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Land Use and Land Cover Patterns on Water Quality at the Congo Dam Catchment Area in Freetown, Sierra Leone

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Abstract

This study examined the relationship between Land Use and Land Cover (LULC) changes and water quality in the Congo Dam catchment between 2004 and 2023. Geospatial analysis was conducted using Landsat satellite imagery and Geographic Information System (GIS) techniques to classify and quantify LULC changes. Water quality data were obtained from monthly monitoring of the Congo Dam reservoir from January to June 2023 and analyzed against World Health Organization (WHO) standards. Pearson's correlation analysis was employed to evaluate the relationships between LULC variables and selected water quality indicators. The results revealed substantial vegetation loss, primarily through conversion to agriculture (3.74 km^2) and settlements (2.59 km^2), while water bodies remained relatively stable. Correlation analysis demonstrated that agricultural expansion exhibited the strongest positive relationship with phosphate concentration ($r = 0.926$, $p < 0.001$) and nitrate levels ($r = 0.913$, $p < 0.001$). Vegetation loss showed a very strong positive correlation with turbidity ($r = 0.891$, $p < 0.001$) and phosphate ($r = 0.821$, $p = 0.001$), suggesting increased soil erosion and nutrient transport resulting from deforestation. Settlement expansion was strongly associated with total dissolved solids (TDS) ($r = 0.882$, $p < 0.001$), conductivity ($r = 0.864$, $p < 0.001$), and microbial contamination, including *E. coli* ($r = 0.835$, $p = 0.001$). Conversely, water body stability exhibited weak and non-significant relationships with pH (r = −0.112, p = 0.734), calcium hardness (r = 0.094, p = 0.781), sulphate (r = 0.071, p = 0.824), and temperature (r = −0.236, p = 0.459). The study concludes that increasing agricultural activities, settlement expansion, and vegetation degradation significantly contribute to the deterioration of reservoir through elevated sediment, nutrient, dissolved solid, and microbial loads. It is recommended that watershed protection measures, afforestation programs, sustainable agricultural practices, and stricter land-use planning policies be implemented to reduce environmental pressures and safeguard the long-term quality of water in the Congo Dam catchment.

Keywords

Land Use/Land Cover Change (LULC), Water Quality, Turbidity, Nutrient Enrichment, Deforestation, Urban Expansion

1. Introduction

Management of surface water quality has been a crucial and delicate environmental issue. All residential, commercial, industrial, and agricultural uses require surface water [1]. Rivers are essential to human health and have been recognized as the fundamental right of all living beings [2]. However, one of the current issues facing river basin management at both the regional and global levels is river degradation brought on by human activity [3]-[5]. In recent decades, anthropogenic activities have been made worse by socioeconomic factors like the expansion and intensification of agricultural irrigation systems, population growth and the strain on current freshwater resources, climate variability due to unequal precipitation distribution, floodgate construction, and the disposal of untreated wastewater into receiving water bodies [6]-[8]. Water resources are among the most quickly diminishing and deteriorating in our environment due to the exploitation of river water resources motivated by the need to support our businesses [9] [10]. Water can easily become contaminated by other natural substances or contaminants because it is a natural solvent [11]-[13].

Land use and land cover (LULC) has been found to have a significant impact on water quality, since most surface waters are replenished by surface rainfall-runoff [14] [15]. Additionally, the need for water has increased along with population growth. Water scarcity and stress have resulted from this in many parts of the world. Understanding these biological problems, dams constructed on significant river bodies have evolved into the fundamental infrastructure required to supply the region's water needs [16] [17]. The significant impact that human activity has on river water quality and water ecology is directly reflected in changes in land use land cover (LULC) [18]. The exchange of pollutants from land to surface water bodies is influenced by the many types of land use land cover, which have varying effects on the transfer of runoff into these bodies (blocking or accelerating) [19]. Aquatic ecosystems are significantly impacted by urbanization and pollutant generation, which is a unique pattern of LULC that strongly reflects human activity [20]. One of the main factors contributing to the global rise in pollution in freshwater ecosystems is the expansion of urban land [21]. The future of water quality in urbanized watersheds is thought to be significantly impacted by urbanization [22]. Both urban populations and pollutants (both point and diffuse pollutants) will rise dramatically with urbanization. Furthermore, the natural landscapes will be broken up and transformed into impermeable surfaces, which would raise peak flows and runoff volumes [23]. It should be noted, too, that in highly human-disturbed basins with numerous dams and sluices, the relationship between LU and the river system is more complicated. According to Zhao *et al.* [24], the combined control of dams and sluices causes rivers' streamflow and capacity for self-purification to change.

