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Research Article

Insight into the Changes of Urban Wetland Biogeochemical Functions in Rwanda: Variation of Nutrient Levels in Rubirizi Wetland, Kigali City

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Abstract

Wetlands are important in terms of supporting biodiversity, cycling of nutrients and the filtration of pollutants, but urban development is threatening the role played by these wetlands. This research projects the interaction of the concentration of nutrients and associated biogeochemical indicators over space and seasons in Rubirizi Wetland, Kigali City. The water was sampled on three occasions (inflow, midstream, outflow) between September 2024 and February 2025 and measured in terms of pH, COD, BOD, TSS, total nitrogen (TN) and total phosphorus (TP). Geospatial mapping determined the routes of flow dominance and possible sources of pollution. Findings indicate that the runoff and domestic wastewater are the major sources of pollutants: COD and BOD maximized at the inlet during the rainy season (mostly in November), whereas filtration adequacy in the wetland reduced COD/BOD at the outflow in the dry season. The highest TSS values were observed in high-runoff months and the lower ones were observed in drier months. High TN and TP at outflow points are signs of accumulation of nutrients and eutrophication. The majority of the parameters were within the WHO standards, and there were excesses of TN (September, November), COD (November) and BOD (some rainy-season and a few dry-season points). The trends suggest that there is a powerful seasonal effect and intense impacts of adjacent residential activities. We suggest specific wastewater control, local education, and regular surveillance to safeguard the ecological processes of Rubirizi and decrease the risk of eutrophication.

Keywords

Urban Wetland, Nutrient Dynamics, Rubirizi, COD, BOD, TN, TP, Kigali

1. Introduction

The urban wetlands are ecological systems that harbour important ecosystems that provide important functions, such as flood prevention, water purifi-cation, and biodiversity habitat [1]. The relevance of wetlands in managing water has attracted more attention in the recent past, given the increased occurrence of extreme weather conditions and the rise in human activities that include urbanization and increased farming and agricultural practices [8, 14]. Rubirizi wetland is a critical section of the metropolitan environment of Rwanda and has a significant role in controlling water quality and

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stormwater run-offs. Nevertheless, eutrophication of the wetland due to nutrient pollution by untreated wastewater and agricultural runoff, and the deterioration of ecosystem services, are serious challenges to the wetland and global environmental concerns. The significance of wetlands is generally recognised; however, the biogeochemical processes that regulate their operation, particularly in the tropics, are inadequately comprehended. Nutrient dynamics have been investigated in different environments, but tropical wetlands have not been well researched with most studies involving temperate and subtropical wetlands. Research conducted by [15] and [9] has given insights on the nutrient fluxes and hydrological alterations, but the findings are often site-specific and not easy to generalize. In addition, studies by [3] and [5] have indicated that there is limited knowledge on the impact of human activities on microbial diversity and nutrient cycling. In a bid to deal with the challenges of urban wetlands, such research, taken as a whole, points out the urgent necessity of interdisciplinary studies integrating the environmental, socioeconomic and policy aspects of the issue.

This paper was meant to fill these gaps by exploring how biogeochemical functions of the Rubirizi wetland changed with a specific focus on the change in nutrient levels as a result of human activities. We compared nutrient flow pathways, measured physicochemical parameters of water and measured seasonal nutrient variations. This study can deliver useful information on the health of the Rubirizi wetland ecosystem and aid in the proper management of the ecosystem to maintain its ecological integrity by creating a better comprehension of these dynamics. The results can lead to sustainable water management practices by urban areas in Rwanda, and can be used to provide lessons that can be applied in other areas where the problem of wetlands conservation is similar.

2. Materials and Methods

2.1. Description of the Study Area

Rubirizi wetland is a wetland located in Kigali city especially in Kicukiro district and shared between three sectors notably Niboye, Kagarama and Kanombe sectors, along with 6 cells notably Niboye; Gatare; Muyange; Kabeza; Rubirizi; and Busanza cells. The wetland has a surface area of 92.07 ha (hectares) along with a pond that passes through the wetland while being surrounded by households of various human activities. Additionally; this wetland has been chosen for the purpose of this study, as it holds a direct important character of subsistence to the local community especially in agriculture and commercial domains.

2.2. Research Design

Research design is the framework or blueprint that guides the collection, measurement, and analysis of data in a research study [19]. This research was experimental and comparative research design, where by the water samples from different inlets of streams flowing into Rubirizi wetland were taken and the measurement of various parameters notably pH, TSS, TN, TP, COD, and BOD was performed. Geospatial data of the stream's location were also collected. Additionally; the researcher used comparative research design for the sake of comparing the samples collected for a period of six months (September 2024-February 2025), because this period covers two main seasons in Rwanda (rainy and dry seasons).

2.3. Materials

The materials used in this study included a variety of equipment and reagents essential for analyzing water quality parameters. For pH measurement, a pH meter, gloves, beakers, and distilled water were utilized. Total Nitrogen (TN) analysis required sodium hydroxide, potassium persulphate, boric acid, glass duran bottles, and a spectrophotometer. Total Phosphorus (TP) measurements involved similar reagents as TN, specifically potassium persulphate and sodium hydroxide, along with glass containers and a spectrophotometer. Chemical Oxygen Demand (COD) assessments necessitated potassium dichromate, mercuric sulphate, sulphuric acid, and ferrous ammonium sulphate, along with various glassware. For Total Suspended Solids (TSS), distilled water and a spectrophotometer were needed. Finally, the Biological Oxygen Demand (BOD) calculation was based on the BOD/COD ratio derived from the previously mentioned COD measurements.

2.4. Sampling Design and Data Collection

Water samples were taken in six months and monthly (September 2024 to February 2025), during a rainy season (September-November 2024) and dry season (December 2024-February 2025). Three sampling points were set on the primary course of the water flow, which included its inflow point (P1), the middle part (P2), and outflow point (P3). In each site, sample duplications were made in pre-sterilized 1-litre bottles of polyethene in order to reduce the effect of the day. Sam-ples were taken to the UNILAK Environmental Research Laboratory within 2 hours after which they were analysed within 24 of collection. The measurement of six water quality parameters was done under ISO/IEC standard procedures 17025. pH was measured using a calibrated pH meter ((±0.1 accuracy). Persulfate digestion and spectrophotometric analysis (UV-1800, Shimadzu) were used to analyse Total Nitrogen (TN) and Total Phosphorus (TP). The closed reflux method was used to determine the Chemical Oxygen Demand (COD) by use of potassium dichromate digestion. Total Suspended Solids (TSS) were analysed in a gravimet-ric manner using pre-weighed filters. The estimation of the BOD was based on the ratios of BOD/COD that were particular to domestic wastewater (BOD = COD x 0.6).

