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The Impact of Land Use and Land Cover Change on Water Quality in Lake Victoria Catchment: A Case Study of Nkangabile River at Nyegezi Bay, Tanzania

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Abstract

Understanding the trends and impacts of anthropogenic activities in the water basins and catchments is key to the effective management and conservation of aquatic environments. This study analyses the land use and land cover (LULC) changes in the Nkangabile catchment and their impacts on water quality in the Nyegezi Bay of Lake Victoria, Tanzanian side. GIS and Remote sensing techniques were used to analyze the multi-temporal changes in LULC that occurred in the past 30 years from 1983 to 2013, split into four epochs of 10-year intervals. The changes in LULC were analyzed using image differencing and cross-tabulation for pairwise methods. The results indicated an increasing deterioration of water quality and a considerable transformation of LULC between the four epochs and more so in the long-term period from 1983 to 2013. The study provides evidence that LULC changes are accelerated by anthropogenic activities that severely affect the ecosystem through increased water pollution. Balancing human activities through proper land use planning as well as conservation awareness are strongly recommended to ensure adequate protection of the Lake Victoria ecosystem.

Keywords: Land use and Land cover change; Nkangabile catchment; Landsat; Support Vector Machine; Water quality

Introduction

In the past 50 years, the human population has experienced a rapid increase, leading to a significant impact on land resources, particularly in ecosystems, at a pace unparalleled in human history (Barnosky et al. 2014). Similar to other regions in the Great Lakes area (Obubu et al. 2021), the Lake Victoria catchment has also been heavily affected by changes in land use and land cover over recent decades (Mugo et al. 2020, Onyango et al. 2021a). For instance, in the Nkangabile River catchment area, there have been rapid transformations in land use, posing substantial threats not only to terrestrial but also to aquatic biodiversity in Lake Victoria (Commey et al. 2023). Previous studies have shown that unregulated human development activities within the Lake

Victoria catchment have increased chemical runoffs and soil destabilization, leading to heightened soil erosion (Scheren et al. 1995, Odada et al. 2006, Bamutaze et al. 2021, Onyango et al. 2021b).

Despite being the most studied lake in the African Great Lakes region, detailed information regarding land use and land cover changes, particularly at the local scale, remains limited for Lake Victoria. This knowledge gap constrains our understanding of the relationship between land-use changes and water quality may contribute to continued deterioration of water quality, loss of biodiversity, and ecosystem imbalance within the Lake Victoria catchment.

Understanding the land-use changes and water quality status is key to decision making and spatial planning. However, this can be costly and slow if conventional field survey methods are used alone. The use of Geographic Information Systems (GIS) and Remote Sensing (RS) provides a robust approach for the collection, analysis, and cartographic representation of data. These technologies offer a cost-effective and efficient approach for understanding spatial and temporal changes in land use and land cover from a spatial perspective. Numerous studies have successfully employed this approach to examine land use and land cover changes and associated changes in water bodies (Aguilera et al. 2012, Li et al. 2012, Dabrowski et al. 2013, Hoque et al. 2016, Ianis and Manuel 2014, Kibena et al. 2014, Wan et al. 2014). Remote sensing and GIS have emerged as reliable research tools for studying complex and dynamic ecosystems like watersheds (Alfred et al. 2016). Building on this background, our study investigated how land-use changes in the Nkangabile River catchment affected the water quality of Nyegezi Bay in Lake Victoria (Tanzania). The study focused on variables such as dissolved oxygen (DO), electrical conductivity (EC), total dissolved solids (TDS), temperature, pH, turbidity, Chlorophyll-a (Chl-a), as well as nutrients including Total Nitrogen (TN) and Total Phosphorus (TP).

Methodology

Study area

The study was conducted within the Nkangabile River catchment area of Nyegezi Bay, situated in Nyegezi Ward of Nyamagana District, Mwanza Region, Tanzania. Geographically, the study area spans between latitudes -2.596850° and -2.576020° and longitudes 32.934467° and 32.883744° (Figure 2). The catchment exhibits an elongated shape, characterized by a temperately dendritic drainage pattern (Gebre et al. 2015). Notably, the area experiences frequent flooding incidents during the rainy seasons, with the long rain period extending from March to May and the short rain period occurring between October and February (Figure 1). These precipitation patterns contribute to the substantial influx of solid and liquid waste, along with other debris, from the catchment into the lake.