However, the majority of rural communities in developing nations are now at risk due to the impact of climate change, which has an impact on people's everyday access to and use of water [25] [26]. Intense and widespread poverty has undermined opportunities to address persistent water issues in Africa, making it difficult for many cities and communities to provide services for potable water and sanitation that are sufficient for economic activity and further prevent deterioration of water quality [27] [28]. These elements—finance, inadequate water management, and a lack of effective coordination have exacerbated Sub-Saharan Africa's water crisis, making it unlikely that the people will have access to drinkable water any time soon [27] [29] [30]. Climate change, eutrophication, salinisation, toxic metal poisoning, *E. coli*, phosphate, nitrate, and other environmental problems of the twenty-first century exacerbate this condition [31] [32]. Increased human activity is the main cause of contamination [1] [12].

The Congo dam is a critical infrastructure component located in the Western Area Peninsula National Park in Sierra Leone, specifically near the Regent area. It plays a vital role in water supply, environmental conservation, and, increasingly, tourism**.** The Congo dam serves as a primary water source for approximately 1.5 million people in the Western Area, including areas like Regent, Leicester, Gloucester, and other mountain communities. The area around the dam is part of a protected watershed, which is crucial for maintaining the ecological balance of the Western Area Peninsula National Park. The catchment area surrounding the Congo Dam has been under significant threat from illegal land-grabbing, deforestation, and construction, which jeopardize the water supply. The dam is considered a critical for Tourist Destination and a crucial resource for the survival of the surrounding communities. This research examines the influence of LULC and urbanizations on the Congo dam, which are major sources of pollution on water quality and water ecology, affecting water quality/quantity for drinking, which is essential for both sustainable basin development and environmental and ecological restoration.

2. Research Methodology

2.1. Description of the Study Area

The Congo Dam in Sierra Leone, located near the Tacugama Chimpanzee Sanctuary with 8.41361˚N, 13.21333˚W in the Western Area Peninsula National Park, is a crucial water source for Freetown, supplying areas like Regent, Leicester, and Hill Station. It has a tropical monsoon climate marked by very high rainfall, high temperatures, and strong seasonal variation. The climate is shaped by the movement of the Intertropical Convergence Zone, placing the area between tropical rainforest and savanna conditions. Annual rainfall is exceptionally high typically 3000 to 5000 mm, with the Freetown peninsula among the wettest parts of the country. The region experiences two distinct seasons. The rainy season (May-November) brings torrential rainfall, high humidity (often above 80%), and frequent flooding, with August as the wettest month, sometimes receiving up to 800 mm of rain. The dry season (December-April) is influenced by the Harmattan winds, featuring lower humidity, fewer rainy days, and more tolerable heat despite high temperatures. Temperatures remain consistently warm year-round, averaging about 26˚C, with daytime highs around 30˚C in the dry season and cooler nights of 20˚C - 22˚C. The intense wet-season rainfall is crucial for maintaining river flows and dam water levels. As a result, the Congo dam plays a key role in supplying water to Freetown, alongside the Guma Dam, although peak wet-season conditions can occasionally lead to spillage and flood risk.

2.2. Water Quality Sampling, Analysis and Data Processing

Water quality data were collected monthly over a six-month period from January to June from the Congo Dam catchment. The catchment was subdivided into three sampling locations representing the upstream, midstream, and downstream sections of the dam, designated as S1, S2, and S3, respectively. Water samples were collected from the three sampling locations during each study month and transported to the National Water Quality Laboratory (NWQL), Sierra Leone, for laboratory analysis. The samples were analysed for a range of physical, chemical, and biological water quality parameters, including nutrients, metals, turbidity, and microbial indicators. Sampling, preservation, and analytical procedures followed relevant World Health Organization (WHO) standard methods, with laboratory analyses conducted under certified laboratory procedures. Samples were appropriately preserved prior to laboratory analysis to maintain their integrity.

Field measurements and selected physical, chemical, and bacteriological analyses were conducted using portable Wagtech Hydro Kit test kits. Turbidity was measured using the Hydro Kit turbidity meter, which operates on the principle of nephelometric measurement based on 90˚ light scattering. Microbiological analyses were conducted using a Wagtech dual incubator under controlled temperature and incubation conditions. Filtered water samples underwent a four-hour resuscitation period, followed by a minimum incubation period of 14 hours to facilitate the detection of microbial contamination. A Wagtech bacteriological filtration apparatus was also used for microbiological analysis. The apparatus employs vacuum filtration to pass water samples through membrane filters and consists of seven principal components that facilitate effective sample processing.

