

Multivariate analysis of land use/land cover (LULC) effects on water quality in the Lower Mara River catchment

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ABSTRACT

The Lower Mara River catchment is increasingly subjected to anthropogenic pressure due to land-use/land-cover (LULC) changes, which significantly influence river water quality. This study assessed the effects of LULC on water quality in the Lower Mara River catchment. Water samples were collected from 12 sampling stations during February, August, and December 2025 and analysed for nine physicochemical and biological parameters. Land use/land cover classification was conducted using satellite imagery and GIS techniques, while Pearson correlation and Redundancy Analysis (RDA) were used to evaluate relationships between LULC and water quality parameters within 500, 1,000 and 1,500 m river buffer zones. The results showed that grassland was the dominant land cover type (63.63%), followed by cropland (17.76%) and forest (11.42%). Turbidity, biochemical oxygen demand (BOD5) and faecal coliform concentrations exceeded Tanzania's standards at several sampling locations, indicating water quality degradation. Pearson correlation and RDA revealed that cropland and built-up areas were significantly positively associated ($p < 0.01$) with turbidity, nutrients, BOD5, and faecal coliforms, while forests, wetlands, and grasslands contributed to improved water quality conditions. The strongest LULC influence occurred within the 500 m riparian buffer zone. The study emphasises the significance of sustainable management and protection of the river ecosystems.

Key words: catchment management, Land Use/Land Cover (LULC), Mara River Basin, Pearson correlation, Redundancy Analysis (RDA)

HIGHLIGHTS

- Land use significantly influences water quality in the Lower Mara River.
- Cropland and built-up areas increase sediment and pollution loads.
- Forests, wetlands, and grasslands improve river water quality.
- Riparian zones within 500 m exert the strongest influence on water quality.

1. INTRODUCTION

Water quality degradation has emerged as one of the most critical environmental challenges affecting river basins globally due to intensified anthropogenic activities and rapid land use/land cover (LULC) transformations (Strokal *et al.* 2021; Gençer & Başaran 2024). Changes in land use patterns, including agricultural expansion, urban development, deforestation, wetland encroachment, and livestock grazing, considerably alter hydrological processes and enhance the movement of pollutants into aquatic ecosystems (Tesfaw *et al.* 2023). These activities modify the physical, chemical, and biological properties of river systems through increased sedimentation, nutrient enrichment, microbial contamination, and organic pollution (William *et al.* 2025). As a result, understanding the interactions between land use dynamics and water quality has become essential for sustainable watershed management and environmental conservation.

Numerous studies worldwide have demonstrated strong linkages between land use patterns and environmental degradation. Oli *et al.* (2025), A study conducted in Atlanta, USA, reported that rapid urbanisation significantly transformed land use and land cover patterns, contributing to increased land surface temperatures

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and intensification of the urban heat island effect. Similarly, [Liu et al. \(2023\)](#) While assessing the impacts of LULC changes on hydrological processes in a loess hilly watershed in China, identified that urbanisation is the major contributor to runoff variation, whereas forest expansion largely influenced evapotranspiration changes. In India, [Lal et al. \(2025\)](#) evaluated historical and future LULC changes within the Ken River Basin and observed that forest loss combined with projected increases in rainfall could intensify environmental degradation, emphasising the need for integrated land and water management approaches. In Africa, land use changes have become major drivers of river water quality deterioration due to rapid population growth, agricultural intensification, and settlement expansion. [Tesfaw et al. \(2023\)](#), using the SWAT model in the Tana sub-basin of Ethiopia, reported continuous declines in forest and grassland cover associated with increasing pressure on water resources. Likewise, [Nkwanda et al. \(2021\)](#), wrote about the Upper Lilongwe River Basin in Malawi, researchers found that cultivated and built-up areas significantly contributed to river pollution and declining water quality conditions.

Studies in East African catchments have further documented increasing sediment loads, eutrophication, and microbial contamination associated with unsustainable land management practices. For instance, [Mwangi et al. \(2020\)](#) reported that agricultural activities and urban runoff in the upper Mara River catchment in Kenya significantly increased nutrient concentrations and turbidity levels in the river system. Similarly, [Balaka Opiyo et al. \(2022\)](#), in the Migori River Watershed of western Kenya, identified settlement expansion, agricultural activities, population pressure, and poverty as the primary drivers of LULC changes. In Southwestern Uganda, [Nuwagira et al. \(2023\)](#) observed that rapid expansion of built-up areas and small-scale agriculture significantly reduced grassland and woodland cover between 2010 and 2022, with strong correlations between temporal land use changes ($r = 0.97$; $p = 0.03$). These studies collectively demonstrate that anthropogenic land use changes are increasingly altering watershed conditions and threatening the sustainability of aquatic ecosystems across East Africa. The Mara River Basin is one of the most ecologically and economically important transboundary river systems in East Africa, shared between Kenya and Tanzania. The river originates from the Mau Forest Complex in Kenya and flows through the Maasai Mara National Reserve and the Serengeti National Park before draining into Lake Victoria ([Mwangi et al. 2020](#)). The basin supports domestic water supply, agriculture, livestock keeping, fisheries, tourism, and wildlife ecosystems. It is also internationally recognised for supporting the annual wildebeest migration within the Mara-Serengeti ecosystem. Due to its ecological significance, the river system is highly sensitive to environmental disturbances and land use changes occurring within the catchment ([Masese et al. 2023](#)).

Over the past decades, the Mara River Basin has experienced substantial land use transformations driven by population growth, agricultural expansion, deforestation, settlement development, and increasing demand for natural resources. [Mwangi et al. \(2020\)](#) reported that deforestation and conversion of natural vegetation to cropland within the basin increased surface runoff and sediment transport into the river system. [Nkinda et al. \(2020\)](#) Further observed elevated nutrient concentrations and declining water quality conditions associated with agricultural and urban activities within the Mara catchment. Additional studies have also shown that increasing human activities within the basin threaten biodiversity conservation, aquatic ecosystems, and water availability for wildlife and local communities ([Mwangi et al. 2020](#)). Likewise, [Alphayo et al. \(2026\)](#) assessed the same Mara River water quality using the Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI), and results showed that the average was 87.03%, classifying the Mara River water quality as 'Good'. However, localised degradation was observed near agricultural, mining, and urban discharge zones.

Although previous studies have examined hydrological changes and water quality degradation within the Mara Basin, limited research has comprehensively evaluated the influence of different land use categories on multiple water quality parameters using multivariate statistical approaches at varying riparian buffer scales. Most previous studies focused primarily on general water quality assessments or hydrological variations without integrating detailed GIS-based land use analysis and ordination techniques such as Redundancy Analysis (RDA). Furthermore, there remains limited information regarding the spatial influence of land use patterns within specific river buffer zones on water quality conditions in the Lower Mara River catchment. Therefore, this study aimed to assess the effects of land use and land cover on water quality within the Lower Mara River catchment using GIS-based LULC analysis, Pearson correlation, and Redundancy Analysis (RDA). Specifically, the study examined the spatial distribution of land use categories, assessed the status of selected physicochemical and biological water quality parameters, and evaluated the relationships between LULC types and water quality conditions within 500, 1,000, and 1,500 m river buffer zones. The findings of this study provide important

scientific information for sustainable watershed management, water resource protection, and ecological conservation within the Mara-Serengeti ecosystem.