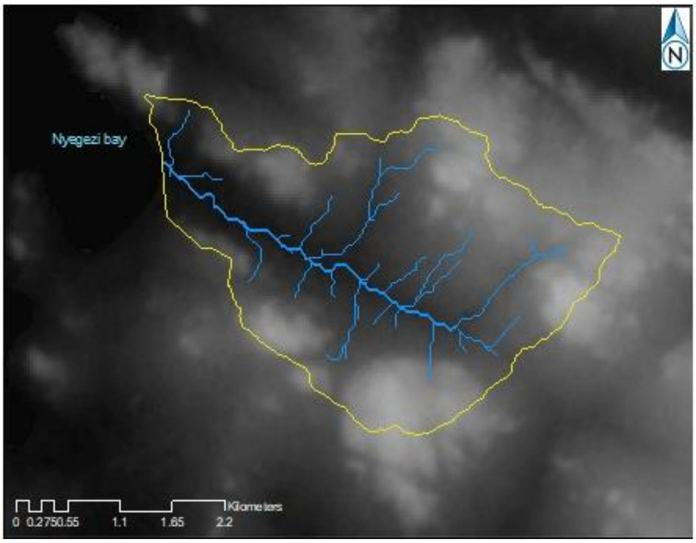

Figure 1: Topography, drainage network, and the boundary of the Nkangabile River catchment

The catchment is characterized by diverse land cover types and uses, including agricultural fields, settlements, and natural vegetation. Soils vary from fertile alluvial soils along the riverbanks to sandy and loamy soils in upland areas. The topography ranges from flat plains near the lake to gently undulating hills further inland. These characteristics influence water quality parameters within the catchment area.

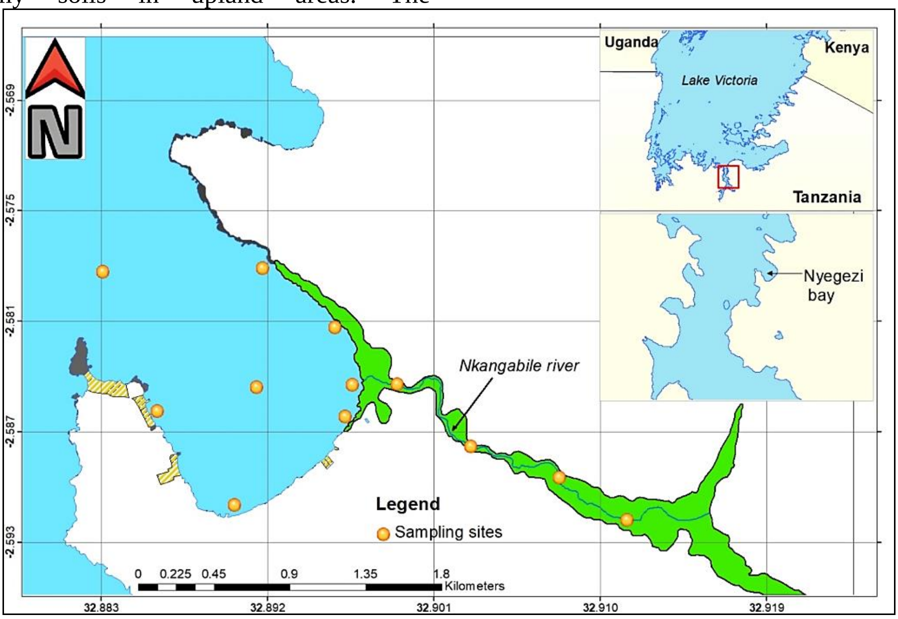

Figure 2: A map showing the study locations of Nyegezi Bay and Nkangabile River in Mwanza gulf of Lake Victoria (Tanzania)

Acquisition and processing of satellite data

Imagery acquisition

Four sets of imagery from the Global Land Survey collection (captured by Landsat Multispectral Scanner (MSS)), Landsat 5 (TM), Landsat 7 (ETM+), and Landsat 8 (OLI) sensors in 1983, 1993, 2003, and 2013, were retrieved from the United States Geological Survey (USGS) Earth Resources Observation Systems data center (http://glovis.usgs.gov/). The Landsat imagery series was chosen for this study due to its high spatial resolution (30 m) and extensive history of imagery collection over the study area. Specifically, images obtained during the dry season were selected to minimize inter-imagery variation. This selection criterion ensured that the images acquired during the dry season exhibited high quality and were less susceptible to cloud contamination. Furthermore, we utilized very high-resolution (0.5 m) GeoEye imagery from Digital Globe and Google Earth exclusively for validating the classification outputs of the 2013 epoch, as outlined in (Visser et al. 2014).

