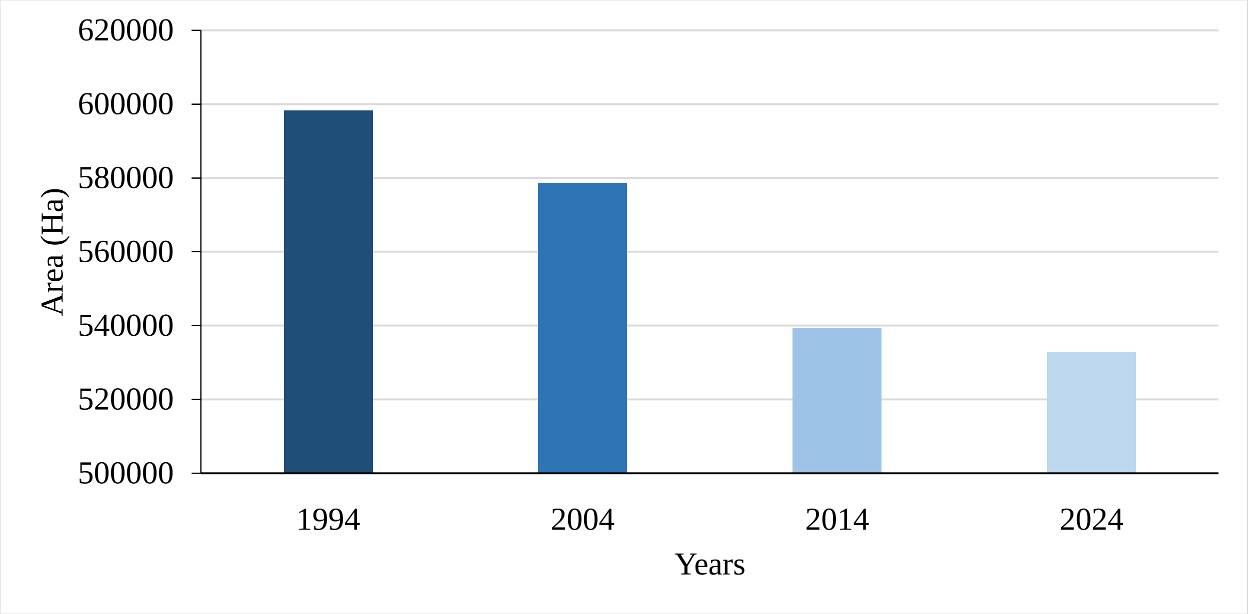

Figure 4: Changes in the area of Lake Rukwa from 1994 to 2024

Additionally, Table 1 shows that Lake Rukwa’s surface area has undergone significant changes over the study period, with the most pronounced decline occurring between 2004 and 2014. During this decade, the lake’s area decreased from 578,686.86 ha to 539,351.73 ha, a total loss of 39,335.13 ha. This equates to an annual rate of change of –0.68% per year, the highest in the study period, indicating a period of accelerated surface area reduction.

By comparison, the 1994–2004 period recorded an annual rate of change of –0.33% per year, while the most recent period, 2014–2024, showed a much slower rate of –0.12% per year. This steady reduction indicates a persistent hydrological imbalance in the basin, aligning with the **“**State**”** component of the PSR framework. The physical manifestation of lake shrinkage represents the ecosystem’s declining capacity to absorb the pressures exerted by land degradation and climatic stressors.

Overall, the calculated annual rates of change confirm a sustained reduction in Lake Rukwa’s surface area over the last three decades, with the highest rate of contraction in the mid-2000s and only a partial slowdown in recent years

Table 1: Decadal changes in Lake Rukwa surface area (1994–2024)

Years	Previous Area (Ha)	Current Area (Ha)	Change detected	Annual Rate Change (%)	Annual Change (Ha/year)
1994–2004	598,220.55	578,686.86	-19,533.69	-0.33	–1,953.37
2004–2014	578,686.86	539,351.73	-39,335.13	-0.68	–3,933.51
2014–2024	539,351.73	532,943.28	-6,408.45	-0.12	–641