2. MATERIAL AND METHODS

2.1. Description of the study area

The study was conducted in the Lower Mara River catchment within the Mara River Basin, located in northern Tanzania near the Kenya–Tanzania border (Alphayo *et al.* 2026). The Mara River is a transboundary river system originating from the Mau Forest Complex in Kenya and flowing southwest through the Maasai Mara National Reserve and the Serengeti National Park before discharging into Lake Victoria (Mwangi *et al.* 2020; Alphayo *et al.* 2026). Figure 1 illustrates the study area at different spatial scales. Figure 1(a) presents the East African region, including Tanzania, Kenya, Uganda, Burundi, and Rwanda. Figure 1(b) shows the Mara River Basin; a transboundary catchment shared between Kenya and Tanzania. Figure 1(c) presents the Lower Mara River catchment, which constitutes the specific study area investigated in this research.

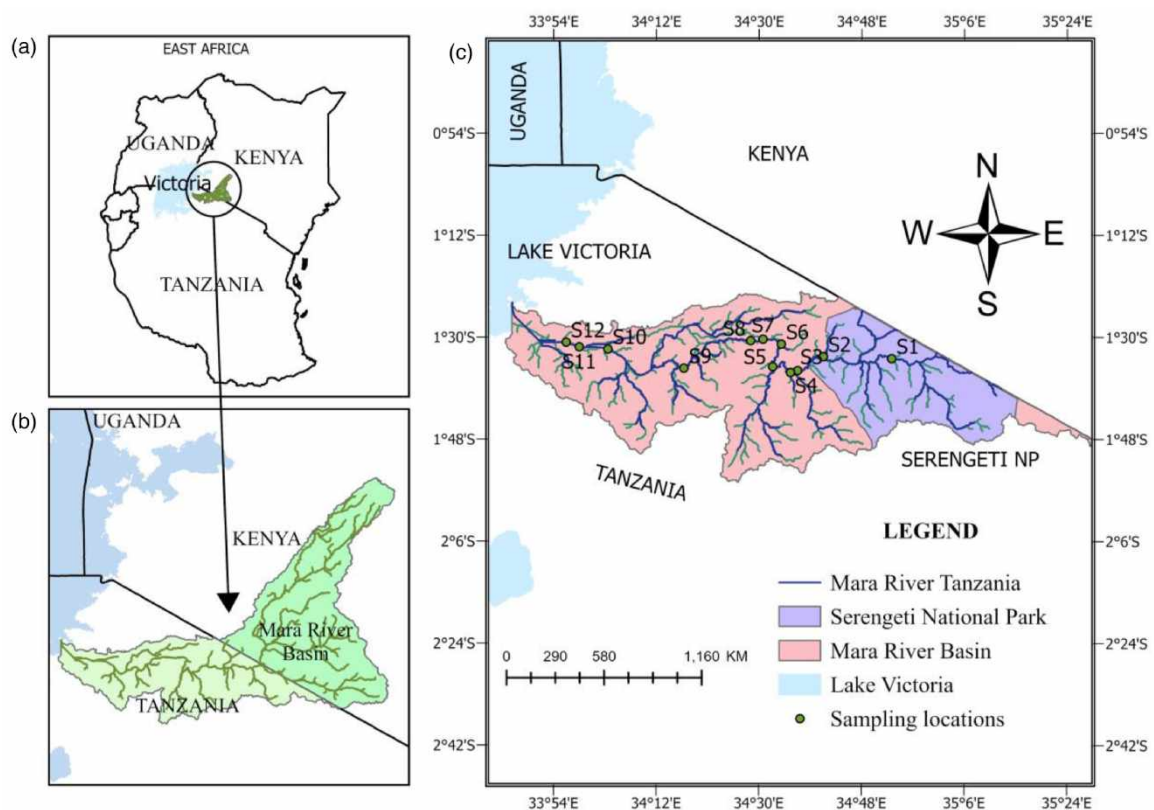


Figure 1 | Location of the Lower Mara River Catchment within the Mara River Basin and East African Region (a) The East Africa Region Map (b) Mara River Basin (c) Lower Mara River Catchment in Tanzania.

The lower catchment forms an important ecological and hydrological zone supporting wildlife ecosystems, local communities, livestock keeping, agriculture, fisheries, and tourism activities (Zhu *et al.* 2023). The study area is characterised by tropical savannah climatic conditions with distinct wet and dry seasons. Rainfall is bimodal, with long rains occurring between March and May and short rains between October and December. Average annual rainfall ranges from approximately 800–1,200 mm, while temperatures generally vary between 20 and 30 °C depending on season and elevation (Das *et al.* 2022). These climatic conditions strongly influence river flow regimes, sediment transport, and seasonal water quality variations within the basin. Topographically, the Lower Mara catchment consists of gently undulating plains, river valleys, wetlands, and grassland ecosystems dominated by savannah vegetation (Ngonyani *et al.* 2025). The area contains diverse land use and land cover types, including grasslands, croplands, forests, wetlands, built-up areas, and water bodies. Grassland is the dominant land cover type and supports extensive livestock grazing and wildlife habitats. Agricultural

activities are mainly concentrated near riverbanks and settlement areas, while wetlands occur along floodplains and low-lying sections of the river system.

The Mara River plays a critical role in sustaining the ecological integrity of the Mara-Serengeti ecosystem, particularly during seasonal wildlife migrations. However, increasing anthropogenic activities such as agricultural expansion, deforestation, settlement development, livestock grazing, and wetland encroachment have contributed to land degradation and declining water quality conditions within the catchment. Due to its ecological significance and increasing environmental pressure, the Lower Mara River catchment provides an important setting for assessing the influence of land use and land cover changes on river water quality.

2.2. Water quality analysis

Water quality assessment was conducted using twelve (12) sampling locations distributed along the Lower Mara River catchment, [Figure 1\(c\)](#). A total of 324 water samples were collected and analysed during three sampling campaigns conducted on 4th February, 18th August, and 10th December 2025 to capture seasonal variations in water quality conditions. The sampling locations were selected strategically to represent different land use and land cover characteristics and hydrological conditions along the river system. Laboratory analysis was carried out at the accredited Musoma Water Quality Laboratory following standard procedures for water quality examination ([American Public Health Association et al. 2017](#)). Nine key physicochemical and biological parameters were analysed, including temperature, pH, total solids (TS), dissolved oxygen (DO), turbidity, phosphate (PO_4^{3-}), nitrate (NO_3^-), biochemical oxygen demand (BOD_5), and faecal coliforms (FC) ([Koshafar & Velayatzadeh 2025](#); [Alphayo et al. 2026](#)). These parameters were selected due to their significance in evaluating river health, nutrient enrichment, organic pollution, sediment loading, and microbial contamination ([Shakerdonyavi et al. 2023](#)).