Image Processing

The imageries from each epoch, encompassing all visible and near-infrared bands, were stacked to create multiband imagery for subsequent analysis. Radiometric and atmospheric corrections were executed employing the FLAASH method within the ENVI 5.2 software, following the approach delineated by (Davaadorj 2019). Further image enhancement involving contrast stretching was conducted (in ENVI 5.2 software) to optimize visual appearance images and feature interpretation (Eastman 2001). Image classification, the Support Vector Machine (SVM), a machine learning algorithm, was utilized. SVM was preferred over the Maximum Likelihood and Artificial Neural Networks due to its superior ability in extracting information during classification, as noted by Pande-Chhetri et al. (2017).

Utilizing the Land Cover Classification System (LCCS) of 2005 developed by Di Gregorio (2005), our study area revealed five primary Land Use and Land Cover (LULC) classes. These categories encompass built-up/bare land, crop/grassland, wetland, water body, and forest (Table 1). Built-up areas and bare land were grouped together due to spectral similarities, while cropland and grassland were merged for analogous reasons. Satellite imagery interpretation involves a combination of digital and visual methods (Ghorbani and Pakravan 2013). False color composite images, alongside topographic maps, high-resolution Google Earth imagery, and expert insights, facilitated the identification of land classes within the images. Employing a random sampling technique, each LULC class per image was allocated 100 sample points, partitioned into training (70%) and accuracy assessment (30%) subsets following (Rahman et al. 2020) methodology.

Table 1: Landcover classification scheme

Land Cover Classes	Description
Built-up/bare land	Residential, commercial, industrial, transportation, and area with no vegetation
Crop/grassland	Spacious, smooth tone and texture lands with very low vegetation and often un interfered by tillage
Waterbody	Lake
Forest	Evergreen and roughly textured including shrubs and trees
Wetland	a distinct ecosystem that is flooded or saturated by water, either permanently or seasonally

Accuracy assessment and Change detection

Accuracy assessment is crucial for evaluating maps derived from Remote Sensing data, with key metrics including overall accuracy, user's and producer's accuracies, and the Kappa statistic, as commonly outlined (Weng et al. 2007). The Kappa statistic, which integrates the off-diagonal elements of error matrices, signifies the agreement achieved beyond chance (Yuan et al. 2005).

In our study, we conducted an accuracy assessment using the Confusion Matrix tool within the ENVI 5.2 software. This tool facilitated automated evaluation of accuracy. Additionally, we employed the image differencing and cross-tabulation for pairwise methods in ENVI 5.2 to compute changes between epochs (Eastman 2001). This streamlined approach ensured efficient analysis and comparison between datasets.

Water quality variables

The water quality assessment in the catchment area involved analyzing water samples from two distinct ecosystems: the Nkangabile River (a lotic system) and the Nyegezi Bay (a lentic system) (Figure 1). Sampling was conducted to account for both spatial and temporal variations. Specifically, samples were collected during the wet season, spanning October to November 2014 and February 2015, as well as during the dry season in June 2015. This sampling strategy aimed to capture potential differences in water quality parameters between the two ecological zones and across different seasons (Yang et al. 2020).

The parameters studied encompassed dissolved oxygen (DO), electrical conductivity (EC), total dissolved solids (TDS), temperature, pH, turbidity, Chlorophyll-*a* (Chl-*a*), as well as nutrients such as Total Nitrogen (TN) and Total Phosphorus (TP). To ensure accuracy, EC, TDS, temperature, and pH measurements were obtained using a calibrated portable pH-EC, TDS, and Temperature Meter (Hanna Instrument Model: HI9811-5). Meanwhile, TN and TP levels were determined simultaneously using the persulfate digestion method. All measurements adhered to standard methods outlined by the American Public Health Association (APHA 1998).

Statistical Analysis

To assess potential spatial-temporal seasonal variations in water quality parameters, descriptive statistics were used to understand the levels of water parameters in the lentic and lotic systems to see whether it was within the recommended levels.

Results

Land use/land cover classification and accuracy

From 1983 to 2013, the percentage change in land use and cover categories shows notable shifts. Builtup/bareland areas increased significantly by 137.30%, indicating substantial urban expansion. Crop/grassland areas decreased by 21.31%, reflecting a notable reduction in agricultural or grassland regions. Forest areas declined by 24.48%, although there was some recovery in the last decade. Water areas remained relatively stable with a slight overall decrease of 1.63%. Wetland areas saw a significant increase of 80.00%, suggesting efforts in wetland conservation or natural expansion (Table 2).