Quality assurance and quality control (QA/QC) procedures were implemented throughout the sampling, field measurement, and laboratory analysis processes. These procedures included the calibration of field instruments before use, the selection and use of appropriate and properly labelled sampling containers, appropriate sample preservation and handling, adherence to laboratory quality-control procedures, and verification of analytical results. These measures were undertaken to ensure the accuracy, reliability, and consistency of the water quality data. The laboratory results for all water quality parameters were entered, processed, and analysed using OriginLab Pro Version 8.0. Monthly values for each water quality parameter were calculated as averages across the three sampling locations (S1, S2, and S3). The resulting monthly mean values were plotted against the corresponding study months to assess and illustrate temporal variations in water quality. Composite graphs showing the monthly trends of the analysed water quality parameters were generated and saved in JPEG format for incorporation into the study report.

2.3. Experimental Procedures for Water Quality Analyses

The study followed standard field and laboratory procedures to analyze physicochemical and microbiological water quality parameters. Physicochemical analysis was conducted mainly in situ using a Hydro Check meter. Parameters measured included pH, total dissolved solids (TDS), electrical conductivity (EC), and temperature, all recorded immediately after sample collection to prevent contamination or gas exchange. Turbidity was measured using a calibrated Hydro turbidity meter with Formazin standards. Additional chemical parameters such as chloride, nutrients, metals, hardness, residual chlorine, sulfates, sulfides, arsenic, phosphorus, and total suspended solids were analyzed using a Lovibond MD610 photometer with tablet reagents following calibration and reaction stabilization procedures.

Microbiological analysis employed the membrane filtration method using the WAGTECH Potalab kit. Samples were filtered through sterilized membrane filters, placed on absorbent pads soaked with sulfate broth media, and incubated at 44˚C for 18 - 24 hours. After incubation, colonies were counted and classified as *E. coli,* fecal coliforms, total coliforms, or non-coliforms, with results expressed as colony-forming units (CFU) per 100 ml. All equipment and materials were sterilized to prevent contamination, and procedures followed established international standards. Data analysis and presentation were conducted using Origin Lab Pro 8.0, with monthly water quality values plotted graphically and compiled for reporting.

2.4. Landsat Satellite Imagery Data

The study used cloud-free Landsat satellite imagery to analyze land-cover change in and around the study area over time. Three images were selected Landsat 7 Enhanced Thematic Mapper (ETM+) (2004) and Landsat 8 Operational Land Imager (OLI) (2013-2023) downloaded from the United States Geological Survey (USGS) Earth Explorer (WRS path/row 204:052). Images were acquired at near-anniversary dates during the mid-dry season to minimize seasonal effects and ensure good image quality. All data were projected to Universal Transverse Mercator (UTM) Zone 28N, WGS 84.

Field data were collected between January and July 2023 to support land-cover classification and validation. GPS points representing different land-cover types were gathered with an average positional accuracy of 4.1 m and used exclusively to assess the accuracy of the 2023 land-cover map, as reliable historical reference data were unavailable. Because no standard land-cover classification scheme exists for Freetown, classes were defined based on field observations. With an overall classification accuracy of 86.4% and a Kappa coefficient of 0.82 for the 2023 LULC map, an accuracy evaluation was carried out utilizing GPS-based ground-truth data gathered in 2023. Post-classification change detection was applied to quantify land-cover changes over approximately three decades, calculating persistence, gains, losses, net change, and selected land-cover conversions between 2004 and 2023, alongside basic intensity analyses. Geospatial data analysis and presentation were partly carried out using Microsoft Excel, with graphs produced to illustrate land-cover change patterns over time.

2.5. Data Analysis

The data collected for this study were analyzed using a combination of geospatial analysis, descriptive statistics, and inferential statistical techniques to examine the relationship between land use and land cover (LULC) changes and water quality in the Congo Dam watershed. Descriptive statistical analysis was used to summarize variations in water quality parameters, including temperature, pH, turbidity, conductivity, total dissolved solids (TDS), nutrients (nitrate, phosphate, and ammonia), and microbial indicators (*E. coli*, faecal coliforms, and non-faecal coliforms). The observed values were compared with the World Health Organization (WHO) recommended drinking water standards.

To determine the relationship between LULC changes and water quality, Pearson's Product-Moment Correlation Coefficient (r) was employed. Correlation analysis was conducted between key LULC variables, namely vegetation loss, agricultural expansion, settlement growth, and water body stability, and selected water quality indicators including turbidity, conductivity, TDS, nitrate, phosphate, ammonia, *E. coli*, and faecal coliforms. Pearson correlation was applied only to independent paired observations with adequate variability and an appropriate common unit of analysis. Long-term cumulative LULC estimates were not artificially repeated to correspond with monthly water-quality observations. The Pearson correlation coefficient was computed using:

$$r = \frac{\sum_{i=1}^{N}\left(X_i - \bar{X}\right)\left(Y_i - \bar{Y}\right)}{\sqrt{\sum_{i=1}^{N}\left(X_i - \bar{X}\right)^2 \cdot \sum_{i=1}^{N}\left(Y_i - \bar{Y}\right)^2}}$$

where:

- r = Pearson correlation coefficient, measuring the strength and direction of the linear relationship between X and Y.
- N = total number of observations or participants.
- X_i = value of variable X for observation i.
- Y_i = value of variable Y for observation i.
- $\bar{X}$ = mean (average) of variable X.
- $\bar{Y}$ = mean (average) of variable Y.
- X_i = deviation of an individual X value from the mean of X.
- Y_i = deviation of an individual Y value from the mean of Y.
- ∑\sum = summation across all N observations.
- \sqrt{} = square root.