Field measurements for temperature, pH, dissolved oxygen, and turbidity were conducted *in situ* using calibrated portable instruments, while nutrient and microbial analyses were performed under laboratory conditions. Quality assurance and quality control procedures were implemented throughout sampling and laboratory analysis to ensure data accuracy and reliability ([Olatunji 2025](#); [Alphayo et al. 2026](#)). Descriptive statistical analysis, including mean, standard deviation, skewness, kurtosis, minimum, and maximum values, was performed using IBM SPSS Statistics ([Gheibi et al. 2022](#)). Graphical presentation and trend visualisation of water quality parameters were generated using OriginPro.

2.3. Land use/Land Cover (LULC) analysis

Land use/land cover analysis was conducted using ArcGIS Pro to determine the spatial distribution of land cover classes within the Lower Mara River catchment. Satellite imagery used for land classification was obtained from the United States Geological Survey (USGS) database ([Geological Survey \(U.S.\) 2023](#)). The selected satellite images were processed and classified into six major land use/land cover categories: forest, wetland, cropland, built-up areas, grassland, and water bodies. Image preprocessing procedures included image correction, clipping to the study area boundary, and enhancement to improve classification accuracy. Supervised classification techniques were applied to generate the final land use/land cover maps. To improve the reliability of the classification results, physical land use verification was conducted through field observations and ground-truthing exercises within the study area. GPS coordinates and direct site observations were used to validate the classified land cover categories.

Classification accuracy assessment was performed using Producer's Accuracy (PA), User's Accuracy (UA), overall accuracy, and Kappa statistics ([Raja Shekar & Mathew 2023](#)). The resulting classification achieved high accuracy levels, indicating that the generated LULC maps were suitable for subsequent spatial and statistical analyses. To assess the influence of adjacent land uses on river water quality, buffer zones of 500, 1,000, and 1,500 m were delineated along the Mara River channel ([Sani et al. 2024](#)). The proportional coverage of each land use category within the respective buffer zones was calculated and used in subsequent correlation and multivariate analyses.

2.4. Assessment of the effects of land use/land cover on water quality

The relationship between land use/land cover types and water quality parameters was evaluated using Pearson correlation analysis and Redundancy Analysis (RDA) ([Sani et al. 2024](#)). These statistical techniques were selected to determine the strength, direction, and multivariate interactions between land use categories and river water quality variables.

Pearson correlation analysis was conducted using IBM SPSS Statistics to examine linear relationships between individual land use categories and specific water quality parameters. Correlation coefficients (r) and significance levels (p) were used to determine the degree of association between variables. Positive correlations indicated that increases in a particular land use category were associated with increases in a specific water quality parameter, whereas negative correlations indicated inverse relationships.

Redundancy Analysis (RDA) was employed to evaluate the combined influence of multiple land use variables on overall water quality conditions across the study area. RDA ordination was performed to identify dominant environmental gradients and to explain the extent to which variations in land use patterns contributed to observed changes in water quality parameters. Separate RDA analyses were conducted for the 500, 1,000, and 1,500 m buffer zones to assess spatial-scale effects of land use on river water quality (Gule *et al.* 2023; Sani *et al.* 2024).

The integration of Pearson correlation and RDA provided a comprehensive understanding of both individual and multivariate relationships between land use/land cover dynamics and water quality conditions within the Lower Mara River catchment.

3. RESULTS AND DISCUSSION

3.1. Water quality data

The descriptive statistics of the analysed water quality parameters were averaged and are presented in Table 1. The results provide important insights into the physicochemical and biological conditions of the Mara River and indicate the influence of both natural processes and anthropogenic activities occurring within the catchment. Comparison with the Tanzania water quality standards further highlights parameters of environmental concern (TBS 2019).

Table 1 | Physicochemical and biological water quality results of the Mara River

Parameters	Minimum	Maximum	Mean	Std. deviation	Skewness	Kurtosis	^a Tanzania Standards
Temperature	24.36	27.09	26.03	0.77	-0.78	0.42	20–35
Ph	7.21	7.62	7.42	0.12	0.32	-0.09	5.5–9.5
Total Solids (TS)	69.93	151.34	119.92	28.24	-0.63	-1.05	1,500
Dissolved Oxygen (DO)	2.8	3.55	3.13	0.21	0.17	0.36	>3
Turbidity (NTU)	103.96	160.85	130.15	20.58	0.17	-1.7	25
Phosphate (PO_4^{3-})	1.35	2.23	1.7	0.3	0.69	-0.6	2.2
Nitrate (NO_3^-)	1.27	3.82	2.46	0.85	-0.25	-1.11	45
Biological Oxygen Demand (BOD)	26.62	39.01	32.33	4.34	0.27	-1.44	<30
Faecal Coliform (FC)/100mls	23.67	163.67	73.47	45.38	0.8	-0.47	0

^aSource: TBS – Natural Portable Water Specification – TZS 789.

The river water temperature ranged from 24.36 to 27.09 °C, with a mean value of 26.03 ± 0.77 °C. These values fall within the permissible range of 20–35 °C in Tanzania, indicating that the thermal condition of the river remains within acceptable ecological limits. The Q-Q plot of temperature in Figure 2(a) shows a good linear relationship between the data obtained, and Figure 3(b) shows the temperature at different locations, indicating the stability of temperature throughout the overall river reach. The relatively stable temperature conditions may be attributed to the tropical climatic setting of the basin and continuous river flow. Temperature is an important factor influencing dissolved oxygen solubility, microbial activity, and aquatic ecosystem functioning (Rezapouraghdam *et al.* 2024).

The pH values varied from 7.21 to 7.62, with an average of 7.42 ± 0.12 , indicating neutral to slightly alkaline water conditions. These values are within the Tanzania acceptable range of 5.5–9.5 and suggest that the river water is chemically stable and suitable for sustaining aquatic life. The narrow variation in pH further indicates limited acidification or industrial contamination within the sampled sections of the river (Olatunji 2025). Total solids (TS) concentrations ranged between 69.93 and 151.34 mg/L, with a mean value of 119.92 ± 28.24 mg/L. These concentrations are considerably below the Tanzania standard limit of 1,500 mg/L, suggesting relatively