The user's and producer's accuracies (PA) of individual classes in all years ranged between 85.57% and 100%. In 1983, builtup/bareland occupied 185.31 ha, crop/grassland (412.28 ha), forest (723.15 ha), water (244.89 ha), and wetland (20.25 ha) (Table 2). Analysis of the Landsat images revealed a considerable change in LULC within the watershed between 1983-2013 (Figure 3 and Table 2). Between 1983 and 1993, the built-up/bareland increased by 137.30% while forest and crop/grassland had a significant net loss of 21.31% and 24.48%, respectively. Initially, the crop/grassland showed an increasing trend between 1983 and 2003, though started shrinking in 2003 through 2013. Between 2003 and 2013, the forest showed a net gain of 49.59%. In all epochs, except for 1993-2003, the water showed a slight decline while wetland area portrayed an increasing trend, especially in those areas close to the water-land interface. The loss in the water area was due to invasion by aquatic vegetation (water hyacinth) in the fringing areas of the bay (Figure 3).

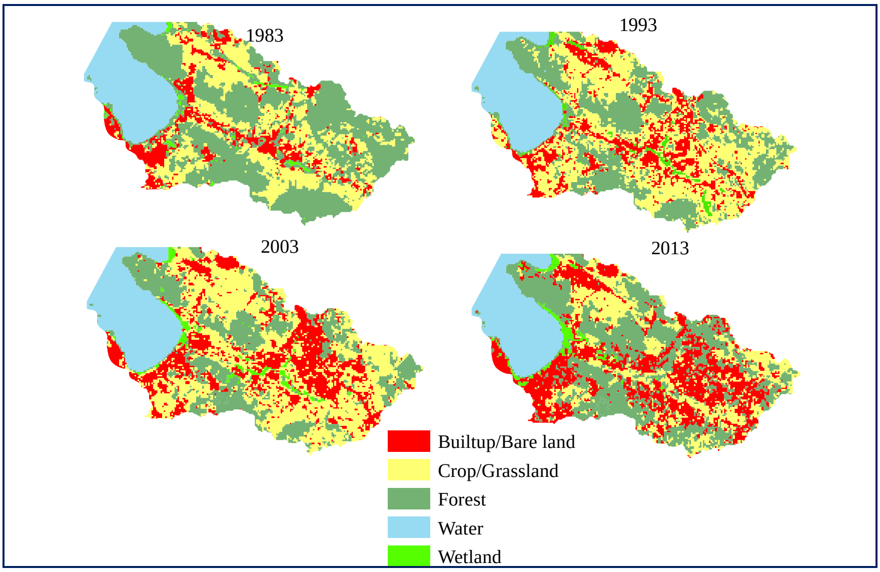

Figure 3: Land use land cover time series in Nyegezi Bay superimposed on Nkangabile River catchment

Table 2: Summary statistics of Landsat classification from 1983 to 2013 at Nyegezi Bay and Nkangabile River in Mwanza gulf of Lake Victoria

Class	Area (ha)				% change			
	1983	1993	2003	2013	1983-1993	1993-2003	2003-2013	1983-2013
Builtup/ bareland	185.31	260.28	348.30	438.66	40.54	33.85	26.15	137.30
Crop/ grassland	412.28	582.39	590.85	324.63	40.92	1.55	-45.01	-21.31
Forest	723.15	471.15	364.50	545.40	-34.85	-22.51	49.59	-24.48
Water	244.89	240.39	244.89	240.66	-2.04	2.08	-1.63	-1.63
Wetland	20.25	31.68	36.81	35.91	60.00	15.63	-2.70	80.00

Seasonal and spatial variation of water quality

Figure 4 indicate the mean and standard deviation of water quality parameters between the lotic and lentic systems in dry and wet seasons. All variables showed spatial and seasonal variation. The mean TDS values varied from 45.56 ± 7.048 mg/l (in the lentic system during dry season) to 248.75 ± 11.26 mg/l (in the lotic system during the dry season) (Figure 4).

The mean EC (439.28 µS/cm) in the lentic system was higher than in the lotic system (96.26 µS/cm). On the other hand, the mean EC in dry season (234.81µS/cm) was higher than in the wet season (188.62 µS/cm). The dry season EC (538.75 µS/cm) in the lotic system was higher than its wet season counterpart (399.50 µS/cm) (Figure 4).