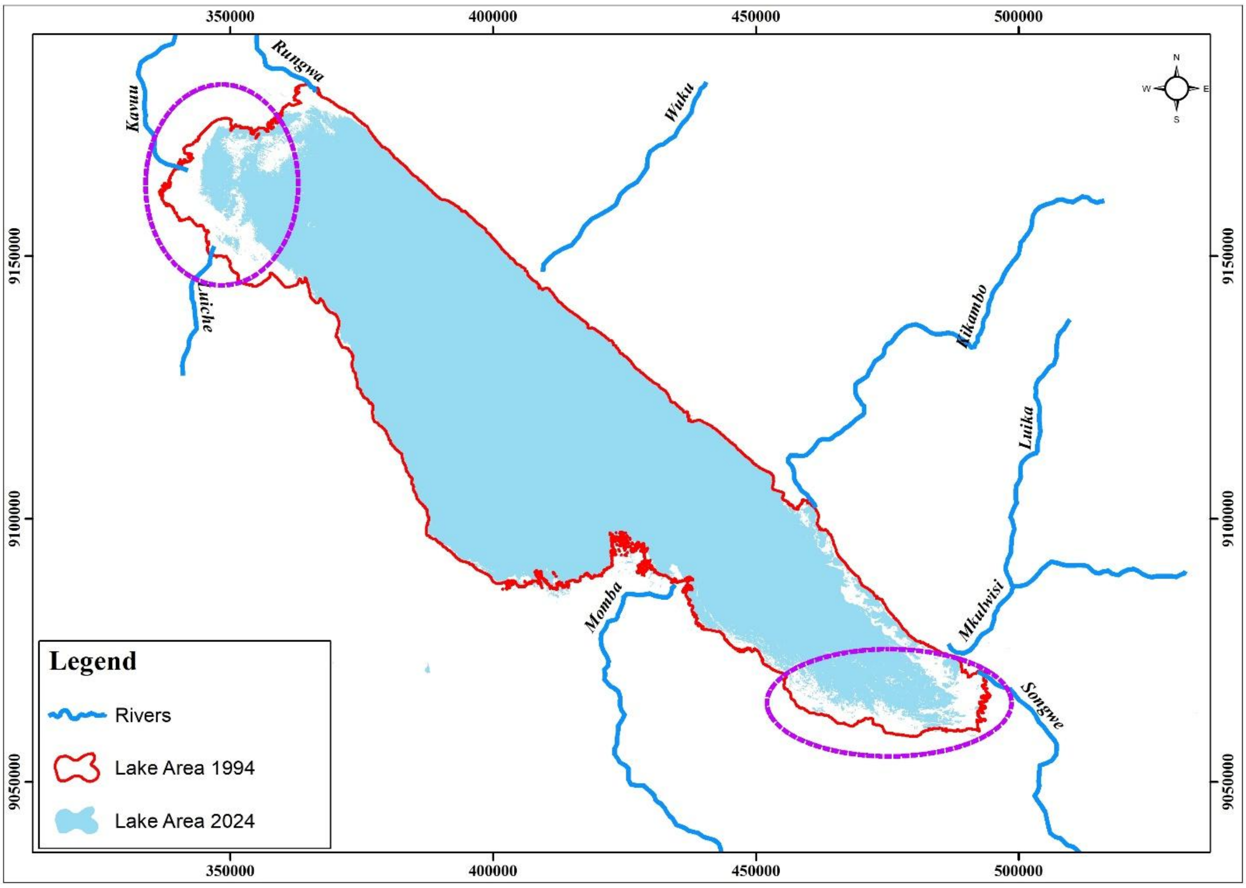

Figure 5: Changes of Lake Boundaries overtime

Since 1994, Lake Rukwa has experienced significant changes as a result of river sedimentation. In 1994, the lake encompassed a much larger area, as shown by the red outline on the map as shown in Figure 5. By 2024, however, the lake's size has noticeably diminished, indicating that substantial sedimentation has taken place during this period. The reduction in the lake's footprint serves as clear evidence that sediments carried by surrounding river systems have gradually filled the lake basin, leading to a receding shoreline. This process of sedimentation-driven infilling is a common occurrence that can dramatically reshape the morphology of lakes and other water bodies over time. The study identified the Songwe, Luiche, Kavu, and Rungwa rivers as significant contributors to sediment deposits in Lake Rukwa. The spatial variations in sedimentation patterns across the region underscore the necessity for targeted management strategies to effectively address this issue. Understanding and mitigating the impacts of sedimentation will be essential for preserving the ecological integrity and ecosystem services provided by this vital water body.

Land Use/Land Cover Dynamics in the Catchment

The LULC change detection analysis (Figure 6, Table 2) revealed pronounced transformations in the Lake Rukwa catchment over the 30-year study period (1994–2024). Forest cover declined markedly, with a net loss of approximately 709,841 ha, representing a reduction of more than 27% of the original forested area. Shrublands and grasslands also diminished significantly, by 536,266 ha and 386,757 ha respectively, while cropland expanded by over 504,500 ha. Built-up areas, though still covering a small fraction of the catchment, nearly doubled in extent, reflecting ongoing settlement growth.