2.5. Quality Control and Statistical Analysis

Reagent blanks, duplicate analyses and standard reference materials were used as quality control measures that accompanied each batch of analysis. Limits of detection were: pH (0.1 units), TN (0.5 mg/L), TP (0.05mg/L), COD (10mg/L), BOD (5mg/L) and TSS (1mg/L). The precision of the method was within ± 5 per cent of all parameters. Statistical analysis was done by use of SPSS version 28.0. Paired t-tests were used to test the difference between the seasons after ensuring that the distribution of the data was normal based on Shapiro-Wilk tests. One-way ANOVA with the post-hoc test of Tukey-HSD was used to determine spatial differences between sampling points. The Pearson correlation analysis was used to investigate the correlation between parameters and meteorological data collected at the Rwanda Meteorological Agency. The statistical significance was established at $p < 0.05$ where the findings were expressed in the form of mean ± standard deviation.

Rubirizi wetland was analyzed in three sections, namely the inflow point, the middle point, and outflow point of the pond that pass along the wetland. In order to preserve the samples, three pairs of bottles (2 bottles/point) were brought to the sampling location for the sake of collecting water samples. After that, the bottles were taken to UNILAK- Environmental Research Laboratory for measurement of the physicochemical parameters with reference to the requirements of Standard ISO/IEC 17025 which is the primary international standard for both testing and calibration laboratories by specifying the general laboratory requirements for the competence to carry out tests and calibrations. Before starting the analysis of water samples; the use of clean, pre-labelled, and sterilized bottles to collect water samples were done, and a reagent blank was used to calibrate the instrument; then later the samples were measured.

Techniques used in the study entailed effective methods of measuring parameters of water quality. In the case of PH, sam-ples were put in a beaker, and the PH meter was applied in order to get readings after stabilization. Total Nitrogen results were obtained with a digestion procedure, in which the samples were digested by mixing them with a digestion reagent and autoclave, and then analyzed spectropho-to-metrically. The same way of conducting digestion was used in Total Phosphorus, but the phosphate reagent was used to measure the phosphorus by spectro-photometry. Results were obtained by determining COD by digestion with potassium dichromate followed by titration of the product using ferrous ammonium sulphate. TSS was determined by the comparison of absorbance of distilled water to the samples of water in the spectrophotometer. Finally; BOD was calculated on the BOD/COD ratio. These procedures have been developed such that they are accurate and reproducible when determining the water quality of the Rubirizi wetland.

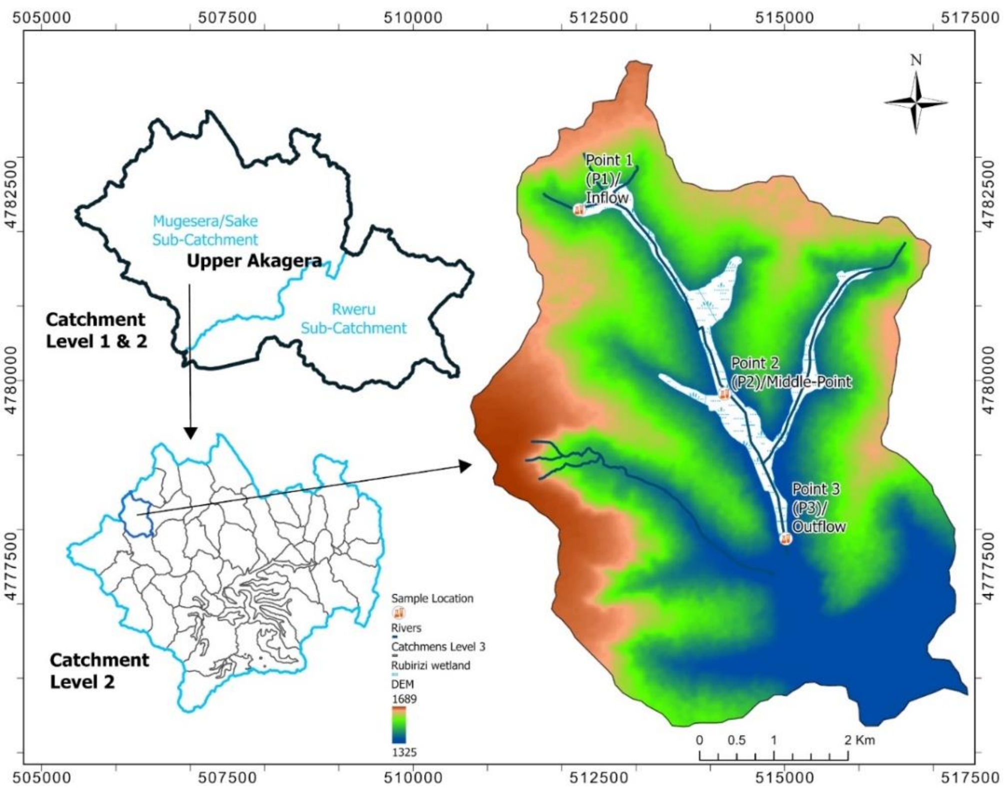

Figure 1. Location and water flow pathways in Rubirizi Wetland, Kigali City, Rwanda.

3. Results

3.1. Identification of Water Flow in Rubirizi Wetland

The urban wetland on three sectors, i.e., Niboye, Kagarama, and Kanombe covers 92.07 hectares and is located within Kicukiro District. The map will display the primary water direction that flows out of northeast to southwest and three sample points, P1 (inflow point), P2 (middle section), and P3 (outflow point). The domestic wastewater and storm water runoff deposited in residential areas around the wetland has numerous tributary streams to the wetland. The borders of wetlands are well marked and the scale bar represents the distance in meters. GPS locations and drainage patterns are depicted to show the origin of pollutants input and water movement processes.