The mean TN values ranged from 315.56 ± 125.99 µg/l (in the lentic system during the dry season) to 1207.50 ± 187.22 µg/l (in the lotic system during the wet season) (Figure 4). The water TP varied from 60.56 ± 19.47 µg/l (in the lentic system during dry season) to 697.50 ± 401.24 µg/l mg/l (in the lotic system during the wet season) (Figure 4)

The mean pH values of water are described in Figure 4. A low mean value of pH (7.30 ± 0.60) was recorded in the lotic system during the wet season and high pH (8.74 ± 0.58) in the lentic system during the same season (Figure 4).

Generally, the water Chl-*a* was higher in the lentic than in the lotic system. The Chl-*a* values of water varied from 16.95 ± 4.12 mg/l in the lentic system and during the wet season to 2.77 ± 1.43 mg/l in the lotic system and during the wet season (Figure 4). For DO, statistical analysis indicated differences between seasons and systems. The DO values varied from 6.92 ± 0.59 mg/l in the dry season to 8.19 ± 0.45 mg/l in the wet season (Figure 4).

Likewise, statistical analysis indicated differences in mean water temperature between seasons, however, water temperature in the lentic environment was higher than in the lotic. The mean water temperature varied from dry season 22.84 ± 0.97 °C (in the lotic system during the dry season) to 26.53 ± 0.638 °C (in the lentic system during dry season) (Figure 4).

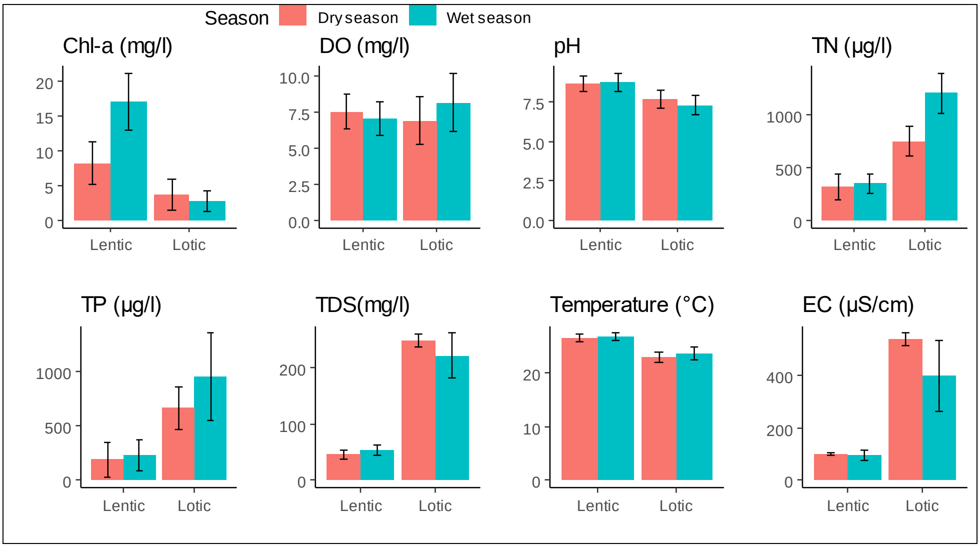

Figure 4: The mean ± SD values of limnological parameters in Nkangabile River (Lotic system) and Nyegezi Bay (Lentic system) as sampled in the wet season (October 2014, November 2014, and February 2015) and dry season (June 2015).

Discussion

The results show that vegetated land generally declined in the catchment over the years. The built-up/bareland has significantly increased over the past 30 years. Between 1983-2003, there was a significant conversion of forest patches into crop/grassland which implies a high deforestation rate in that period. Later, these crop/grasslands started shrinking by being converted into built-up/bareland probably due to high urbanization rates in the Mwanza region (URT 2022). The human population growth has been paralleled by the rapid conversion of land into built-up and agriculture areas resulting in a decline in water through increased pollutants, nutrients, and sediments loading into Lake Victoria (Mgaya and Mahongo 2017). If these expansions continue, there would be more pressure in the Nkangabile catchment area thus negatively impacting the aquatic system as well as the remaining vegetation. A previous study by (Kajuni et al. 2024) also found the decline in land cover in the Mara River Basin resulted in the deterioration of water quality in the Tanzanian side of Lake Victoria. The

Kenya side of the Mara River Basin has been also investigated by Oruma (2017), and similar declining trends in forest land were reported. The ongoing shrinkage in vegetated land and increase in built-up and agriculture land have been reported to be common in all tributaries of Lake Victoria (Kajuni et al. 2024).