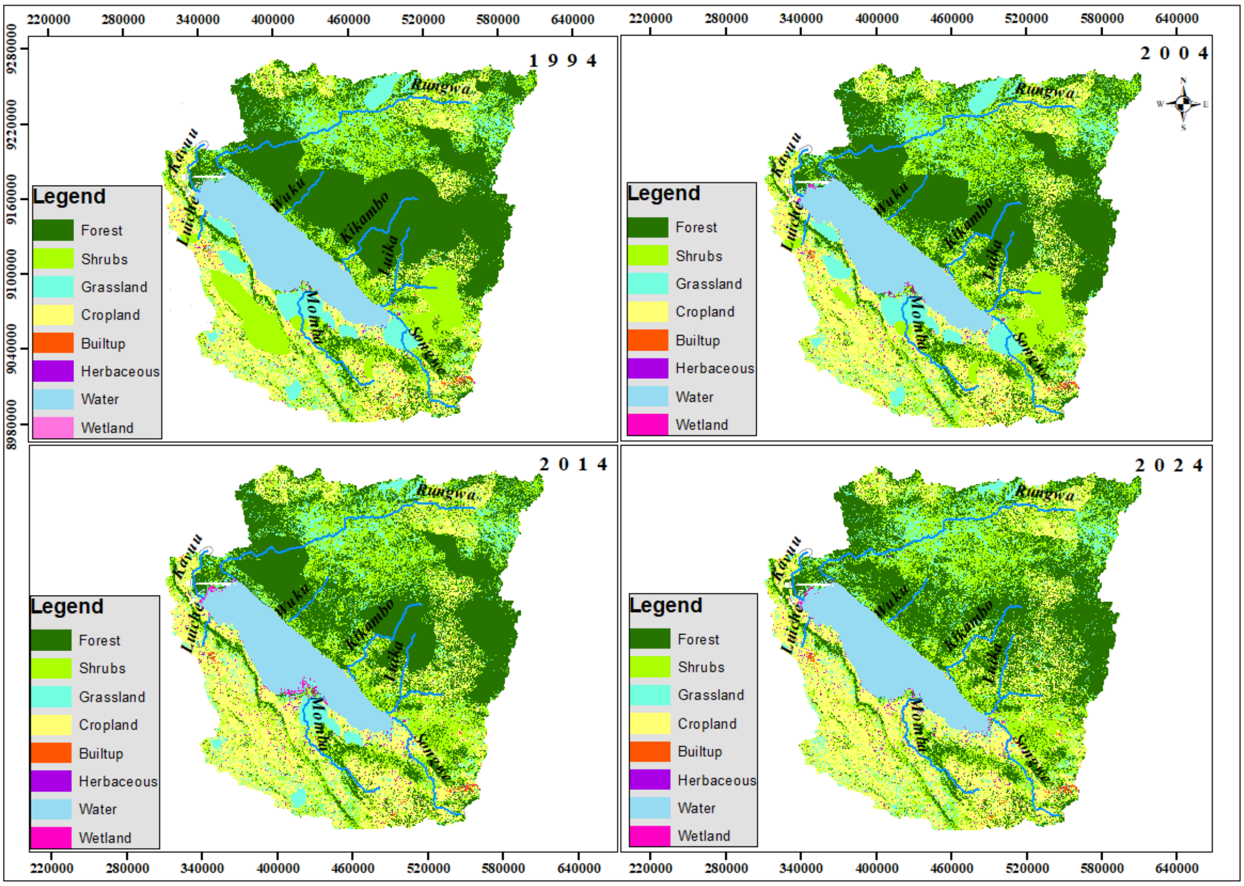

Figure 6: LULC of Lake Rukwa Catchment

These land cover changes are strongly linked to increased erosion potential and sediment delivery into the lake. The loss of forest and shrubland, particularly in the upper catchments of the Mbeya Highlands, Ufipa Plateau, and Chunya District, has reduced vegetative cover that previously stabilised soils and moderated runoff. In turn, agricultural expansion especially on sloping terrain and along riverbanks has exposed bare soils to intense seasonal rains, amplifying sediment transport.

The spatial correspondence between zones of deforestation and cropland expansion with high turbidity areas (as indicated by NDTI values) suggests a direct link between catchment LULC change and sedimentation within Lake Rukwa. This catchment degradation has not only accelerated infilling in shallow lake margins but also contributed to the long-term contraction of lake surface area observed in Section 3.1.

These results underline the role of land use practices as a key driver of hydrological and morphological changes in the lake, providing a critical connection between terrestrial activities and aquatic system responses. The following section (3.3) examines how these land cover shifts manifest in measurable increases in turbidity and sedimentation at major river inflows.

Table 2: Land cover change detetction

		LULC 2024									
		Forest	Shrubs	Grassland	Cropland	Built up	Water	Herbaceous	Wetland	Total	Loss
LULC 1994	Forest	1825931.2	234279	114331	133227	49323.1	73829.4	47424.7	57427.2	2535772	-709841
	Shrubs	128390.3	812910	64399.9	204444	36480.2	22029.5	34537.2	45984.5	1349175	-536266
	Grassland	47487.6	67818.4	332062	156601	20751.3	16892.9	46292.1	30913.5	718819	-386757
	Cropland	27849.3	40257.2	26272.5	863930	5685.8	4248.2	15947.3	9631.9	993823	-129892
	Builtup	2603.9	9759.7	2117.6	4856.3	6630.3	1847.8	4192.1	4145.8	36153.5	-29523.2
	Water	6528	3058.5	3848.6	2537.4	793.1	548879	1824.2	2384.3	569853	-20974.1
	Herbaceous	806.8	2402.4	1493.1	2560.4	242.1	6820	6476.7	147.7	20949.2	-14472.5
	Wetland	527.1	547.3	1396.8	278.6	372.8	311.2	300.8	12513.8	16248.4	-3734.6
	Total	2040124.2	1171032	545922	1368435	120279	674858	156995.1	163149		
	Loss	214193	358122.4	213859.8	504504.3	-113648	125979	150518.4	150634.9		

Sedimentation Proxy (NDTI) Trends

The Normalized Difference Turbidity Index (NDTI) analysis revealed distinct spatial and temporal variations in turbidity across monitored river buffers from 1994 to 2024 (Figure 7, Figure 8). Spatially, high turbidity zones (NDTI 0.2–0.3) were concentrated along certain river reaches adjacent to Lake Rukwa, notably in 1994 and 2024, with noticeable shifts in their distribution over time.