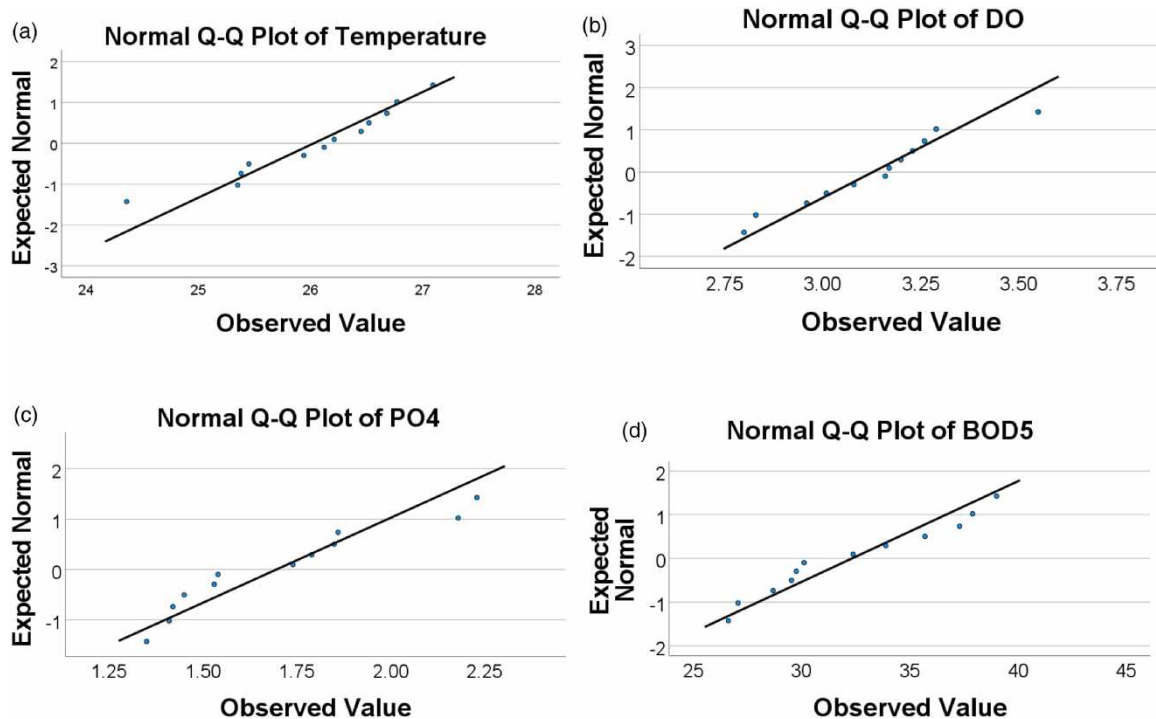


Figure 2 | a–d The Q-Q plot for selected water quality parameters of the Mara River (a) Q-Q plot for Temperature (b) Q-Q plot for Dissolved Oxygen (c) Q-Q plot for Phosphorus (d) Q-Q plot for Biological Oxygen Demand of the Mara River.

low mineral and suspended particulate accumulation within the river. However, variations in TS may reflect localised erosion processes, sediment transport, and runoff from agricultural and grazing areas (Nkinda *et al.* 2020). Turbidity values were notably high, ranging from 103.96 to 160.85 NTU, with a mean concentration of 130.15 ± 20.58 NTU. These values greatly exceeded the Tanzania permissible limit of 25 NTU, indicating severe sediment loading and poor water clarity within the river. Elevated turbidity is likely associated with soil erosion, agricultural runoff, riverbank degradation, and surface runoff from disturbed landscapes. High turbidity levels may reduce light penetration, impair photosynthesis, increase water treatment costs, and negatively affect aquatic habitats (Balaka Opiyo *et al.* 2022).

Dissolved oxygen (DO) concentrations ranged from 2.80 to 3.55 mg/L, with a mean value of 3.13 ± 0.21 mg/L. Although the average DO slightly exceeded the minimum Tanzania guideline value (>3 mg/L), some sampling sites recorded concentrations below the recommended threshold. The Q-Q plot shows that DO is linearly associated, as shown in Figure 2(b). Low dissolved oxygen levels may indicate elevated organic pollution and increased microbial decomposition within the river system. Reduced DO concentrations can negatively affect aquatic organisms, particularly fish and benthic macroinvertebrates, by limiting oxygen availability necessary for respiration and ecological productivity (Marselina *et al.* 2022).

Biological Oxygen Demand (BOD₅) values ranged from 26.62 to 39.01 mg/L, with a mean concentration of 32.33 ± 4.34 mg/L, and the Q-Q plot shows a good statistical linear distribution in Figure 2(d). The average BOD₅ exceeded the Tanzania permissible limit of <30 mg/L, indicating considerable organic pollution within the river system. Elevated BOD₅ levels suggest increased decomposition of organic matter, likely originating from agricultural runoff, sewage discharge, livestock waste, and decaying vegetation. High BOD₅ concentrations contribute to oxygen depletion and ecological stress in aquatic environments (Uddin *et al.* 2023).

Phosphate (PO₄³⁺) concentrations ranged from 1.35 to 2.23 mg/L, with a mean value of 1.70 ± 0.30 mg/L, and the Q-Q plot in Figure 2(c) shows a good linear correlation. Although most values remained within or close to the Tanzania standard limit of 2.2 mg/L, some locations approached the threshold, suggesting nutrient enrichment within the river system. Elevated phosphate concentrations are commonly associated with fertiliser application, livestock waste, and domestic wastewater discharge. Increased Phosphate loading may accelerate eutrophication processes and promote excessive algal growth (Xu *et al.* 2022). Nitrate (NO₃) concentrations varied between 1.27 and 3.82 mg/L, with an average concentration of 2.46 ± 0.85 mg/L. These concentrations