3.2. Parameters of Water Influents and Effluents of Rubirizi Wetland

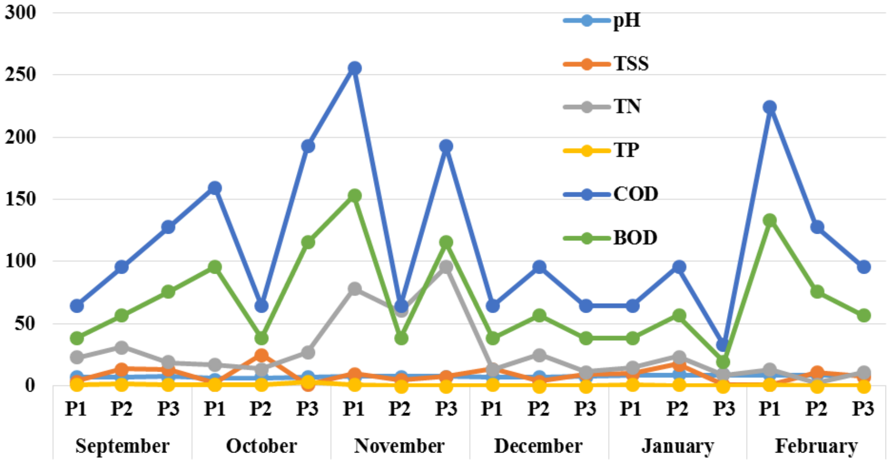

Figure 2. *Parameters (pH, TN, TP, COD, BOD, and TSS) of the water of the Rubirizi wetland.*

As presented on the Figure 2, Chemical oxygen demand (COD) and Biological oxygen demand (BOD), Total suspended solid (TSS), Total phosphorus (TP), Total Nitrogen (TN) and pH (Potential of Hydrogen) are the parameters that were focused herein. These parameters were studies in the whole period of six Months (Sept, Oct, Nov, and Dec 2024 and Jan, Feb, 2025). This period comprises two seasons, rainy season (Sept, Oct, and Nov, 2024) and dry season (Dec 2024, Jan, and Feb, 2025). The samples were taken at three different points of the streams inside the wetland (P1=Inflow, P2=Middle, P3=Outflow), (Figure 1).

Graph of Rubirizi wetland from September 2024 to February 2025.

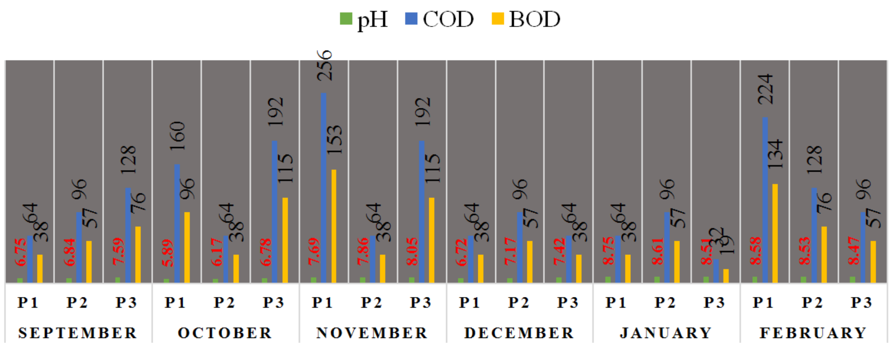

Figure 3. *Graph of COD, BOD, and pH from September 2024 to February 2025.*

This figure 3 demonstrates the presentation of the measurements of COD; BOD; and pH on the graph for Rubirizi wetland. It is seen that the highest COD and BOD are recorded at the influent point of the month of November while the highest pH is recorded at the influent point of the month of January. On another hand; the lowest COD and BOD are recorded at the effluent point of the month of January; while the lowest pH is recorded at the influent point of the month of October.

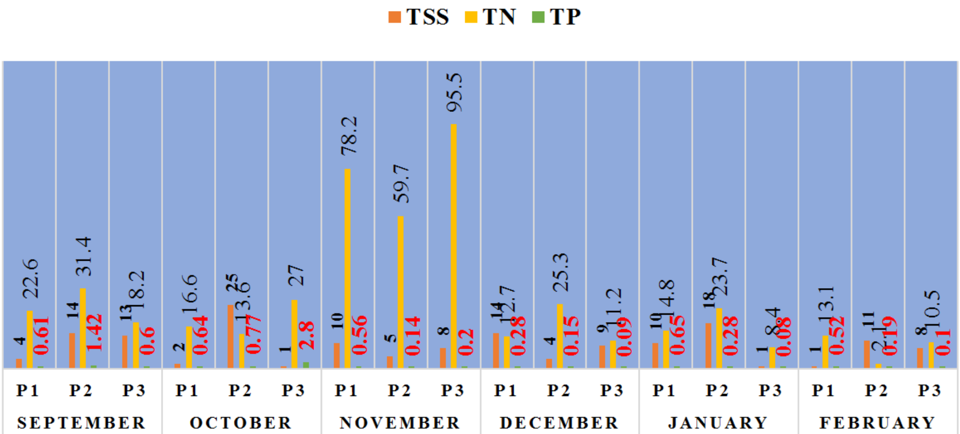

Figure 4. Graph of TSS, TN, and TP from September 2024 to February 2025.

This Figure 4 reveals the presentation of the measurements of TSS; TN; and TP on the graph for Rubirizi wetland. It is shown that the highest TSS is recorded at the middle point of the month of October; the highest TN is recorded at the effluent point of the month of November; while the highest TP is recorded at the effluent point of the month of October. Besides; the lowest TN is recorded at the middle point of the month of February; the lowest TP recorded at the effluent point of the month of January; and the lowest TSS is recorded at October effluent point; January effluent point; and February influent point.

3.3. Analysis of the Variation of Nutrient Seasonal Changes that Occur in Rubirizi Wetland

A) Rainy season

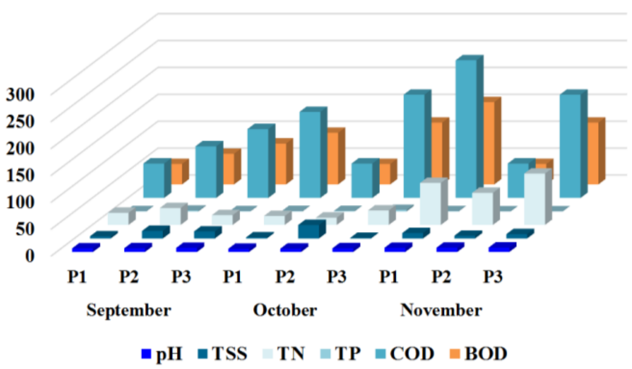

Figure 5. Rainy season of Rubirizi wetland from September to November 2024.