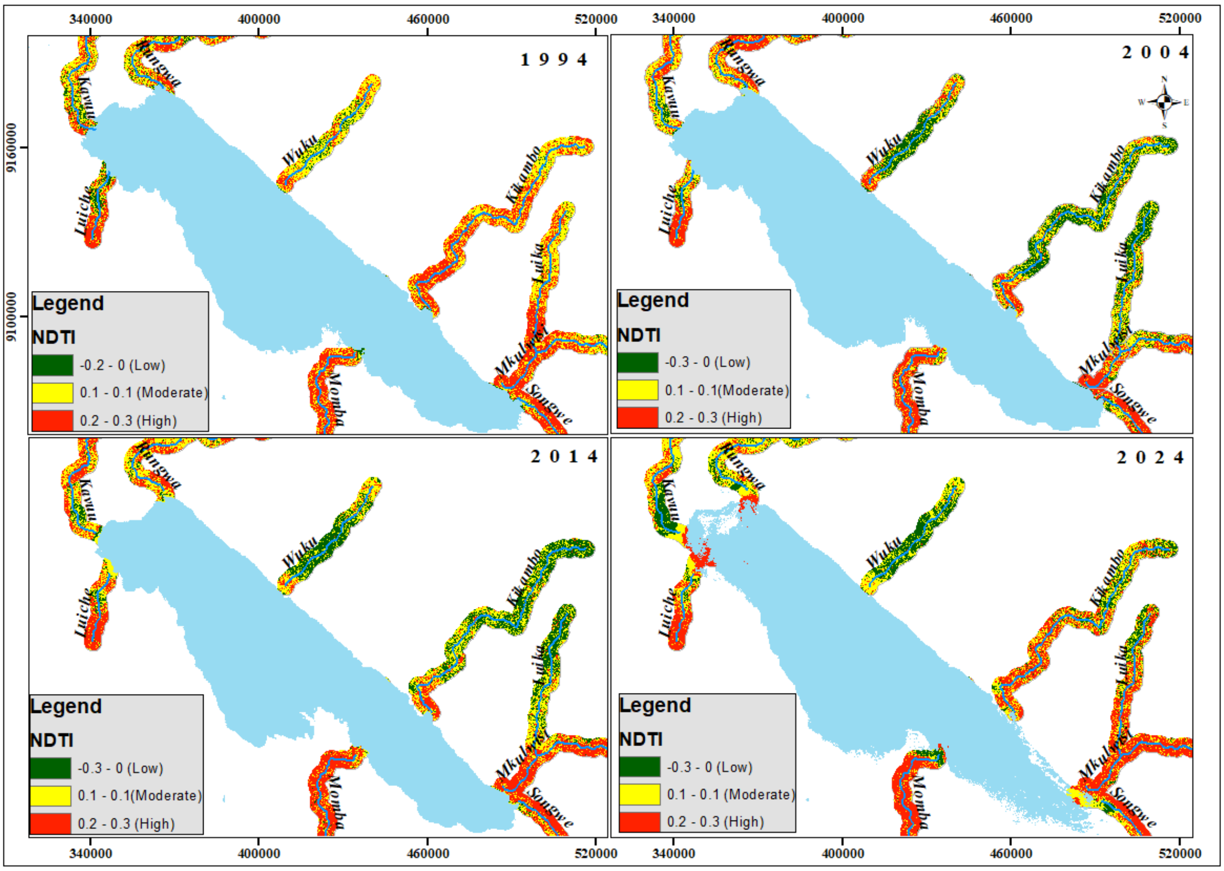

Figure 7: Spatial Dynamics of Normalized Turbidity Index from 1994 – 2024

Mean NDTI values showed variable trajectories among rivers. Mkulwisi, Momba, and Songwe exhibited consistent increases over the 30-year period, with Songwe rising from 0.08 in 1994 to 0.24 in 2024 — the most pronounced trend among all inflows. This pattern suggests a long-term escalation in suspended sediment loads, likely linked to catchment deforestation, agricultural expansion, and riverbank erosion in upstream zones identified in Section 3.2. Luiche also displayed a gradual increase, from 0.06 (1994) to 0.095 (2024), indicating persistent sedimentation pressures.

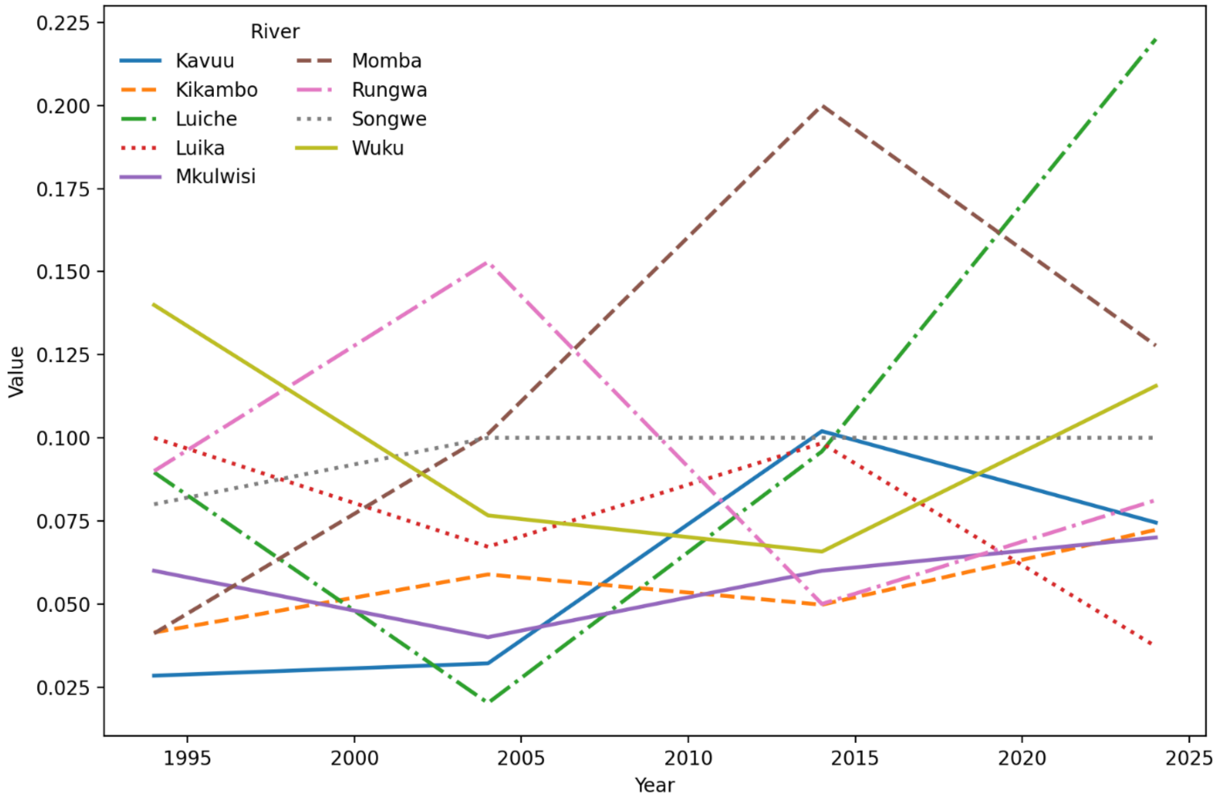

Figure 8: Temporal trends of Normalized turbidity index from 1994 to 2024

In contrast, Wuku recorded a sharp decline in NDTI from 0.07 in 1994 to near-zero in 2024, potentially reflecting reduced sediment input due to upstream damming, natural vegetation recovery, or altered hydrological connectivity. Kikambo and Luika showed fluctuating trends, with declines between 1994 and 2014 followed by increases in 2024, possibly tied to episodic land-use change or high-flow events. Rungwa remained relatively stable, with only minor fluctuations, implying consistent catchment conditions.

The NDTI maps (Figure 7) further reveal that low turbidity zones (green) became more dominant in certain rivers between 2004 and 2014, particularly along Wuku and parts of Kavuu. However, by 2024, high turbidity areas (red) re-emerged in rivers such as Luika and Kikambo, highlighting the persistent vulnerability of some sub-catchments to sediment inputs.

Overall, the variability in turbidity trends underscores that sediment drivers are catchment-specific. Rivers with steadily increasing NDTI, such as Songwe and Mkulwisi, align closely with deforestation and cropland expansion zones detected in Section 3.2, reinforcing the direct link between land use change and sediment delivery. Elevated turbidity not only accelerates infilling of shallow lake margins but also degrades water quality, exacerbating the contraction of Lake Rukwa’s surface area observed in Section 3.1. Addressing these issues will require targeted sediment control measures, such as riparian buffer restoration, bank stabilisation, and erosion management in the most impacted sub-catchments.