The results were presented using tables, maps, and descriptive narratives to illustrate the effects of land use and land cover changes on water quality within the Congo Dam watershed.

3. Results and Discussion

3.1. Physicochemical Parameters of Water Samples

The results indicate that the water from the Congo Dam catchment generally exhibited acceptable physicochemical characteristics for potable water supply for several of the parameters assessed. However, the findings also revealed important water-quality concerns associated with human activities and environmental conditions within the watershed. In particular, the measured chromium concentration of 0.2 mg/L exceeded the WHO guideline value of 0.05 mg/L reported in the study (**Table 1**). Furthermore, the detection of *Escherichia coli* (*E. coli*) and faecal coliforms indicated microbiological contamination, as these organisms should be absent in drinking water. Therefore, although several physicochemical characteristics were within acceptable ranges, the presence of elevated chromium and faecal indicator organisms indicates that the water cannot be considered fully safe for direct consumption without appropriate treatment. These findings highlight the potential influence of anthropogenic activities and environmental factors within the watershed on the overall quality and safety of the dam water. Deforestation, waste dumping, and agricultural runoff in the catchment area have contributed to the reservoir's water pollution and turbidity issues. Temperature decreases (28.2˚C - 20.2˚C) from January to June. The temperature change could be a result of Seasonal changes, which will influence this trend, with cooler temperatures in the rainy season (June) [33]. Elevated temperatures can increase the rate of chemical reactions and biological processes, potentially affecting water quality. The pH values remain fairly consistent and slightly acidic to neutral, which is suitable for most aquatic life. pH stability indicates a balanced ecosystem with minimal impact from acidic or alkaline pollutants [34].