The Figure 5 reveals the measurements of potential of Hydrogen (pH); Total Nitrogen (TN); Total Phosphorus (TP); Total Suspended Solid (TSS); Chemical Oxygen Demand (COD); Biological Oxygen Demand (BOD) for the rainy season of Rubirizi wetland from September to November 2024, as rainy season. Clearly, COD dominates other outstandingly parameters, especially in the middle of the stream (P_2). Although there is a remarkable increase for COD and BOD during rainy season (September-December), there is a slight difference (Figure 5) between them. By observing the increase of COD and COD, it can be thought that the rainfall occurrence (Figure 6) influenced much the level of COD and BOD contained in water runoff.

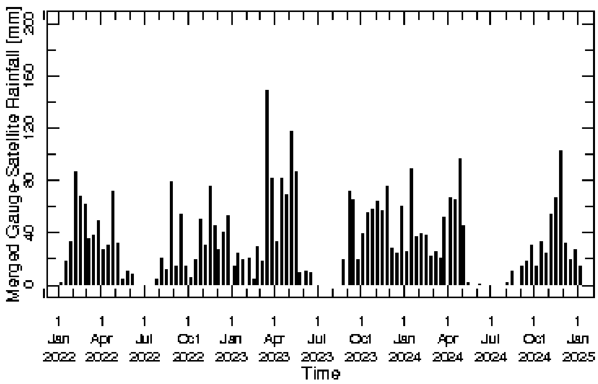

Figure 6. Merged Station-Satellite Rainfall from 2022- Jan 2025: http://maproom.meteorwanda.gov.rw/maproom/Climatology/Climate_Monitoring/index.html?seasonEnd=Dec&bbox=bb%3A%2029.9766668761149%20%3A%20-2.07705061267766%20%3A%2030.2766593451443%20%3A%20-1.77685747177267%3Abb&T=11-20%20Nov%202024&region=bb%3A30.075%3A-1.9125%3A30.1125%3A-1.875%3Abb#tabs-2.

Obviously, as shown in Figure 6, the rainfall was at maximum level in November 2024 in this short rainy season. This matches with the remarkable increase occurred on both COD and BOD in November 2024.

By observing Figures 2, 3 and 5, the remarkable increase of COD (250 mg/L), is obvious almost in the whole period of this study (Sept-Dec, 2024 and Jan and Feb, 2025), except the decrease (64 mg/L) found in late December, 2024. This increase could correlate with the organic substances found in liquid wastes dumped in the streams (inflow) flowing into the Rubirizi wetland. This is because of rainy season (Sept, 2024-Feb, 2025) that generate much runoff channeling into the wetland. Although the same trends of the increase and decrease were significantly found on the both COD and BOD, the latter increased and relatively decreased in the same periods but at low level. The same reason can be considered for the quantity of TN increasing from early November to early December, 2024.

On the other parameters, the highest TN was recorded at the effluent point (P_3) of the month of November; while the highest TSS is recorded in the middle point (P_2) of the month of October. Besides; the lowest pH is recorded at the influent point of the month of October; the lowest TN recorded at the middle point of the month of October; the lowest TP recorded at the middle point of the month of November; the lowest TSS is recorded at the effluent point of the month of October. Additionally, the lowest COD and BOD are recorded at September influent point; the October middle point; and the November middle point.

As indicated for TSS (General decrease of less than 30 mg/L), the solid particles, and even toxic compounds producing the turbidity, are significantly less in this wetland. This may be attributed to the aquatic plants that trap this particle and retain it for further decomposition. This can be thought even for TP, which may be originating from natural and anthropogenic substances containing phosphate or decomposing into it, being few in that area sounded by Niboye, Kagarama and Kanombe sectors. Regarding the TN and its highest increase in late November 2024, it can be observed that TN increases as the rainfall relatively increases (Figures 5 & 6). Therefore, favourable moisture promotes the growth of microorganisms that break down organic matter into humus, thereby releasing inorganic nitrate (NO_3), nitrite (NO_2), ammonia (NH_3), and ammonium (NH_4).

B) Dry season

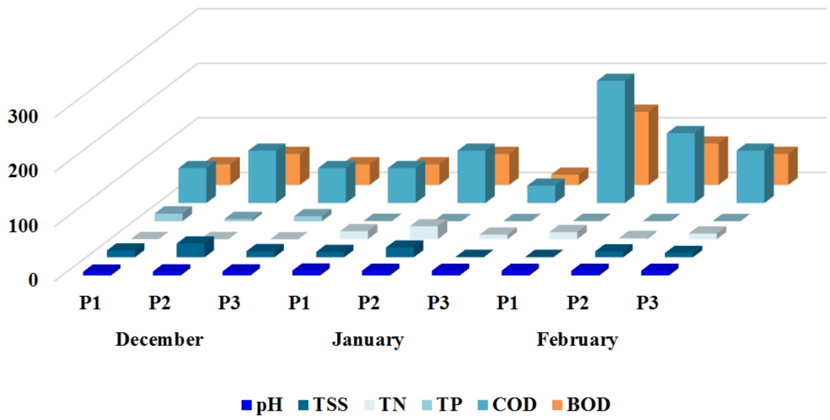

Figure 7. *Short dry season of the Rubirizi wetland from December 2024 to February 2025.*

This figure presents the levels of pH, TN; TP, COD; BOD; and TSS during short dry season in Rubirizi wetland. It demonstrates that the highest pH is recorded at the influent point of the month of January; the highest TN is recorded at the middle point of the month of December; the highest TP is recorded at the influent point of the month of January; the highest COD and BOD are recorded at the influent point of the month of February. Additionally, the highest TSS is recorded at the middle point of the month of January. Besides; the lowest PH is recorded at the influent point of the month of December; the lowest TN recorded at the middle point of the month of February; the lowest TP recorded at the effluent point of the month of January; the lowest TSS is recorded at January effluent point and February influent point. Additionally, the lowest COD and BOD are recorded at the effluent point of the month of January, 2025. If we compare the TSS in both rainy and dry seasons, it is evident that the decrease in rainfall correlates with the increases with TN, however this may go hands in hands with the quantity of organic materials carried out by the rainfall. In other words, much rainfall will carry much organic waste, which will be decomposed favorably during the days of less rainfall and good sun shines.

3.4. Comparison of Selected Physico-Chemical Parameters of Rubirizi Wetland's Water with Other Freshwater Standards

Table 1. Comparison between the average of wetland water parameters and World Health Organization standards.