The results from LULC analysis showed a net increase in the wetland area similar to (Bregoli et al. 2019) findings in Mara Wetland, Tanzania. However, our findings are contrary to (Okotto-Okotto et al. 2018) in the fringing Nyando wetland of Lake Victoria in Kenya who observed a decline of wetlands by 31% between 1984 and 2010. However, results from our study should be interpreted with care because most of the increase was due to invasion by water hyacinth. Expansion of wetland was highly confined to the sheltered areas around the water-land interface. Previous reports (Kipng'eno 2019, Kiyemba et al. 2023, Thamaga and Dube 2019) show that, since its first appearance in Lake Victoria in 1987, water hyacinth has continued to invade water bodies and wetlands in most areas in the lake basin.

Except for TDS, temperature, DO and pH, all other studied water parameters exceed the recommended limit for a healthy aquatic ecosystem (UNECE 1994). According to (UNECE 1994), the recommended values for EC, TN, TP, and Chl-*a* in aquatic environments such as lakes and rivers are <250 µS/cm, <300µg/l <1022µg/l and <2.5mg/l, respectively. Based on the findings of the present study the mean EC, TN, TP, and Chl-*a* were respectively found to be 538.75 µS/cm, 1207.50µg/l, 697.50µg/l and 16.95 mg/l which are relatively higher than the recommended values. The mean values of physicochemical parameters seem to exceed the permissible limit, except for EC which was found to be higher in the wet season than in the dry season probably due to increased intrusion of human-impacted runoffs (Magero et al. 2023). The incidence of intrusion of human impacted runoffs has been reported to cause pollution in Lake Victoria (Nyamweya et al. 2023). Our results are also consistent with a previous study by Sitoki et al. (2010) in the Lake Victoria who reported higher EC in the wet season than in the dry season. Conversely, (Simiyu et al. 2022, Nyamweya et al. 2023) reported lower EC values in the wet season than in the dry season Kenyan part of Lake Victoria. The catchment of the Nkangabile River supplies water for the catchment inhabitants and supports small-scale agriculture, especially vegetables, water, and pasture for cattle and other domestic animals grazing around the catchment area (Shen et al. 2022, Frank et al. 2023). All these human activities are the principal cause of land cover changes in the catchment of the Nkangabile and might be responsible for the deterioration quality of the water in the river and the Nyegezi Bay as it has been observed elsewhere around Lake Victoria basin in Mara River (Kajuni et al. 2024, Wafula et al. 2018), Uganda (Akurut et al. 2017) and Kenya (Njagi et al. 2022, Onyango et al. 2021a and 2021b). Although it is difficult to conclude about the causal effect of LULC on water quality due to limited information on monitoring efforts over several spatial scales (Afed et al. 2018), other studies in East Africa (Mutie 2006, Kajuni et al. 2024), had reported a high correlation of LULC in the Lake Victoria catchment with declining water quality. Proper and well guided land use coupled with environmental education is necessary to mitigate the trend in the aquatic ecosystem.

Conclusion and recommendations

Our findings conclude that the land use and land cover (LULC) in the Nkangabile catchment is changing at an alarming rate. The once-vegetated land is being rapidly converted into other land uses, particularly settlement development and agriculture, thereby jeopardizing the health of the aquatic ecosystem downstream. These changes have significant implications for the water quality in Lake Victoria, emphasizing the urgent need for effective land management practices. Additionally, our study highlights the necessity of reinforcing the relationship between observed LULC changes and water quality to better inform future conservation and management strategies.

Based on the result presented in this paper, the authors recommend more sensitization for local communities to adopt good environmental practices to safeguard the health of the aquatic ecosystem in the catchment. There should also be stringent efforts to regulate human activities which interfere with the ecosystem's integrity. Proper use of agrochemicals would reduce nutrient pollution in the river system. Regular environmental monitoring involving space technology coupled with long-term monitoring of water quality parameters should be consolidated for sustainable environmental protection.

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Author's contribution

HDJ and RK devised the project and main conceptual ideas and participated in field data collection. CNE, MAS, and BBK, contributed to sample preparation and interpretation of the results CAM, MS & MM took the lead in writing the manuscript, Image processing, and interpretation. IK and AS aided in interpreting the results and worked on the manuscript. All authors provided critical feedback and helped shape the research, analysis, discussed the results and final manuscript.

Conflicts of Interest

The authors state that they have no conflicts of interest related to this study. Specifically, the study sponsors did not influence any aspect of the research process. They had no role in designing the study, collecting data, analyzing data, interpreting data, writing the manuscript, or deciding to publish the results.

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