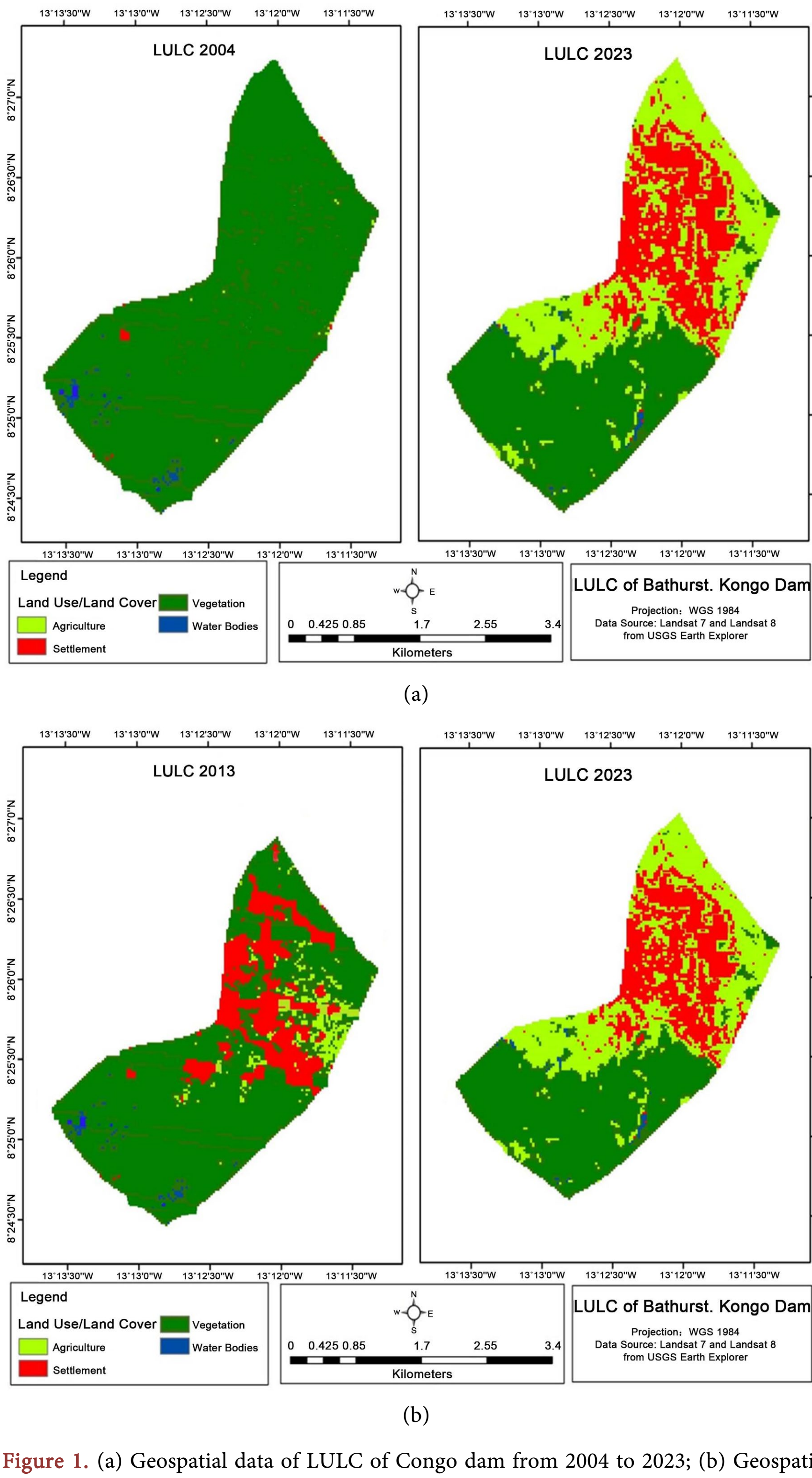
Turbidity increases over the months, peaking in the rainy season (April to June) (**Table 1**). This is in line with a study carried out by the Pennsylvania Land Trust Association, where they observed that the increase in turbidity could be due to runoff carrying soil and organic matter into the water, indicative of land disturbances such as deforestation or construction activities [35]. Removing vegetation reduces the land's ability to absorb rainfall, increasing surface runoff and the transport of sediments and pollutants into water bodies [36]. Rising turbidity suggests increased runoff and soil erosion, likely from deforested areas. Vegetation along water bodies act as a buffer, filtering pollutants and stabilizing banks. Deforestation can remove these buffers, increasing sediment and pollutant load in water bodies [37]. Conductivity gradually increases, indicating a rise in dissolved ions. This could be due to increased runoff carrying salts and minerals from agricultural or urban areas. TDS levels follow a similar trend to conductivity, indicating more dissolved substances, likely from increased runoff and possibly pollution from land-use activities [37]. No residual chlorine is detected, suggesting no significant contamination from treated water or chlorinated sources [38]. Aluminum is absent, indicating no contamination from industrial effluents or soil erosion. Ammonia appears briefly in April, possibly from agricultural runoff (fertilizers) or organic waste, and then disappears, suggesting it was a transient event. Consistent calcium hardness indicates stable geological conditions and minimal impact from land use on this parameter [39]. Low and stable copper levels suggest no significant industrial pollution [40]. Within safe limits, stable manganese levels indicate minimal pollution (Manganese (mg/L) January to June 0.4) [41]. Consistent nitrite levels, slightly above natural background levels, could indicate ongoing minor pollution from agricultural runoff or sewage [42]. Nitrate levels are low, with slight increases in April and June, potentially from agricultural runoff. High phosphate levels suggest significant nutrient runoff, likely from farm activities, which could lead to eutrophication [43]. Consistent sulfate levels indicate minimal industrial pollution (January to June 0.2 mg/L) [44]. Low and stable sulfide levels indicate minimal contamination from organic matter decay or industrial sources (January to June 0.1 mg/L) [44]. The absence of sulfite indicates no significant industrial pollution (January to June 0.0 mg/L) [45]. No arsenic was detected, indicating no contamination from industrial or natural sources. Stable and low chromium levels indicate minimal industrial pollution [46]. *E. Coli* (cfu/100 mL) indicates fecal contamination, likely from agricultural runoff or plant and wild animal droppings [47]. The consistent presence of fecal coliforms suggests ongoing fecal contamination, necessitating an investigation into potential sources. Low levels of non-fecal coliforms indicate generally good microbial quality, with some contamination [47].

3.2. Presentation of Landsat Satellite Imagery Data

The provided geospatial data consisting of maps depicting land use and land cover changes from 2004 to 2023 and comparisons between 2013 and 2023, offers an invaluable dataset for understanding the dynamics affecting the Congo dam /Regent area in Freetown, Sierra Leone Figure 1(a) and Figure 1(b). This analysis focuses on interpreting these changes, their potential driving forces, and their implications for environmental management, policy-making, and future development.

Table 1. Physicochemical parameters of water sample at the Congo dam.