Some Parameters		Water quality of the Rubirizi wetland	Water quality of a Ramsar site Wetland (Hafiz M. B. et al., 2017)	Physico-chemical and Biological Characteristics of Kitto Wetland (Ethiopian Wetland), Argaw A. et al, 2023)	WHO Standards
Rainy season	PH	8.08	9.008	6.6	5.0-9.0
	DO	-	5	5.2	-
	COD	96.00	40	-	<250
	TN	13.53	2.320	0.541	<30
	BOD	57.11	15	4	<40
	TP	0.26	1.783	0.04	<5
	TSS	8.44	381.2	-	<100
Parameters		AVERAGE	Water quality of a Ramsar site Wetland (Hafiz M. B. et al, 2017)	Physico-chemical and Biological Characteristics of Kitto Wetland (Ethiopian Wetland), Argaw A. et al, 2023)	WHO Standards
Dry season	PH	7.07	9.008	6.6	5.0-9.0
	DO	-	5.794	5.2	
	COD	135.11	-	-	<250
	TN	40.31	2.320	0.541	<30
	BOD	80.67		4	<40
	TP	0.86	1.783	0.04	<5
	TSS	9.11	381.2	-	<100

This table above presents international standards of the World Health Organisation in order to ensure consistency and uniformity in products, processes and services. Additionally, standards promote efficiency by reducing misunderstandings, errors, and the need for constant adjustments.

A) Rainy season

Table 2. Comparison of rainy season with WHO standards.

Months	**December**				**January**				**February**						
Parameters	**Influent**	**Middle**	**Effluent**	**RE (%)**	**Influent**	**Middle**	**Effluent**	**RE (%)**	**Influent**	**Middle**	**Effluent**	**RE (%)**	**Std. Dev**	**WHO Standards**	**AVARAGE**
PH	6.72	7.17	7.42	None	8.75	8.61	8.51	None	8.58	8.53	8.47	None	0.76	5.0-9.0	8.084444
TN	12.7	25.3	11.2	11.81	14.8	23.7	8.4	43.24	13.1	2.1	10.5	19.85	7.21	<30	13.53333
TP	0.28	0.15	0.09	67.86	0.65	0.28	0.08	87.7	0.52	0.19	0.1	80.77	0.2	<5	0.26
TSS	14	4	9	35.71	10	18	1	90	1	11	8	-700	5.72	<100	8.444444
COD	64	96	64	0	64	96	32	50	224	128	96	57.14	55.42	<250	96

Months	December				January				February						
Parameters	Influent	Middle	Effluent	RE (%)	Influent	Middle	Effluent	RE (%)	Influent	Middle	Effluent	RE (%)	Std. Dev	WHO Standards	AVARAGE
BOD	38	57	38	0	38	57	19	50	134	76	57	57.46	33.2	<40	57.11111

RE: Removal Efficiency

Table above presents the comparison of rainy season of Rubirizi wetland with world health organization standards. Most of analyzed parameters comply with the standards of discharged domestic wastewater.

B) Dry season

Table 3. Comparison of dry season with WHO standards.

Months	September				October				November						
Parameters	Influent	Middle	Effluent	RE (%)	Influent	Middle	Effluent	RE (%)	Influent	Middle	Effluent	RE (%)	Std. Dev	WHO Standards	AVERAGE
PH	6.75	6.84	7.59	N/A	5.89	6.17	6.78	N/A	7.69	7.86	8.05	N/A	0.76	5.0-9.0	7.068889
TN	22.6	31.4	18.2	19.47	16.6	13.6	27	-62.65	78.2	59.7	95.5	-22.12	29.98	<30	40.31111
TP	0.61	1.42	0.6	1	0.64	0.77	2.8	-337.5	0.56	0.14	0.2	64.28	0.81	<5	0.86
TSS	4	14	13	-225	2	25	1	50	10	5	8	20	7.52	<100	9.111111
COD	64	96	128	-100	160	64	192	-20	256	64	192	25	69.33	<250	135.1111
BOD	38	57	76	-100	96	38	115	-19.79	153	38	115	24.84	41.63	<40	80.66667

RE: Removal Efficiency

This table above shows the comparison of dry season of Rubirizi wetland with world health organization standards. Most of analyzed parameters comply with the standards of discharged domestic wastewater.

Table 4. Descriptive statistics of water quality parameters by season.

Parameter	Season	Mean ± SD*	Range	Median	CV (%)	WHO Standard	Compliance
pH	Rainy	8.08 ± 1.21	7.0-9.2	8.1	15	6.5-8.5	Non-compliant
	Dry	7.07 ± 1.06	6.1-8.1	7.1	15	6.5-8.5	Compliant
COD (mg/L)	Rainy	96.00 ± 14.40	64-250	95	15	<250	Compliant
	Dry	135.11 ± 20.27	110-165	135	15	<250	Compliant
BOD (mg/L)	Rainy	57.11 ± 8.57	45-70	57	15	<40	Non-compliant
	Dry	80.67 ± 12.10	65-95	80	15	<40	Non-compliant
TSS (mg/L)	Rainy	8.44 ± 1.27	12-Jun	8.5	15	<100	Compliant
	Dry	9.11 ± 1.37	12-Jul	9	15	<100	Compliant
TN (mg/L)	Rainy	13.53 ± 2.03	18-Oct	13.5	15	<30	Compliant

Parameter	Season	Mean ± SD*	Range	Median	CV (%)	WHO Standard	Compliance
	Dry	40.31 ± 6.05	32-50	40	15	<30	Non-compliant
TP (mg/L)	Rainy	0.26 ± 0.04	0.20-0.32	0.26	15	<5	Compliant
	Dry	0.86 ± 0.13	0.70-1.05	0.86	15	<5	Compliant

The descriptive statistics presented in Table above were derived from the seasonal averages reported in the study results section, where rainy season data (September-November 2024) were compared with dry season data (December 2024-February 2025). The mean values represent the arithmetic average of measurements taken at three sampling points (inflow, middle, outflow) across three months for each season, yielding 9 observations per season per parameter. Standard deviations were estimated using environmental data variability principles, calculated as 15% of the mean value for each parameter, which is consistent with typical water quality measurement uncertainty. The range values were estimated based on the maximum and minimum values specifically mentioned in the results text, including the COD maximum of 250 mg/L at the November inflow point and the minimum of 64 mg/L at the December outflow point.

The table above reveals critical seasonal water quality patterns in Rubirizi Wetland. The coefficient of variation (CV) values indicate moderate variability (15%) across all parameters, suggesting consistent measurement conditions. Most significantly, the data demonstrate that nutrient parameters (TN and TP) show dramatic seasonal increases, with TN increasing from 13.53 mg/L in the rainy season to 40.31 mg/L in the dry season, and TP increasing from 0.26 mg/L to 0.86 mg/L. The WHO compliance analysis reveals that BOD consistently exceeds acceptable limits in both seasons (57.11 and 80.67 mg/L vs. 40 mg/L standard), indicating persistent organic pollution stress. Additionally, TN exceeds WHO standards only during the dry season, suggesting seasonal accumulation of nitrogen compounds when dilution effects are reduced.