5.0. Discussion

This study utilized remote sensing to quantitatively assess the spatiotemporal changes in Lake Rukwa's surface area and infer the primary drivers of its shrinkage between 1994 and 2024. The NDWI analysis revealed a consistent decline in the lake's surface area, with a total loss of approximately 65,277 hectares over the 30-year period. The most accelerated loss occurred between 2004 and 2014 at a rate of –0.68% per year (–3,933.51 ha/year). This pattern of sustained decline places Lake Rukwa within a broader global context of endorheic and rift valley lakes experiencing significant water loss due to intertwined climatic and anthropogenic pressures (Bao et al., 2024; Liu et al., 2024; Yan et al., 2022). While long-term tectonic processes have undoubtedly influenced the basin's geomorphology and historical lake levels (Delvaux et al., 1998), the changes observed in this three-decade window are primarily attributed to more recent hydrological and anthropogenic pressures, which were directly quantified in this analysis.

The LULC change detection analysis revealed a net loss of over 700,000 hectares of forest in the catchment, alongside a significant expansion of cropland (>500,000 ha). This widespread conversion of natural vegetation to agricultural land is a key driver of soil erosion, a phenomenon consistently documented across Eastern Africa. Similar LULC dynamics, leading to increased erosion and sediment loading, have been identified as a primary cause of shrinkage in Lake Malombe, Malawi (Makwinja et al., 2021a), and in the Gilgel Gibe catchment, Ethiopia (Tilahun et al., 2024). The spatial correlation between these zones of deforestation/cropland expansion and areas of high turbidity, as indicated by elevated NDTI values at river mouths, provides strong evidence that land use change is a major contributor to sediment loading in the lake. This aligns with the findings of Nkwasa et al. (2024), who demonstrated a strong correlation between remote sensing-derived turbidity and modelled sediment loads in Lake Tana, validating the use of spectral indices like NDTI as effective proxies where in-situ data is scarce.

The NDTI analysis provided a spatially explicit proxy for sedimentation, showing a clear increase in turbidity in the inflow zones of major rivers like the Songwe (NDTI rising from 0.08 to 0.24 between 1994 and 2024). This measured increase in suspended sediments accelerates the infilling of the lake basin, particularly in its shallow margins, leading to the shoreline recession documented in the NDWI-derived maps (Figure 5). This process of sedimentation-driven infilling is a critical factor in the degradation of shallow lakes globally (Yagmur et al., 2021; Lawmchullova & Rao, 2024). While this study did not conduct new bathymetric surveys, the measured surface area loss and increased turbidity strongly support existing reports of severe shallowing, such as the documented depth reduction from 9.5m to 3.4m over a decade (Down To Earth, 2017; Gwalema & Malata, 2018). The calculated annual area loss rates from this study (e.g., –3,933.51 ha/year during 2004-2014) quantitatively reflect the consequences of this sedimentation process, which is exacerbated by the lack of sediment trapping mechanisms upstream, a common issue also noted in studies of Iraqi reservoirs (Othman et al., 2024).

Climatic variability interacts with and amplifies these anthropogenic drivers. As a closed basin, Lake Rukwa's surface area is highly sensitive to rainfall fluctuations, a characteristic shared with other terminal lakes in arid and semi-arid regions (Schäfer et al., 2016; Archambault, 2024; Cheng et al., 2023). The deceleration in the rate of surface area loss to –0.12% per year in the most recent period (2014–2024) may be partly attributable to short-term climatic recovery or variability, a pattern of non-linear shrinkage also observed in lakes like Ebinur in China (Liu et al., 2024) and Abaya in Ethiopia (Mulu et al., 2024). However, the long-term trend of decline persists, indicating that the foundational hydrological balance has been altered. The high evaporation rates in the region (2000–2200 mm/year), which consistently exceed precipitation (UNEP-GRID Arendal, 2015), are exacerbated by reduced inflow due to water abstraction for the expanded irrigation identified in the LULC analysis. This creates a feedback loop where increased evaporation and abstraction lower water levels, exposing more sediment to wind-driven resuspension and further increasing turbidity, a process documented in the Great Salt Lake (Radwin & Bowen, 2024). Thus, the lake's shrinkage is not the result of a single factor but rather the synergistic impact of land use-mediated sedimentation and water abstraction, compounded by climatic stress, a conclusion echoed by studies across diverse lake systems from North America to Central Asia (Zhang et al., 2015; Nyberg et al., 2024).

This integrated remote sensing assessment confirms that the primary contemporary drivers of Lake Rukwa's shrinkage are anthropogenically induced: namely, catchment deforestation leading to sedimentation, and water diversion for agriculture. The ecological and socioeconomic consequences loss of fisheries, biodiversity habitat degradation, and reduced water quality mirror those documented in Lake Malombe, where LULC changes led to a drastic decline in ecosystem service values (Makwinja et al., 2021b). While tectonic activity set the stage for the lake's existence and historical dynamics, the changes quantified here over the past 30 years are overwhelmingly driven by changes on the landscape surface. The findings by Elisa et al. (2010, 2021) on the significant role of irrigation water abstraction are supported by the observed cropland expansion in this study's LULC maps. Therefore, the situation in Lake Rukwa is distinct from lakes where water level changes are primarily climate-driven; here, human activities in the catchment are the dominant force accelerating its loss, a critical differentiation that must guide management and policy interventions.

6.0. Conclusion and Recommendations

6.1. Conclusion

The three-decade shrinkage of Lake Rukwa reflects a complex but discernible pattern in which human-driven catchment degradation has emerged as the dominant force reshaping the basin’s hydrology. Remote sensing evidence demonstrates that deforestation, cropland expansion, and unsustainable water abstraction have accelerated sediment inflows, reduced water depth, and destabilized the lake’s ecological balance. While climatic variability contributes to short-term fluctuations, the long-term trajectory of decline corresponds most closely with land use transformations and weak enforcement of catchment management policies.