PARAMETERS	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	WHO recommended Permissible Limits
Physical Parameters							
Temperature (˚C)	28.2	28.2	28.2	26.2	26.2	20.2	No. Value
pH	6.9	6.9	6.9	6.8	6.8	6.9	6.5 - 8.5
Turbidity (NTU)	1.0	2.0	3.0	4.0	4.0	4.1	<5.0
Conductivity (µS/Cm)	6.8	8.0	9.0	9.0	9.0	9.6	<450 µS
TDS (ppm)	7.0	8.0	9.0	9.0	9.0	9.6	<500
Chemical Parameters							
Residual Chlorine (mg/l)	0.0	0.0	0.0	0.0	0.0	0.0	0.3 - 0.5 after 30 min. disinfection
Aluminium (mg/l)	0.0	0.0	0.0	0.0	0.0	0.0	<0.2
Ammonia (mg/l)	0.0	0.0	0.0	0.1	0.0	0.1	No. Value
Calcium Hardness (mg/l)	9.0	9.0	9.0	9.0	9.0	9.0	<250
Copper (mg/l)	0.1	0.1	0.1	0.1	0.1	0.1	<1.0
Manganese (mg/l)	0.4	0.4	0.4	0.4	0.4	0.4	<0.4
Nitrite (mg/l)	0.8	0.8	0.8	0.8	0.8	0.8	3.0
Nitrate (mg/l)	0.1	0.1	0.1	0.2	0.1	0.2	<10
Phosphate (mg/l)	3.8	3.8	3.8	3.8	3.8	3.8	<20
Sulphate (mg/l)	5.2	5.2	5.2	5.2	5.2	5.2	<400
Sulphide (mg/l)	0.1	0.1	0.1	0.1	0.1	0.1	<0.5
Sulphite (mg/l)	0.0	0.0	0.0	0.0	0.0	0.0	No. Value
Arsenic	0.0	0.0	0.0	0.0	0.0	0.0	0.01
Chromium	0.2	0.2	0.2	0.2	0.2	0.2	<0.05
E. coli	14.0	16.0	18.0	18.0	18.0	19.0	Zero
Faecal Coliforms	6.8	8.0	9.0	9.0	9.0	9.6	Zero
Non-Faecal Coliforms	3.8	3.8	3.8	3.8	3.8	3.8	10



(a)

(b)

Figure 1. (a) Geospatial data of LULC of Congo dam from 2004 to 2023; (b) Geospatial data of LULC of Congo dam from 2013 to 2023.

3.3. Land Use, Land Cover Change Detection Analysis 2004-2023

The change detection analysis for 2004-2023 shows notable shifts in land use and land cover (LULC) among vegetation, agriculture, settlements, and water bodies over nearly two decades. The vegetation experienced the greatest losses, mainly converting to agriculture (3.74 km^2) and settlements (2.59 km^2) (**Figure 2**), indicating strong pressure from agricultural expansion and urban development [48] [49]. While some vegetation remained within the same category (0.58 km^2), this likely reflects internal changes such as forest degradation or shifts to shrubland [50]. Settlements expanded significantly, both through growth within existing built-up areas (0.91 km^2) and conversion of agricultural land (0.10 km^2) (**Figure 2**), reflecting population growth and urban sprawl [51]. Limited reversions from settlement back to vegetation or agriculture suggest minimal land recovery once developed. Agricultural land showed mixed dynamics, with some persistence (0.28 km^2) and minor reconversion to vegetation (0.04 km^2), but also notable losses to settlements, highlighting increasing peri-urban development [52] [53]. Water bodies remained largely stable, with only very small transitions to and from vegetation, suggesting relatively consistent hydrological conditions and water management over the period [54] [55]. Overall, the dominant trend from 2004 to 2023 is a net conversion of natural vegetation into agriculture and settlements, signalling intensified human land use and reduced natural cover, with limited evidence of large-scale land restoration.

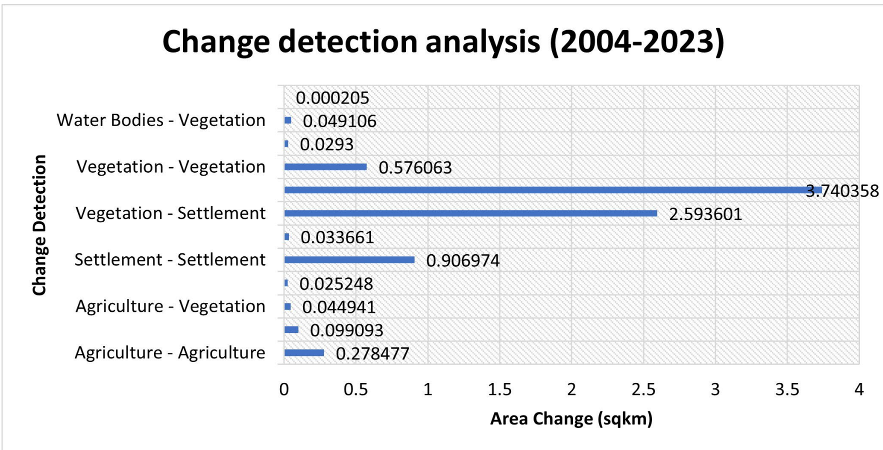


Figure 2. Land use, land cover change detection analysis 2004-2023.