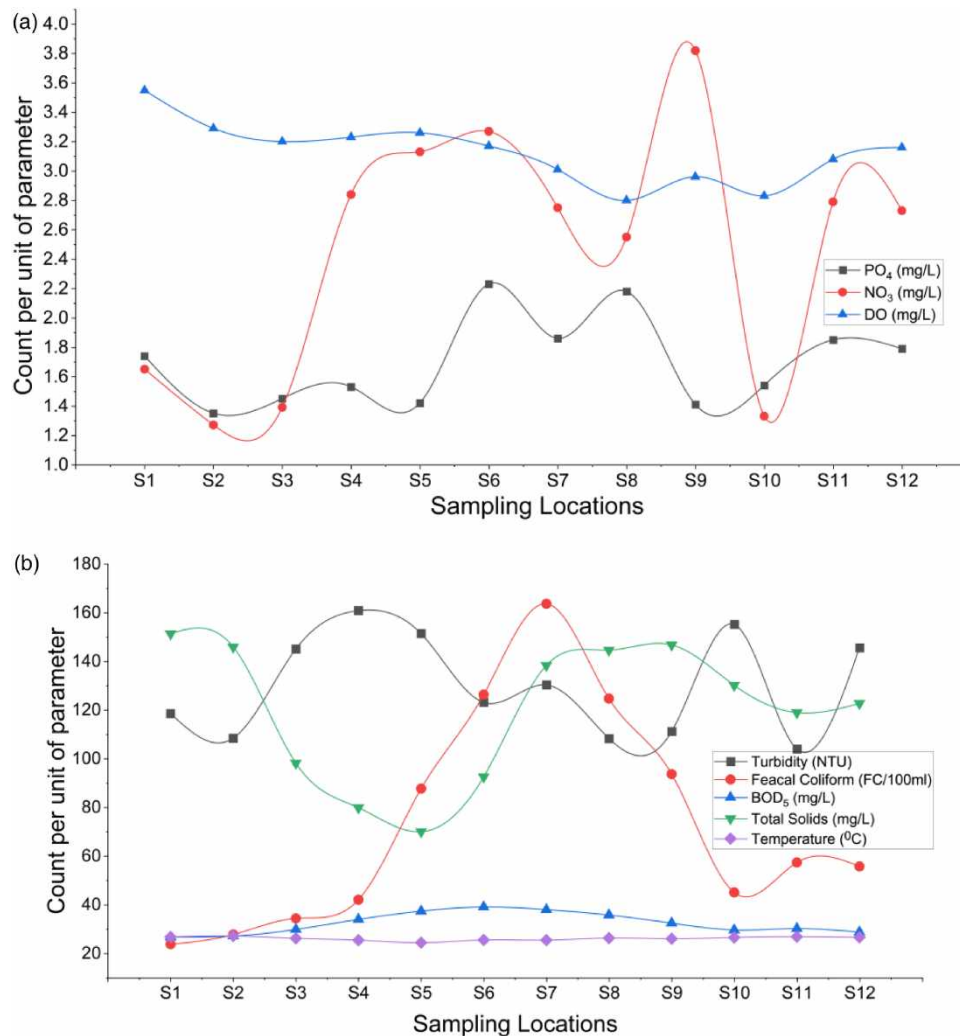


Figure 3 | a–b Spatial trends of the Water quality parameters of the Mara River (a) Spatial trends of the three Water quality parameters (b) Spatial trends of the five Water quality parameters of the Mara River.

were substantially below the Tanzania standard limit of 45 mg/L, indicating relatively low nitrate pollution levels within the catchment. Nevertheless, the observed nitrate presence likely reflects diffuse agricultural runoff and organic waste inputs from human settlements and livestock activities (Xu *et al.* 2022).

Faecal coliform (FC) concentrations ranged from 23.67 to 163.67 counts/100 mL, with a mean value of 73.47 ± 45.38 counts/100 mL trend is also presented in Figure 3(b). These concentrations substantially exceeded the Tanzania guideline value of 0 counts/100 mL for safe water, indicating serious microbial contamination of the river. High faecal coliform levels suggest contamination from untreated sewage, livestock activities, open defecation, and surface runoff from built-up areas. Such contamination poses significant public health risks, particularly for communities relying on the river for domestic use, livestock watering, and irrigation (Hasim *et al.* 2023).

The skewness and kurtosis statistics indicated moderate variability and near-normal distribution for most parameters, suggesting that the dataset was suitable for subsequent multivariate statistical analyses such as Pearson correlation and Redundancy Analysis (RDA). Overall, the results demonstrate that while some physicochemical parameters remained within acceptable limits, turbidity, BOD_5 , and faecal coliform concentrations exceeded recommended standards, indicating substantial impacts of land use activities on the water quality of the lower Mara River catchment. The spatial trends illustrated in Figure 3 indicate noticeable variations in water quality conditions along the Mara River catchment. Sampling locations S3 to S8 and S11 to S12, particularly near the river mouth, exhibited signs of slight to moderate water quality deterioration, as reflected by elevated concentrations of pollutants such as turbidity, BOD_5 nutrients, and faecal coliforms. The observed decline in water

quality within these sections is likely associated with increased agricultural activities, settlement expansion, livestock grazing, and surface runoff transporting sediments and contaminants into the river system.

In contrast, sampling stations S9 and S10 demonstrated relatively improved water quality conditions, which may be attributed to the presence of wetland ecosystems surrounding these areas. Wetlands play a critical ecological role in enhancing water quality through natural filtration, sediment trapping, nutrient retention, and microbial pollutant reduction. The improvement observed in these sections highlights the importance of wetland environments as natural buffers that regulate and maintain river ecosystem health.

Furthermore, sampling points S1 to S3, located within the Serengeti National Park, recorded comparatively better water quality conditions. The relatively low levels of pollution in these upstream protected areas may be linked to minimal anthropogenic disturbance, restricted land use activities, and the preservation of natural vegetation cover within the conservation zone. This finding underscores the ecological significance of protected areas in safeguarding river water quality and maintaining the integrity of the Mara River ecosystem.

Overall, the spatial distribution pattern suggests that land use intensity and ecosystem protection status strongly influence water quality variations along the river continuum. Areas characterised by natural vegetation cover and wetlands generally exhibited better water quality, whereas sections exposed to intensive human activities showed increased levels of environmental degradation.

3.2. Land use categories distribution

The land use/land cover (LULC) composition of the study area was classified into six major categories: forest, wetland, cropland, built-up areas, grassland, and water bodies. See Figure 4.

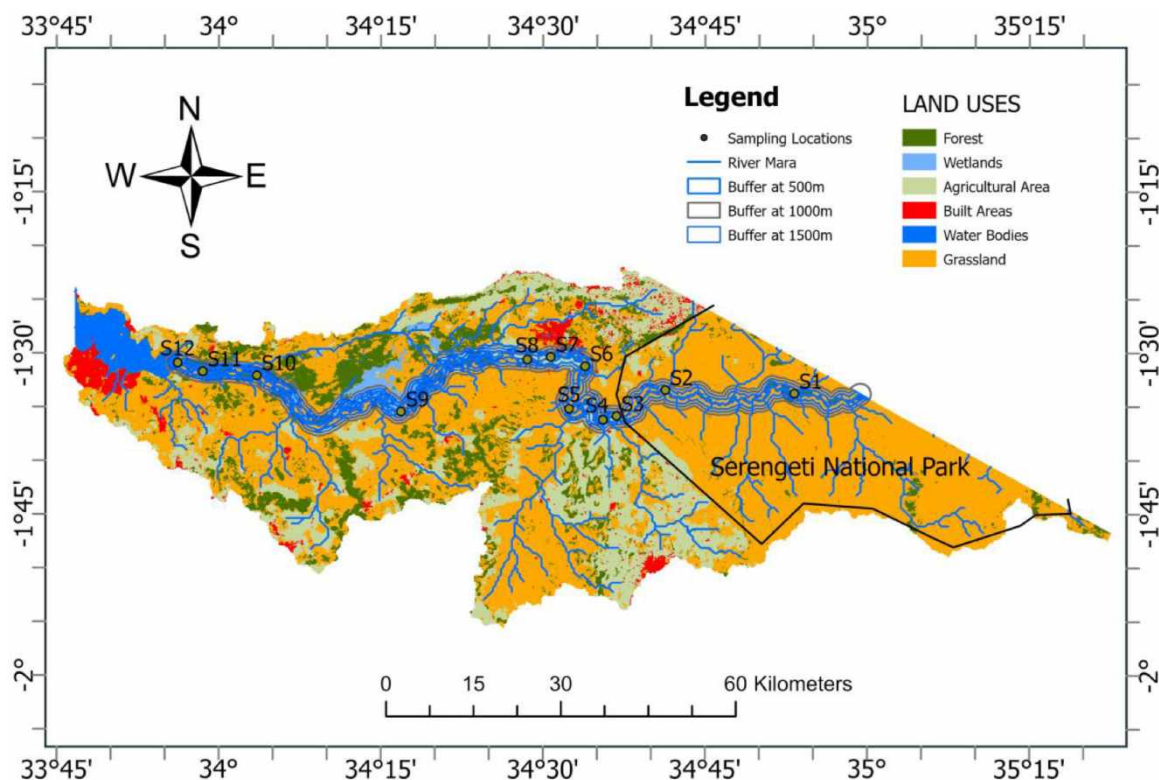


Figure 4 | The land use land cover classification of Mara River Catchment.