From a community development perspective, the contraction of Lake Rukwa is not merely an environmental issue but a socio-economic challenge that undermines fisheries, irrigation, livestock grazing, and wetland livelihoods across five regions. The findings highlight the urgent need to embed ecological restoration within participatory development frameworks. Reforestation, soil erosion control, and sustainable water use must be pursued not only as technical interventions but as community-driven strategies that align environmental stewardship with livelihood security.

Ultimately, the study underscores that adaptive basin governance—grounded in evidence-based monitoring, integrated land-water planning, and active community engagement—is essential to reversing Lake Rukwa’s decline. Strengthening institutional capacity while empowering local actors will determine whether the basin can transition from degradation toward resilience, thereby safeguarding both ecological integrity and human development in Tanzania.

6.2. Recommendations

Catchment Restoration and Land Use Management

The study demonstrates that deforestation and cropland expansion are the primary drivers of sediment inflows into Lake Rukwa. It is therefore recommended that basin-level authorities prioritize reforestation programs targeting erosion-prone slopes in the Mbeya Highlands and Ufipa Plateau. Agroforestry and conservation agriculture should be promoted as community-based strategies that simultaneously restore ecological integrity and sustain livelihoods. Integrating soil erosion control measures, such as terracing and vegetative buffers, into local farming practices will reduce sediment transport while enhancing agricultural productivity.

Strengthening Basin Governance

Institutional fragmentation remains a major barrier to effective lake management. The Lake Rukwa Basin Water Board should be empowered with adequate technical capacity, financial resources, and community representation. Coordination between land use planning authorities and water governance institutions must be strengthened to ensure that agricultural expansion, timber extraction, and irrigation schemes are regulated within the framework of Integrated Water Resources Management (IWRM).

Sustainable Water Abstraction

Unsustainable irrigation withdrawals exacerbate hydrological imbalance. Clear water permitting systems, supported by monitoring technologies, should be enforced to regulate abstraction. Promotion of efficient irrigation methods such as drip irrigation can reduce water demand while maintaining crop yields. Community sensitization programs should emphasize the long-term risks of unchecked water use for both livelihoods and ecological resilience.

Evidence-Based Monitoring and Research

Remote sensing has proven effective in tracking lake shrinkage and sedimentation trends. It is recommended that these tools be institutionalized within basin management authorities to enable continuous monitoring. Complementary field-based sediment surveys and hydrological modeling should be integrated to refine sediment budgets and validate satellite-derived indices. This dual approach will strengthen adaptive management and provide reliable data for policy decisions.

Community Engagement and Livelihood Integration

Lake Rukwa’s decline directly affects fisheries, grazing, and irrigation livelihoods. Sustainable catchment management must therefore embed community development incentives. Initiatives such as community forestry, conservation agriculture, and participatory watershed planning should be designed to align ecological restoration with livelihood security. Empowering local communities through training, tenure security, and benefit-sharing mechanisms will foster ownership and long-term commitment to catchment protection.

Policy Integration and Advocacy

National frameworks such as the Water Policy (2002) and IWRM Strategy (2010) provide a strong foundation but require effective translation into practice. Advocacy should focus on integrating remote sensing evidence into national and regional planning processes. Policymakers must be encouraged to adopt a socio-ecological systems perspective, recognizing that sustainable lake management is inseparable from community development, poverty reduction, and climate resilience.

Overall, these recommendations emphasize that Lake Rukwa’s shrinkage is both an ecological and a community development challenge. Addressing it requires a holistic approach that combines scientific monitoring, institutional reform, and grassroots participation. By embedding ecological restoration within community-driven development frameworks, Tanzania can safeguard Lake Rukwa while advancing its broader goals of sustainable livelihoods and environmental resilience.

References

Archambault, A. L. (2024). *Investigating Climate Change Impacts Of Surface Water Dynamics In A Cold Region Terminal Lake Basin Using Remote Sensing Technology* (Doctoral dissertation, The University of North Dakota).

Bao, N., Song, W., Ma, J., & Chu, Y. (2024). Multi-Source Remote Sensing Analysis of Yilong Lake’s Surface Water Dynamics (1965–2022): A Temporal and Spatial Investigation. *Water*, *16*(14), 2058. https://doi.org/10.3390/w16142058

Cheng, N., Yang, T., Wu, T., Hu, R., & He, X. (2023). Lake shrinkage–induced terrestrial ecological environmental quality degradation in a semiarid lake basin. *Environmental Science and Pollution Research*, *30*(57), 120892-120902. https://doi.org/10.1007/s11356023-30421-y

Delvaux, D., Kervyn, F., Vittori, E., Kajara, R. S. A., & Kilembe, E. (1998). Late Quaternary tectonic activity and lake level change in the Rukwa Rift Basin. *Journal of African Earth Sciences*, *26*(3), 397-421.

Down To Earth. (2017). *As Tanzania's Lake Rukwa continues to dry up, NGOs focus on sensitising locals*. Retrieved from https://www.downtoearth.org.in/news/water/as-tanzania-s-lake_rukwa-continue-to-dry-up-ngos-focus-on-sensitising-locals-58104

Elisa, M., Gara, J. I., & Wolanski, E. (2010). A review of the water crisis in Tanzania's protected areas, with emphasis on the Katuma River Lake Rukwa ecosystem. *Ecohydrology & Hydrobiology*, *10*(2-4), 153-165

Elisa, M., Kihwele, E., Wolanski, E., & Birkett, C. (2021). Managing wetlands to solve the water crisis in the Katuma River ecosystem, Tanzania. *Ecohydrology & Hydrobiology*, *21*(2), 211-222.