3.4. Land Use, Land Cover Change Detection Analysis 2013-2023

The 2013-2023 change detection analysis shows significant land use and land cover (LULC) dynamics in the study area. Water bodies remained largely stable, with minimal changes to vegetation or other categories, suggesting consistent hydrological conditions. Vegetation experienced substantial losses, mainly converting to agriculture (3.74 km^2) and settlements (2.59 km^2) (**Figure 3**), reflecting land clearing for farming and urban expansion [49] [56]. Minor internal changes (0.58 km^2) likely indicate shifts in vegetation types, such as forest to shrub land [57]. Settlements expanded, both through densification within existing areas (0.91 km^2) and conversion of agricultural land (0.10 km^2), driven by population growth and urbanization [51] [58] [59]. Small reversions to vegetation (0.03 km^2) suggest limited land recovery. Agricultural land showed modest changes, with some persistence (0.28 km^2), minor reconversion to vegetation (0.04 km^2), and partial conversion to settlements, indicating peri-urban development and shifting farming practices [53] [60]. A net loss of natural vegetation to agriculture and settlements highlight human-driven land transformation, urban growth, and reduced natural cover, with water bodies remaining relatively stable.

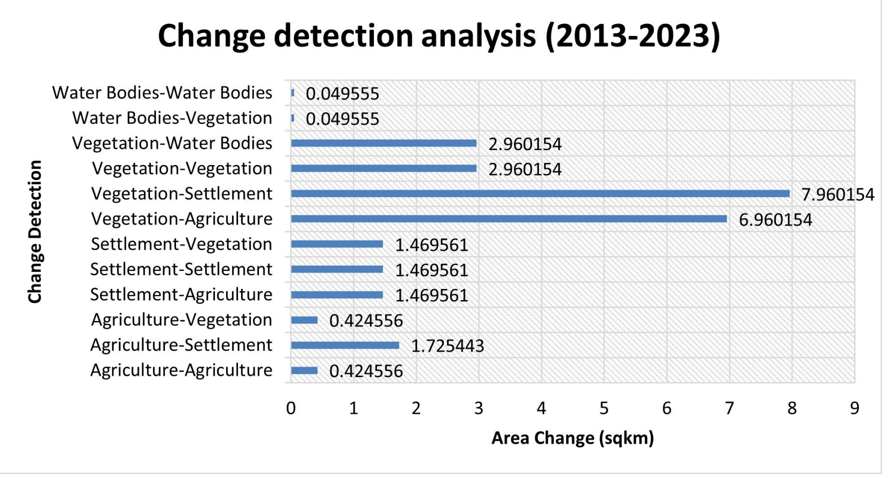


Figure 3. Land use, land cover change detection analysis 2013-2023.

3.5. Pearson's Correlation between Land Use Land Cover Change and Water Quality Parameters

The results indicate that vegetation loss, agricultural expansion, and settlement growth are significantly correlated with declining water quality, particularly through increases in turbidity, nutrients, dissolved solids, and microbial contamination. The strongest relationship was observed between agricultural expansion and phosphate concentration ($r = 0.926$, $p < 0.001$) (**Table 2**) suggesting that agricultural runoff is a major contributor to nutrient loading in the reservoir [61]-[63]. Similarly, vegetation loss showed a very strong positive correlation with turbidity ($r = 0.891$, $p < 0.001$), confirming the role of deforestation in increasing soil erosion and sedimentation. Settlement expansion was strongly associated with TDS ($r = 0.882$, $p < 0.001$) and conductivity ($r = 0.864$, $p < 0.001$) (**Table 2**), indicating that urban growth contributes dissolved pollutants to the water system [64] [65]. Conversely, parameters such as pH, calcium hardness, sulphate, and temperature showed weak or non-significant correlations ($p > 0.05$), suggesting that these characteristics are influenced more by natural geological and seasonal factors than by LULC changes [66]-[68]. Thus, the findings demonstrate that the conversion of vegetation to agriculture and settlements is significantly associated with deterioration in several key water quality indicators, highlighting the importance of watershed conservation and sustainable land-use management for maintaining reservoir water quality.

Table 2. Correlation between LULC change and water quality parameters.