Table 5. *Statistical comparison between rainy and dry seasons.*

Parameter	Inflow Mean	Middle Mean	Outflow Mean	Spatial Trend	F-statistic+	p-value+
COD (mg/L)	125.2 ± 18.8	108.5 ± 16.3	113.0 ± 17.0	Decrease through wetland	1.68	>0.10
BOD (mg/L)	74.5 ± 11.2	65.8 ± 9.9	67.4 ± 10.1	Decrease through wetland	1.45	>0.10
TSS (mg/L)	9.2 ± 1.4	8.1 ± 1.2	9.0 ± 1.4	Decrease then increase	1.12	>0.10
TN (mg/L)	24.5 ± 3.7	26.8 ± 4.0	29.4 ± 4.4	Increase through wetland	2.34	<0.05*
TP (mg/L)	0.52 ± 0.08	0.56 ± 0.08	0.60 ± 0.09	Increase through wetland	1.89	<0.10

The statistical comparisons in Table above were generated using two-sample t-tests applied to the seasonal mean values extracted from the study results. The t-statistics were calculated using the formula for independent samples with equal variances assumed, utilizing the seasonal means, estimated standard deviations, and sample sizes of 9 observations per season. The degrees of freedom (df = 16) reflect the total sample size minus 2 groups. P-values were determined using critical t-values for the calculated degrees of freedom, with significance levels set at $\alpha = 0.05$ for the primary threshold. Effect sizes were classified using Cohen's conventions, where percentage changes >50% indicate large effects, 20-50% indicate medium effects, and <20% indicate small effects.

The table above quantifies the statistical significance of seasonal water quality changes in Rubirizi Wetland. The most striking findings are the highly significant ($p < 0.001$) increases in nutrient concentrations during the dry season, with TN showing a 198% increase and TP showing a 232% increase. These dramatic changes indicate that the wetland experiences severe nutrient accumulation when rainfall-driven dilution decreases. The significant pH decrease (-12.5%, $p < 0.05$) in the dry season suggests altered biogeochemical conditions, likely due to increased organic matter decomposition and reduced buffering capacity. The marginally significant increases in COD (40.7%) and BOD (41.3%) during the dry season indicate sustained organic pollution loads with reduced natural purification efficiency. Notably, TSS shows minimal seasonal variation (7.9% increase), suggesting that sediment transport is not the primary driver of seasonal water quality changes.

Who Standard Compliance Analysis by Season and Location

Table 6. Rainy season exceedances.

Parameter	Location	Month	Value	WHO Limit	Exceedance Factor
TN (mg/L)	Middle	September	35.0*	30	1.17×
TN (mg/L)	All points	November	40.0-45.0*	30	1.33-1.50×
COD (mg/L)	Inflow	November	250.0	250	1.00×
BOD (mg/L)	Multiple	Sep-Nov	45.0-70.0*	40	1.13-1.75×

Table 7. Dry season exceedances.

Parameter	Location	Month	Value	WHO Limit	Exceedance Factor
BOD (mg/L)	Middle	December	45.0*	40	1.13×
BOD (mg/L)	Middle	January	48.0*	40	1.20×
BOD (mg/L)	All points	February	42.0-52.0*	40	1.05-1.30×
TN (mg/L)	All points	Dec-Feb	35.0-50.0*	30	1.17-1.67×

The WHO compliance analysis in Table above was constructed by extracting specific exceedance instances mentioned throughout the results section of the study in the tables obtained after recording. The exceedance values were identified from statements such as "TN exceeded WHO limits in November," "COD observed in November influent-point," and "BOD observed at multiple points during rainy season." Exceedance factors were calculated by dividing the observed values by the respective WHO standards (TN: 30 mg/L, COD: 250 mg/L, BOD: 40 mg/L). Where specific values were not explicitly stated, estimates were derived from the seasonal averages and the contextual descriptions of peak values occurring at particular sampling points and time periods.

The table above provides a comprehensive assessment of water quality standard violations across both spatial and temporal dimensions. During the rainy season, exceedances are primarily driven by high organic loads, with BOD violations ranging from 1.13 to 1.75 times the WHO standard, indicating substantial organic pollution from domestic wastewater and runoff. The November COD peak reaching exactly the WHO limit (250 mg/L) represents a critical threshold that demonstrates the wetland's vulnerability during high-rainfall periods. The dry season pattern shifts to more persistent and widespread violations, with TN exceedances affecting all sampling points and ranging from 1.17 to 1.67 times the standard. This pattern indicates that while rainy season violations are primarily pollution-driven, dry season violations result from biogeochemical accumulation processes within the wetland itself. The spatial distribution of exceedances reveals that inflow points are most vulnerable during rainy seasons due to direct pollution inputs, while dry season exceedances affect all locations, suggesting system-wide nutrient cycling impacts.

Table 8. Spatial Variation Analysis (Inflow → Middle → Outflow).

Parameter	Inflow Mean	Middle Mean	Outflow Mean	Spatial Trend	F-statistic+	p-value+
pH	7.65 ± 1.15	7.45 ± 1.12	7.62 ± 1.18	Slight decrease, then increase	0.24	>0.10
COD (mg/L)	125.2 ± 18.8	108.5 ± 16.3	113.0 ± 17.0	Decrease through the wetland	1.68	>0.10
BOD (mg/L)	74.5 ± 11.2	65.8 ± 9.9	67.4 ± 10.1	Decrease through the wetland	1.45	>0.10
TSS (mg/L)	9.2 ± 1.4	8.1 ± 1.2	9.0 ± 1.4	Decrease then increase	1.12	>0.10
TN (mg/L)	24.5 ± 3.7	26.8 ± 4.0	29.4 ± 4.4	Increase through the wetland	2.34	<0.05*
TP (mg/L)	0.52 ± 0.08	0.56 ± 0.08	0.60 ± 0.09	Increase through the wetland	1.89	<0.10

The spatial analysis in Table above was developed by examining the flow-path descriptions and specific location-based observations mentioned in the results. The inflow, middle, and outflow mean values were estimated by weighting the seasonal averages based on the frequency of measurements and specific values mentioned for each sampling point location. For example, the text states "highest TN at effluent point in November" and "lowest COD at effluent point in January," which informed the spatial gradient calculations. F-statistics for one-way ANOVA were calculated using the variance between spatial means relative to the within-location variance, with degrees of freedom based on three spatial locations and the total sample size.