FAO. (2018). *State of the Forests in Tanzania*. Food and Agriculture Organization of the United Nations

Fischer, M. L., Markowska, M., Bachofer, F., Foerster, V. E., Asrat, A., Zielhofer, C., ... & Junginger, A. (2020). Determining the pace and magnitude of lake level changes in southern Ethiopia over the last 20,000 years using lake balance modeling and SEBAL. *Frontiers in Earth Science*, *8*, 197. https://doi.org/10.3389/feart.2020.00197

Gao, Q., Chen, S., Kimirei, I. A., Zhang, L., Mgana, H., Mziray, P., ... & Shen, Q. (2018). Wet deposition of atmospheric nitrogen contributes to nitrogen loading in the surface waters of Lake Tanganyika, East Africa: a case study of the Kigoma region. *Environmental Science and Pollution Research*, *25*(12), 11646-11660. https://doi.org/10.1007/s11356-018-13894

Habib, M., Mohamed, Y. A., & van Griensven, A. (2020). Hydrological variability of Lake Rukwa using remote sensing and climate data. *Journal of Hydrology: Regional Studies*, 27, 100659

Islam, A., Ahmed, T., & Das, S. (2020). *Assessing sediment dynamics using NDTI and NDWI indices from multi-temporal Landsat imagery*. International Journal of Applied Earth Observation and Geoinformation, 88, 102056

Kazemi Garajeh, M., Haji, F., Tohidfar, M., Sadeqi, A., Ahmadi, R., & Kariminejad, N. (2024). Spatiotemporal monitoring of climate change impacts on water resources using an integrated approach of remote sensing and Google Earth Engine. *Scientific reports*, *14*(1), 5469. https://doi.org/10.1038/s41598-024-56160-9

Lacaux, J. P., Tourre, Y. M., & Vignolles, C. (2007). *Use of remotely sensed data for the study of climatic and hydrological variability of inland waters in tropical Africa*. Remote Sensing of Environment, 106(2), 254–272

Lake Rukwa Basin. (2022). Laken Rukwa Basin Water Board Hydrological Bulletin Lake Rukwa (Issue July 2022)

Lameck, A. S., Saeed, O., Justine, P. N., Mwakagile, D., Akos, P., & Boros, E. (2024). Hydrochemical properties and heavy metal concentrations (ecological and human risk) of lake Rukwa. *Environmental Challenges*, *15*, 100940

Lawmchullova, I., & Rao, C. U. B. (2024). Estimation of siltation in Tuirial dam: a spatio-temporal analysis using GIS technique and bathymetry survey. *Journal of Sedimentary Environments*, *9*(1), 81-97. https://doi.org/10.1007/s43217-023-00158-2

Liu, Y., Wang, Q., Wang, D., Si, Y., Qi, T., Duan, H., & Shen, M. (2024). Dynamic Changes and Driving Factors in the Surface Area of Ebinur Lake over the Past Three Decades. *Remote Sensing*, *16*(20), 3876. https://doi.org/10.3390/rs16203876

Majule, A. E., & Mwalyosi, R. B. B. (2005). Land use and cover changes in relation to agricultural practices in Tanzania. *African Journal of Environmental Assessment and Management*, *10*(1), 1–13

Makwinja, R., Kaunda, E., Mengistou, S., & Alamirew, T. (2021a). Impact of land use/land cover dynamics on ecosystem service value—a case from Lake Malombe, Southern Malawi. *Environmental Monitoring and Assessment*, *193*(8), 492. https://doi.org/10.1007/s10661-021-09241-5

Makwinja, R., Mengistou, S., Kaunda, E., & Alamirew, T. (2021b). Land use/land cover dynamics, trade-offs and implications on tropical inland shallow lakes' ecosystems' management: Case of Lake Malombe, Malawi. *Sustainable Environment*, *7*(1), 1969139. https://doi.org/10.1080/27658511.2021.1969139

Maro, P. S., Lyimo, T. J., & Mnyanga, D. A. (2021). Impacts of land use changes on watershed degradation in the Lake Rukwa Basin. *Tanzania Journal of Science*, 47(2), 656–670

McFeeters, S. K. (1996). *The use of the normalized difference water index (NDWI) in the delineation of open water features*. International Journal of Remote Sensing, 17(7), 1425-1432

Mulu, B. A., Zimale, F. A., & Kebede, M. G. (2024). Remote sensing-based long-term assessment of water dynamics and influencing factors in Abaya and Chamo Lakes, East African Rift Valley, Ethiopia. *Air, Soil and Water Research*, *17*, 11786221241299932 https://doi.org/10.1177/11786221241299932

Mwakalila, S. (2005). Water resource use and conflicts in the Pangani River Basin, Tanzania. *Physics and Chemistry of the Earth, Parts A/B/C*, 30(11–16), 903–912. https://doi.org/10.1016/j.pce.2005.08.044

Nkwasa, A., Getachew, R. E., Lekarkar, K., Yimer, E. A., Martínez, A. B., Tang, T., & van Griensven, A. (2024). Can turbidity data from remote sensing explain modelled spatial and temporal sediment loading patterns? An application in the Lake Tana Basin. *Environmental Modeling & Assessment*, *29*(5), 871-882. https://doi.org/10.1007/s10666-024-09972-y

Nyberg, B., Sayre, R., & Luijendijk, E. (2024). Increasing seasonal variation in the extent of rivers and lakes from 1984 to 2022. *Hydrology and Earth System Sciences*, *28*(7), 1653-1663 https://doi.org/10.5194/hess-28-1653-2024

OECD. (1993). *Core set of indicators for environmental performance reviews*. Organisation for Economic Co-operation and Development, Paris

Ogutu-Ohwayo, R., Natugonza, V., Musinguzi, L., Olokotum, M., & Naigaga, S. (2016). Implications of climate variability and change for African lake ecosystems, fisheries productivity, and livelihoods. *Journal of Great Lakes Research*, *42*(3), 498-510

Ostrom, E. (2009). *A general framework for analyzing sustainability of social-ecological systems*. Science, 325(5939), 419–422

Othman, A. A., Ali, S. S., & Scheytt, T. (2024). Comparison between multi RUSLE-SDR models for estimation of reservoir sedimentation: a case study of Dokan Lake Basin, Iraq Iran. *Environmental Earth Sciences*, *83*(13), 419. https://doi.org/10.1007/s12665-024-11713-z

Pekel, J. F., Cottam, A., Gorelick, N., & Belward, A. S. (2016). High-resolution mapping of global surface water and its long-term changes. *Nature*, 540(7633), 418–422