The LULC classification in Figure 4 revealed that grassland was the dominant land cover type, accounting for 63.63% of the total study area, followed by cropland at 17.60%. Forest cover constituted 11.42%, while built-up areas and water bodies accounted for 2.88 and 2.59%, respectively. Wetlands represented the smallest proportion of the catchment, covering only 1.72% of the total area. The classification accuracy of the land use categories was evaluated using Producer's Accuracy (PA) and User's Accuracy (UA), with all classes achieving accuracy levels above 85%, See Table 2.

Table 2 | Land use categories, area and accuracy statistics

Land Use/Land cover (LULC)	Area in hectares (Ha)		Accuracy	
	Area	(%)	PA	UA
Forest	62,533.80	11.42	94	88
Wetland	9,393.28	1.72	91	94
Cropland	97,245.78	17.76	85	86
Built-up	15,752.05	2.88	88	90
Grassland	348,570.38	63.63	92	90
Waterbodies	14,167.31	2.59	90	92
Overall Accuracy			93	
Kappa Statistics			0.9	

The overall classification accuracy was 93%, while the Kappa coefficient was 0.90, indicating a high level of agreement between the classified image and reference data. These results demonstrate that the land use-/land cover classification of the basin was highly reliable and suitable for subsequent spatial and statistical analyses.

The percentage of land use categories of the study area was divided into Forest, Wetland, Cropland, Built-up, Grassland and Waterbodies and percentage for each land use was obtained where grassland was dominant by having 63.63% followed by cropland having 17.6% the rest are forest 11.42%, builtup 2.88%, water bodies 2.59% and Watland the last having 1.72% as shown in the Table 2. The accuracy of land uses was verified by using PA and UA in each of the land use which was above 85% and the overall accuracy was 93% and kappa statistics was 0.9 this data shows that the basin was accurately classified.

The land use/land cover classes were subsequently delineated into three buffer zones of 500, 1,000, and 1,500 m from the riverbanks to examine the spatial influence of surrounding land uses on water quality. The proportional distribution of each land use category within the respective buffer zones was calculated and expressed as percentages (Sani *et al.* 2024). The summarised results for each buffer distance are presented in Table 3.

Table 3 | Distribution of land use categories within the respective buffer zones

Land Uses	N	Percentage (%) at 500 m	Percentage (%) at 1,000 m	Percentage (%) at 1,500 m
Water Bodies	12	2.01 ± 3.40	5.62 ± 7.18	5.16 ± 4.85
Forest	12	0.79 ± 1.78	8.94 ± 11.01	8.57 ± 9.94
Wetland	12	0.76 ± 1.74	4.79 ± 9.96	10.82 ± 8.43
Cropland	12	5.29 ± 7.38	16.01 ± 17.79	16.29 ± 16.42
Built-up	12	0.09 ± 0.32	0.98 ± 3.14	1.07 ± 3.18
Grassland	12	91.04 ± 7.36	63.64 ± 19.70	62.74 ± 20.69

3.3. Effects of LULC change on water quality

3.3.1. Pearson correlation analysis

Pearson correlation analysis was used to evaluate the relationships between land use categories and water quality parameters (Gule *et al.* 2023). The results of the Pearson correlation analysis are presented in Table 4. Land use categories were arranged in the vertical columns, while water quality parameters were presented in the horizontal rows. The land cover classifications were compared with the corresponding water quality data to determine the influence of each land use type on water quality. The analysis revealed strong associations between land use patterns and the measured water quality parameters. See Table 4a–c for Pearson correlation analysis showing the relationship between LULC variables and water quality parameters of the Mara River at different buffer distances.

Table 4 | a–c Pearson correlation at different buffer zones (a) Pearson correlation at 500 m buffer zones (b) Pearson correlation at 1,000 m buffer zones (c) Pearson correlation at 1,500 m buffer zones

(a) Pearson Correlation at 500m									
	Temp	Ph	DO	TS	Turb	PO ₄	NO ₃	BOD	FC
Water Bodies	0.36	0.027	-0.054	0.034	-0.40	0.27	0.092	-0.18	-0.090
Forest	0.43	0.30	-0.0092	0.16	-0.044	0.094	0.14	-0.43	-0.23
Wetland	0.17	0.26	-0.55	0.29	0.12	-0.31	-0.023	-0.21	-0.10
Cropland	-0.70	0.16	-0.34	-0.25	0.24	0.077	0.38	0.69	0.58
Builtup	-0.29	0.48	-0.18	0.19	0.017	0.17	0.12	0.42	0.64
Grassland	0.22	-0.53	0.64	-0.052	-0.11	-0.095	-0.46	-0.28	-0.41
(b) Pearson Correlation at 1000m									
	Temp	Ph	DO	TS	Turb	PO ₄	NO ₃	BOD	FC
Water Bodies	0.44	0.11	0.090	-0.29	0.13	0.062	-0.13	-0.41	-0.28
Forest	0.27	-0.020	0.18	-0.46	0.33	-0.18	-0.36	-0.30	-0.24
Wetland	0.10	0.35	0.32	-0.51	0.023	-0.35	0.11	-0.14	-0.029
Cropland	-0.65	-0.31	-0.78	0.20	0.64	-0.44	0.067	0.27	-0.15
Builtup	-0.27	0.48	0.20	-0.18	0.0053	0.17	0.11	0.41	0.63
Grassland	0.37	0.16	0.62	0.18	-0.78	0.53	0.048	9.5E-4	0.31
(c) Pearson Correlation at 1500m									
	PO ₄	Temp	Ph	TS	DO	Turb	NO ₃	BOD	FC
Water Bodies	0.28	0.35	0.019	0.030	-0.059	-0.37	0.092	-0.18	-0.083
Forest	-0.0032	0.34	0.39	0.22	-0.054	0.14	0.13	-0.40	-0.18
Wetland	-0.16	0.32	0.22	0.23	-0.51	-0.12	0.039	-0.27	-0.15
Cropland	0.090	-0.63	0.28	-0.16	-0.42	0.14	0.45	0.67	0.60
Builtup	0.20	-0.29	0.48	0.20	-0.21	0.0017	0.12	0.44	0.66
Grassland	-0.082	0.13	-0.60	-0.14	0.67	-0.029	-0.48	-0.23	-0.39