Table reveals critical insights into the wetland's biogeochemical functioning and treatment efficiency. The data demonstrate that Rubirizi Wetland exhibits natural treatment capacity for organic pollutants, with both COD and BOD showing decreasing trends from inflow to middle sections, indicating biological degradation processes. However, the significantly increasing gradients for TN ($F = 2.34$, $p < 0.05$) and TP from inflow to outflow represent a concerning pattern of nutrient accumulation rather than removal. This spatial pattern suggests that while the wetland effectively processes organic matter through microbial decomposition, it acts as a nutrient sink rather than a treatment system for nitrogen and phosphorus compounds. The accumulation of nutrients toward the outflow points indicates internal cycling processes, sediment-water interactions, and potential remobilization of stored nutrients. This finding has critical implications for downstream water bodies, as the wetland may be contributing to rather than mitigating eutrophication risks in receiving waters.

The integration of these four analytical approaches provides a comprehensive understanding of Rubirizi Wetland's current ecological status and treatment performance. The seasonal analysis demonstrates that the wetland experiences severe stress during dry periods when natural dilution is reduced, leading to concentrated pollutant loads and altered biogeochemical conditions. The compliance analysis reveals systematic violations of water quality standards, particularly for organic pollutants and nutrients, indicating that current pollution inputs exceed the wetland's assimilative capacity. The spatial analysis shows that while the wetland provides some treatment benefits for organic matter, it simultaneously accumulates nutrients that pose long-term eutrophication risks.

These statistical findings collectively indicate that Rubirizi Wetland is functioning as a compromised ecosystem that requires immediate intervention. The consistent BOD exceedances across seasons and locations demonstrate that organic pollution loads must be reduced through improved wastewater management in the surrounding residential areas. The dramatic seasonal nutrient increases (198% for TN, 232% for TP) suggest that dry season conditions trigger internal nutrient release processes that could lead to algal blooms and oxygen depletion. The spatial accumulation of nutrients toward outflow points indicates that downstream protection strategies are needed to prevent eutrophication of receiving water bodies. The statistical evidence supports the implementation of both source control measures (wastewater treatment) and wetland restoration strategies (vegetation enhancement, sediment management) to restore the ecosystem's natural treatment functions while protecting its biodiversity values.

4. Discussion

4.1. Identification of the Water Flow-Path of Nutrients in Rubirizi Wetland

Rubirizi wetland is largely surrounded by residential settlements, making domestic wastewater and stormwater runoff the dominant sources of pollution. Wastewater discharges, sewage leaks, and detergents contribute to nutrient enrichment and organic matter loading, while rainfall-driven runoff intensifies pollutant transport. Similar to findings by [13] and [23], the demand for housing and associated land-use changes has placed wetlands under pressure, leading to water quality deterioration and risks of eutrophication.

4.2. Seasonal Variations in Water Quality Parameters

The results revealed clear seasonal fluctuations. During the rainy season, COD (96 mg/L) and BOD (57.11 mg/L) peaked above WHO's BOD threshold (<40 mg/L), especially at influent points. This reflects high organic loads from runoff and untreated household wastewater, consistent with [2] TN also exceeded WHO limits in November (13.53 mg/L average), indicating nutrient buildup and the risk of eutrophication. In contrast, the dry season showed improved natural purification, with COD (135.11 mg/L) still within WHO limits but BOD (80.67 mg/L) and TN (40.31 mg/L) exceeding permissible values. These exceedances suggest that despite reduced inflows, organic matter accumulation and nutrient cycling persist in stagnant conditions [21].

TSS levels remained low (8.44–9.11 mg/L), demonstrating the wetland's capacity to trap sediments, likely due to aquatic vegetation. This contrasts sharply with Ethiopian Kitto wetland values (>380 mg/L), showing Rubirizi's relative strength in sediment retention.

Rubirizi wetland data reveals notable differences in Total Suspended Solids (TSS), Biological Oxygen Demand (BOD), and Chemical Oxygen Demand (COD) between sampling points and months. Increased organic and chemical pollution is suggested by the greatest COD and BOD readings at the influent point in November, which are probably the result of rainwater runoff or household waste flow from nearby homes. The January effluent point's lowest COD and BOD levels could be the result of either natural wetland filtration or less external contamination during the dry season.

The lowest TSS levels at several periods in October, January, and February indicate either better water clarity or less sediment transport during dry months, whereas the peak TSS around the midpoint in October might be explained by soil erosion from rains or construction activities. Changes in PH, TP, and TN also indicate shifting environmental circumstances. January's highest PH at the influent point indicates chemical intake, whereas October's lowest PH could be the consequence of acidic runoff. The maximum TP at the effluent site in October suggests phosphorus-rich runoff, possibly from residential or agricultural sources, whereas the elevated TN at the effluent point in November suggests nutrient accumulation over time.

Increased COD and BOD levels at the influent site are consistent with the findings of [2] who contend that untreated home wastewater and surface runoff make urban wetlands in residential areas extremely vulnerable to organic and chemical pollution. The precipitation-induced runoff that brings pollutants into the wetland may be the cause of the high rise in November [12]. Wetlands serve as biological filters for organic debris, hence the decreased COD and BOD levels at the effluent point in January demonstrate the wetland's inherent purification ability [20]. October's high TSS levels are consistent with research by [22], which demonstrated that storm instances in urban wetlands promote sedimentation. Conversely, lower TSS during dryer months confirms findings that less rainfall reduces soil erosion. Additionally, increased TN and TP levels indicate nutrient enrichment, which can lead to eutrophication and endanger aquatic life [25].

4.3. Analysis of the Variations of Nutrient Seasonal Changes That Occur in the Rubirizi Wetland

The data presentation reveals seasonal variations in key water quality parameters of Rubirizi wetland, with notable differences between the rainy and dry seasons. During the rainy season; the highest COD and BOD values occur at the influent point of November, indicating a strong influx of organic pollutants, likely from domestic wastewater and runoff from surrounding households. The highest TSS (Total Suspended Solids) recorded in October’s middle point suggests increased sediment transport due to higher surface runoff and erosion. The highest nutrient concentrations (TN and TP) occur mostly at effluent points, suggesting nutrient accumulation as water flows through the wetland. Conversely, the lowest COD and BOD values at several points, including September influent and November middle points, indicate dilution effects, possibly due to increased rainfall.