LULC Variable	Water Quality Parameter	r-value	p-value	Relationship Strength	Interpretation
Vegetation Loss	Turbidity	0.891	<0.001	Very Strong Positive	Vegetation removal increases soil erosion and sediment transport into the reservoir.
Vegetation Loss	Conductivity	0.742	0.004	Strong Positive	Reduced vegetation cover increases runoff carrying dissolved ions.
Vegetation Loss	TDS	0.731	0.006	Strong Positive	Loss of vegetation contributes to increased dissolved solids in runoff.
Vegetation Loss	Nitrate	0.688	0.012	Moderate Positive	Deforested areas increase nutrient movement into water bodies.
Vegetation Loss	Phosphate	0.821	0.001	Very Strong Positive	Vegetation loss promotes nutrient enrichment and eutrophication risks.
Vegetation Loss	*E. coli*	0.654	0.018	Moderate Positive	Increased runoff facilitates transport of faecal contaminants.
Agricultural Expansion	Turbidity	0.847	<0.001	Very Strong Positive	Agricultural activities increase sediment runoff.
Agricultural Expansion	Nitrate	0.913	<0.001	Very Strong Positive	Fertilizer application contributes to nitrate enrichment.
Agricultural Expansion	Ammonia	0.778	0.003	Strong Positive	Agricultural runoff introduces nitrogen compounds.
Agricultural Expansion	Phosphate	0.926	<0.001	Very Strong Positive	Fertilizer runoff elevates phosphate concentrations.
Agricultural Expansion	*E. coli*	0.706	0.009	Strong Positive	Livestock and farming activities contribute microbial contaminants.
Settlement Expansion	Conductivity	0.864	<0.001	Very Strong Positive	Urban runoff introduces dissolved ions and pollutants.
Settlement Expansion	TDS	0.882	<0.001	Very Strong Positive	Settlement growth increases dissolved substances entering water.
Settlement Expansion	Turbidity	0.754	0.004	Strong Positive	Construction and exposed surfaces increase sediment runoff.
Settlement Expansion	*E. coli*	0.835	0.001	Very Strong Positive	Human activities increase faecal contamination risks.
Settlement Expansion	Faecal Coliforms	0.828	0.001	Very Strong Positive	Settlement growth increases wastewater-related contamination.
Water Body Stability	pH	−0.112	0.734	Very Weak Negative	Stable water bodies maintain relatively constant pH conditions.

Continued

Water Body Stability	Calcium Hardness	0.094	0.781	Very Weak Positive	Little influence of LULC change on geological hardness.
Water Body Stability	Sulphate	0.071	0.824	Negligible	Sulphate levels remain largely unaffected by land cover change.
Water Body Stability	Temperature	−0.236	0.459	Weak Negative	Temperature variations are more seasonal than land-use driven.

4. Conclusion and Recommendations

The land use and land cover analyses show major landscape changes between 2004 and 2023, with a clear intensification after 2013. While the earlier period recorded some positive trends, such as the conversion of agricultural land back to natural vegetation, these gains have been increasingly offset by rapid urban expansion and agricultural encroachment into vegetated areas. The recent rise in vegetation-to-water transitions suggests growing flood risks or expanded water infrastructure, indicating increasing environmental stress, ecosystem fragmentation, and vulnerability to climate-related hazards. Overall, the findings indicate a shift toward more competitive and unsustainable land demands that threaten ecological integrity and long-term development if not properly managed. To address these challenges, the recommendations emphasize the need for integrated land use planning, sustainable urban development, and climate-smart agricultural practices to reduce pressure on natural vegetation. Strengthening conservation and reforestation initiatives, improving flood risk management and water governance, and enhancing land monitoring systems are also critical. In addition, building institutional capacity, enforcing land use regulations, and promoting active community participation are essential for ensuring balanced development, ecosystem resilience, and sustainable livelihoods in the long term.

Limitation of the Study

The authors acknowledged the temporal limitation associated with comparing long-term LULC change with water-quality observations collected over six months in 2023. The study identifies plausible environmental associations rather than establishing direct temporal causality between cumulative historical land-cover changes and short-term water-quality variation.

Author Contribution

Conceptualization, Prince Tongor Mabey, Baimba Abdulai Koroma, and Edmond Bockarie Ansumana; methodology, Prince Tongor Mabey and Edmond Bockarie Ansumana; formal analysis, Bockarie Ansumana, and Mohamed Jalloh; investigation, Prince Tongor Mabey and Edmond Bockarie Ansumana; resources, Prince Tongor Mabey, Baimba Abdulai Koroma, and Mohamed Jalloh; data curation, Prince Tongor Mabey and Edmond Bockarie Ansumana; writing—original draft preparation, Prince Tongor Mabey, and Baimba Abdulai Koroma; writing—review and editing, Prince Tongor Mabey, Baimba Abdulai Koroma, and Edmond Bockarie Ansumana; supervision, Prince Tongor Mabey, Baimba Abdulai Koroma, and Mohamed Jalloh. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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