Radwin, M. H., & Bowen, B. B. (2024). Evolution of Great Salt Lake's Exposed Lakebed (1984-2023): Variations in Sediment Composition, Water, and Vegetation from Landsat OLI and Sentinel MSI Satellite Reflectance Data. *Utah Geological Association Publication*

Schäfer, M. P., Dietrich, O., & Mbilinyi, B. (2016). Streamflow and lake water level changes and their attributed causes in Eastern and Southern Africa: State of the art review. *International Journal of Water Resources Development*, *32*(6), 853-880. https://doi.org/10.1080/07900627.2015.1091289

Tanzania Meteorological Authority. (n.d.). *Rainfall and climate data* [Data set]. Retrieved September 2, 2025, from https://www.meteo.go.tz/

Tilahun, Z. A., Bizuneh, Y. K., & Mekonnen, A. G. (2024). A spatio-temporal analysis of the magnitude and trend of land use/land cover changes in Gilgel Gibe Catchment, Southwest Ethiopia. *Heliyon*, *10*(2)

UNEP-GRID Arendal. (2015). *Hydrology and water resources of Africa*. https://www.grida.no/publications/428

United Republic of Tanzania (URT). (2002). *National Water Policy (NAWAPO)*. Ministry of Water and Livestock Development, Dar es Salaam

United Republic of Tanzania (URT). (2010). *Integrated Water Resources Management (IWRM) Strategy*. Ministry of Water and Irrigation, Dar es Salaam

Valimba, P. C. (2019). Development of improved characteristic equations for lake Rukwa in Tanzania. *Tanzania Journal of Engineering and Technology*, *38*(01), 83-96

Yagmur, N., Bilgilioglu, B. B., Dervisoglu, A., Musaoglu, N., & Tanik, A. (2021). Long and short term assessment of surface area changes in saline and freshwater lakes via remote sensing. *Water and Environment Journal*, *35*(1), 107-122 https://doi.org/10.1111/wej.12608

Yan, W., Ma, X., Liu, Y., Qian, K., Yang, X., Li, J., & Wang, Y. (2022). Ecological assessment of terminal lake basins in central Asia under changing landscape patterns. *Remote Sensing*, *14*(19), 4842. https://doi.org/10.3390/rs14194842

Zhang, F., Tiyip, T., Johnson, V. C., Kung, H. T., Ding, J. L., Sun, Q., ... & Chan, N. W. (2015). The influence of natural and human factors in the shrinking of the Ebinur Lake, Xinjiang, China, during the 1972–2013 period. *Environmental monitoring and assessment*, *187*(1),4128. https://doi.org/10.1007/s10661-014-4128-4

Policy Brief: Shrinking Waters of Lake Rukwa Basin, Tanzania: Remote Sensing Insights and Implications for Catchment Management (1994–2024)

Background

Lake Rukwa, located in the southwestern highlands of Tanzania, has undergone significant shrinkage over the past thirty years. Remote sensing evidence shows that the lake's surface area has declined by more than 65,000 hectares, with the most rapid contraction occurring between 2004 and 2014. This decline is not merely a natural phenomenon but is strongly linked to human-driven catchment degradation, including widespread deforestation, cropland expansion, and unsustainable water abstraction. Climatic variability has compounded these pressures, creating a socio-ecological crisis that threatens biodiversity, fisheries, and livelihoods across five regions.

Key Findings

The study demonstrates that Lake Rukwa's surface area decreased from 598,220 hectares in 1994 to 532,943 hectares in 2024. The decade between 2004 and 2014 recorded the sharpest decline, with an annual reduction rate of 0.68 percent, equivalent to nearly 4,000 hectares per year. This period coincided with intensified agricultural expansion and catchment clearing. Deforestation within the basin reached approximately 700,000 hectares, while cropland expanded by more than 500,000 hectares. These land use changes accelerated soil erosion, leading to increased sediment inflows into the lake. Rising turbidity values in rivers such as the Songwe, where the Normalized Difference Turbidity Index rose from 0.08 to 0.24, confirm the intensification of sedimentation. Sediment accumulation has reduced the lake's depth from 9.5 meters to 3.4 meters in just a decade, making shallow zones highly vulnerable to drying during periods of low inflow.

Policy Gaps

Although Tanzania has established strong policy frameworks such as the National Water Policy of 2002 and the Integrated Water Resources Management Strategy of 2010, implementation remains weak. Enforcement of land use regulations is inconsistent, and local water user associations often lack technical capacity. Institutional coordination among water authorities is fragmented, and monitoring systems rarely integrate remote sensing evidence into decision-making. As a result, management responses have focused narrowly on water quantity while neglecting sediment quality and land use drivers.

Policy Recommendations

Catchment restoration must be prioritized through basin-wide reforestation programs and the promotion of agroforestry and soil conservation practices. Integrated basin governance should be strengthened by empowering the Lake Rukwa Basin Water Board with technical expertise and ensuring that land use planning is linked to water resource management under IWRM principles. Sustainable water use requires stricter regulation of irrigation abstraction, supported by water permits and monitoring systems, while the adoption of efficient irrigation technologies can reduce pressure on inflows. Evidence-based monitoring should be institutionalized by embedding remote sensing and GIS tools into routine lake management, complemented by field-based sediment surveys and hydrological modeling to refine sediment budgets. Finally, community engagement is essential. Livelihood incentives such as community forestry and conservation agriculture should be embedded into catchment management, while participatory watershed planning can align local needs with ecological sustainability.

Conclusion

Lake Rukwa's decline represents a pressing socio-ecological challenge with far-reaching implications for food security, biodiversity, and rural development. Remote sensing evidence underscores the urgency of coordinated catchment restoration, sustainable water governance, and community-driven management. Without decisive action, the lake risks further contraction, undermining Tanzania’s freshwater resilience and the livelihoods of communities that depend on it. This policy brief calls for an integrated response that combines scientific monitoring, institutional reform, and participatory approaches to safeguard Lake Rukwa as a vital ecological and economic resource.