Pearson correlation analysis showed that faecal coliform (FC) exhibited a strong and statistically significant positive correlation with built-up areas, with correlation coefficients ranging from $r = 0.63$ to 0.68 and significance levels of $p < 0.014$. This relationship suggests that increasing urbanisation and settlement expansion contribute substantially to microbial contamination of the river system, likely due to inadequate sanitation infrastructure, domestic wastewater discharge, and surface runoff carrying faecal matter into water bodies. The findings indicate that built-up areas are important sources of bacteriological pollution within the catchment. Similarly, biochemical oxygen demand (BOD₅) showed a significant positive correlation with cropland areas, with correlation coefficients ranging between $r = 0.67$ and 0.69 ($p < 0.01$). This implies that agricultural activities contribute to elevated organic loading in the river, possibly through fertiliser runoff, crop residue decomposition, livestock waste, and soil erosion. Increased BOD₅ levels reflect greater oxygen consumption by microorganisms during the decomposition of organic matter, which may lead to oxygen depletion and ecological stress in aquatic ecosystems (Gule *et al.* 2023).

Turbidity demonstrated a highly significant positive association with cropland within the 1,000 m buffer zone ($r = 0.64$, $p = 0.012$), whereas correlations within other buffer distances were comparatively weaker. This finding highlights the influence of intensive agricultural practices near river channels on sediment transport and suspended particulate matter. Soil disturbance, vegetation removal, and runoff from cultivated land are likely major contributors to increased turbidity levels. In contrast, grassland exhibited a strong negative correlation with turbidity ($r = -0.78$, $p = 0.001$), indicating that grassland cover plays an important role in reducing sediment runoff and improving water clarity through enhanced soil stabilisation, infiltration, and erosion control. Wetland cover showed a negative association with dissolved oxygen (DO) concentrations, suggesting that wetlands may increase organic matter accumulation and microbial decomposition processes, which consume dissolved oxygen in aquatic systems. Conversely, forest cover exhibited a significant negative relationship with BOD₅, indicating that forested areas contribute positively to water quality by reducing organic pollution, minimising surface runoff, regulating erosion, and enhancing natural filtration processes within the catchment.

Furthermore, nitrate and phosphate concentrations were positively associated with increases in cropland and built-up areas. This suggests that agricultural intensification and urban development are major drivers of nutrient enrichment in the basin. Excessive nutrient loading from fertiliser application, sewage discharge, and stormwater runoff may accelerate eutrophication processes, promote algal blooms, and degrade the ecological integrity of the river ecosystem. Overall, the Pearson correlation results demonstrate that anthropogenic land use activities, particularly agriculture and urban expansion, exert considerable influence on river water quality, whereas natural land cover types such as forests and grasslands contribute to the protection and regulation of aquatic environmental conditions.

3.3.2. Redundancy Analysis (RDA)

Redundancy Analysis (RDA) was conducted within 500, 1,000, and 1,500 m buffer zones along the Mara River to evaluate the multivariate relationships between land use/land cover types and water quality parameters. A similar study conducted in the N'Djili River catchment, Congo, reported that approximately 70% of the variability in water quality parameters was explained by land use categories, with urbanised areas exerting a negative influence on water quality, whereas forested and rangeland areas contributed positively to maintaining water quality conditions (Sani *et al.* 2024). Consistent with these findings, the present study in the Mara River catchment revealed strong associations between land use patterns and water quality variations across all buffer distances, underscoring the significant role of land cover dynamics in shaping river water quality. At the 500 m buffer, the first two principal components (PC1 and PC2) explained 96.77% of the total variation in the dataset, indicating a very strong land use influence on river water quality in areas immediately adjacent to the river channel. Similarly, the 1,000 and 1,500 m buffer zones explained 87.38% and 90.03% of the total variation, respectively, demonstrating that land use activities at broader spatial scales also significantly affect water quality conditions in the Mara River catchment. These relationships are illustrated in Figure 5(a)–5(c).

The RDA ordination further demonstrated that cropland and built-up areas were strongly and positively associated with elevated concentrations of phosphate (PO_4^{3-}), turbidity, BOD₅, and faecal coliforms. This indicates that agricultural intensification and urban development are major contributors to nutrient enrichment, sediment loading, organic pollution, and microbial contamination within the river system. Agricultural runoff carrying fertilisers, animal waste, and eroded sediments, together with untreated domestic wastewater and stormwater discharge from settlements, are likely the principal sources of these pollutants. In contrast, forest

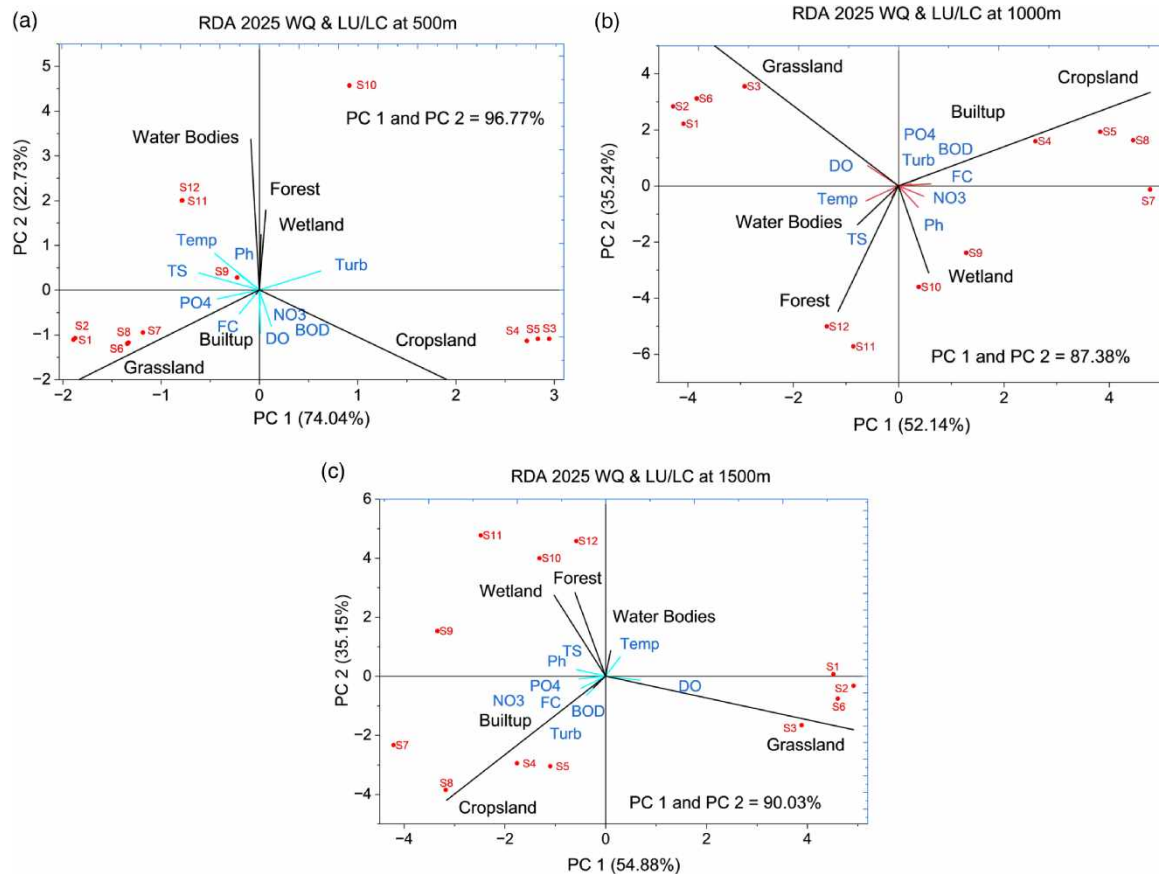


Figure 5 | a–c The Redundancy Analysis (RDA) showing the relationship between LULC variables and water quality parameters of the Mara River at (a) 500 m buffer zones (b) 1,000 m buffer zones (c) 1,500 m buffer zones.

and wetland land cover types showed positive associations with pH stability and total solids regulation, highlighting their ecological role in maintaining water quality balance through filtration, nutrient retention, and sediment trapping processes. Forested areas reduce soil erosion and regulate hydrological flow, while wetlands function as natural biofilters that intercept pollutants before they enter the river system. Grassland areas were positively associated with dissolved oxygen (DO), suggesting that these landscapes contribute to healthier aquatic conditions by minimizing sediment input and enhancing infiltration. Improved oxygen conditions may also result from reduced organic pollution and lower microbial oxygen demand in areas dominated by natural vegetation cover.

The RDA findings further emphasize the ecological importance of protected landscapes within the Mara River Basin, particularly because the river traverses internationally significant conservation areas, including the Serengeti National Park and the Maasai Mara National Reserve. Land use changes occurring upstream and within surrounding catchments therefore have direct implications not only for water quality but also for biodiversity conservation, wildlife migration, and ecosystem sustainability within the Mara-Serengeti ecosystem. Poor water quality may threaten aquatic habitats and wildlife species that depend on the river as a primary water source, particularly during dry seasons and annual migration periods. Overall, the RDA results demonstrate that anthropogenic land uses, especially cropland and built-up areas, are key drivers of water quality degradation in the lower Mara catchment, whereas natural land cover types such as forests, wetlands, and grasslands contribute positively to the maintenance of river ecosystem health and ecological resilience.

The findings from the Pearson correlation analysis were consistent with the results obtained from the Redundancy Analysis (RDA), indicating similar patterns of association between land use/land cover types and water quality parameters. Both analyses demonstrated that cropland and built-up areas were positively associated with increased levels of turbidity, BOD₅, nutrients, and faecal coliforms, reflecting the influence of agricultural and urban activities on water quality degradation. Likewise, both methods showed that natural land cover types

such as forests, wetlands, and grasslands were associated with improved water quality conditions, including higher dissolved oxygen levels and reduced pollutant concentrations. The similarity between the two analytical approaches strengthens the reliability of the findings and confirms that land use dynamics play a significant role in determining water quality variations within the Mara River catchment.

3.4. Study limitations

Although this study provides valuable insights into the influence of land use and land cover on water quality in the Lower Mara River catchment, several limitations should be acknowledged. First, the study was based on water quality data collected during three sampling campaigns in 2025. While these sampling periods captured important seasonal conditions, they may not fully represent long-term interannual variability in hydrological and water quality dynamics. Future studies should incorporate continuous monitoring over multiple years to better capture temporal fluctuations.

Second, the land use analysis was based on a single-period land use/land cover classification. Consequently, the study evaluated the influence of existing land use patterns on water quality but did not explicitly quantify historical land use changes and their temporal impacts on river conditions. Incorporating multi-temporal satellite imagery would provide a more comprehensive understanding of land use change trajectories and their effects on water quality.

Third, the study focused on nine physicochemical and biological water quality parameters. Other important indicators, including heavy metals, pesticides, emerging contaminants, and biological integrity indices, were not investigated and may provide additional insights into environmental pressures within the catchment.

Finally, although Pearson correlation and Redundancy Analysis (RDA) successfully identified significant relationships between land use categories and water quality parameters, these statistical approaches primarily demonstrate associations rather than direct causality. Water quality variations may also be influenced by additional factors such as rainfall intensity, river discharge, soil characteristics, geological conditions, and climate variability, which were beyond the scope of the present study.

Despite these limitations, the integration of GIS-based land use analysis, field water quality monitoring, and multivariate statistical techniques provides a robust framework for understanding land use-water quality interactions and offers important information for sustainable management of the Mara River Basin.

4. CONCLUSIONS

This study evaluated the influence of land use and land cover (LULC) on water quality in the Lower Mara River catchment using GIS analysis, Pearson correlation, and Redundancy Analysis (RDA). The results demonstrated that land use dynamics significantly affect river water quality within the basin. Grassland was identified as the dominant land cover type, accounting for 63.63% of the catchment, followed by cropland (17.76%) and forest cover (11.42%), while wetlands and built-up areas occupied relatively smaller proportions. Water quality analysis revealed that several parameters exceeded Tanzania's permissible standards, indicating increasing environmental degradation within the river system. Turbidity recorded a mean value of 130.15 NTU compared to the permissible limit of 25 NTU, while biochemical oxygen demand (BOD₅) averaged 32.33 mg/L against the recommended standard of <30 mg/L. Faecal coliform concentrations also exceeded acceptable limits, indicating significant microbial contamination associated with human and livestock activities.

Pearson correlation and RDA produced consistent findings, showing strong positive relationships between cropland and built-up areas with turbidity, nutrients, BOD₅, and faecal coliform concentrations at significant levels ($p < 0.01$). These results indicate that agricultural activities and urban development are major contributors to sediment loading, nutrient enrichment, organic pollution, and microbial contamination in the Mara River. In contrast, forests, wetlands, and grasslands contributed positively to water quality improvement through sediment retention, nutrient regulation, and enhanced dissolved oxygen conditions. The strongest land use influence on water quality was observed within the 500 m riparian buffer zone. Sampling stations located within the Serengeti National Park showed comparatively better water quality conditions due to minimal anthropogenic disturbance and preserved vegetation cover. The study recommends strengthening riparian buffer protection, promoting sustainable agricultural practices, conserving wetlands, improving sanitation infrastructure, and implementing integrated catchment management to enhance water resource sustainability within the Mara River Basin.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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