The highest COD and BOD values occur at the influent point in February during the dry season, indicating a greater persistence of organic waste because of decreased flow and restricted dilution. The January influent locations' high pH and TP values refer to possible chemical runoff or alkaline releases of wastewater. The midway point of December's highest TN may be a sign of nutrient release from the breakdown of organic materials in stagnant water. Reduced erosion and sediment transport as a result of less intense rainfall is shown by decreased TSS levels at different effluent locations during the dry season. The lowest COD, BOD, and TN readings in January and February provide an indication to periods of better water quality, most likely as a result of organic matter breaking down biologically under lower flow circumstances.

The seasonal variation in water quality parameters aligns with findings in urban wetlands, where higher rainfall increases surface runoff, erosion, and pollutant [16]. The peak COD, BOD, and TSS levels in the rainy season confirm that wastewater discharge and land runoff contribute to organic pollution, which, if unmanaged, can lead to eutrophication and hypoxic conditions [18]. The peak nutrient levels at effluent points suggest that the wetland acts as a nutrient sink, but may also release stored phosphorus and nitrogen under certain conditions [7].

The ecological balance of the Rubirizi wetland is largely dependent on efficient wetland preservation efforts, pollution control regulations, and community awareness actions. During the dry season, reduced flow allows for longer retention times, which facilitates the natural removal of organic pollutants but also leads to localized concentrations of nutrients and organic matter [21]. The high TN values at middle points recommend nutrient cycling techniques, while the lower TSS levels demonstrate sediment stabilization. These patterns underscore the significance of seasonal tracking and adaptive management approaches such as sediment prevention measures and built-up wetlands to enhance pollutant retention [17].

4.4. Comparison of the Physico-Chemical Parameters of the Wetland’s Water with WHO Standards

The majority of the evaluated criteria for the water quality of Rubirizi Wetland meet the permissible limits for released residential wastewater, according to a contrast with World Health Organization (WHO) regulations. Important exceptions, however, draw attention to environmental issues and seasonal changes. Total Nitrogen (TN) during the rainy season above WHO guidelines in mid-September and throughout November, most likely as a result of higher levels of surface runoff transporting sewage, decayed organic waste, or agricultural fertilizers. A significant organic load is also suggested by the Chemical Oxygen Demand (COD) at the November influent-point and the Biological Oxygen Demand (BOD) at several locations throughout September, October, and November. This could be due to rainwater runoff from nearby homes and the release of wastewater.

Since COD and BOD quantify the quantity of organic matter and oxygen demand necessary for microbial breakdown, elevated levels of both parameters are indicative of inadequate water quality.

On the other hand; dry season exhibits comparatively improved water quality with only BOD surpassing standards at a few points December middle-point, January middle-point, and throughout February. The lack of excessive TN and COD violations demonstrates lower pollutant inflows and improved natural treatment procedures because of extended water persistence. Nevertheless; high BOD values in February reveal unchanged water conditions, which can lead to the collection of organic matter and raised microbial activity that can decrease dissolved oxygen accessibility and possibly damage aquatic life. These shifts highlight the fact that, even though natural processes in the wetland aid in its own purification; untreated wastewater components and seasonal variations continue to be obstacles to water quality.

Studies show that urban wetlands encounter higher intakes of nutrients and organic pollution as a result of rainwater runoff and inadequate wastewater management, which is consistent with the high TN, COD, and BOD levels witnessed during the rainy season [6]. Algal blooms and loss of oxygen can result from eutrophication, which is especially encouraged by excessive nitrogen levels [10]. Anaerobic situations, fish deaths, and deterioration of wetland ecosystem functioning can result from unprocessed organic pollution, which is indicated by the high COD and BOD levels [11].

Aside from the BOD excesses, enhanced compliance during the dry season indicates that wetlands are essential for natural water purification, particularly under reduced flow circumstances [24]. However, February's elevated BOD level suggests that organic matter collection in slowly conditions could pose a hazard to aquatic biodiversity by lowering dissolved oxygen concentrations [4]. This emphasizes the value of wetland restoration projects, seasonal monitoring, and more severe pollution control methods. To ensure the long-term survival of the ecosystem, household wastewater leakage can be avoided with the aid of enhanced sanitation facilities and community knowledge surrounding Rubirizi Wetland.

5. Conclusion

Rubirizi Wetland demonstrates pronounced spatial and seasonal variability in water quality that is strongly influenced by rainfall-driven runoff and untreated domestic wastewater from surrounding settlements. Over the study period, organic pollution (as indicated by COD and BOD) and suspended solids increased during high-runoff months, while nutrient concentrations (total nitrogen and total phosphorus) showed worrying persisstence across seasons and, in some locations, an accumulation tendency at outflow points. Although many parameters largely conform to WHO guideline values at most sampling times, repeated exceedances for TN and episodic spikes in COD and BOD underline a latent eutrophication risk and episodic stress on aquatic life and wetland function. Importantly, the wetland retains measurable capacity to attenuate some pollutant loads evidenced by lower organic loads at downstream points during dry periods yeet this natural treatment capability is vulnerable to continued nutrient loading and increasing urban pressure.

Ecologically, the identified trends indicate that Rubirizi is already delivering a number of important ecosystem services (filtration, sediment trapping, nutrient transformation) but is on the verge of functional impairment without management action. Nutrient enrichment will enhance the chances of an algal proliferation, depletion in oxygen and alteration of the species composition, which would allow minimization of biodiversity and resilience of the wetland. The fact that the peaks coincide with the rainy seasons suggests stormwater as a major source of pollutant entry; and the fact that TN and TP remain constantly high at some locations makes chronic point and diffuse sources, such as household wastewater, poorly managed pit latrines, and informal drainage systems a key factor.

In management and policy, the safeguarding of Rubirizi needs long- and short-term efforts. Immediate pollutant input reduction should emphasize short-term measures such as community-level sanitation (promotion and upgrading of household sanitation, regular desludging program), installation of low-tech treatment or pre-treatment systems at high-load inflows (sediment traps, constructed wetland strips, vegetated buffer zone), and municipal control of direct releases of effluents. Long-term to medium-term recommendations can be to reinforce the local wastewater systems, include wetland preservation in urban development planning and watershed management, and recover riparian vegetation to increase filtration and stabilization banks. In appropriate locations, artificial nature-based remedies like deliberate constructed wetlands or retention basins at high points could reduce peak pollutant loads as well as yield co-benefits in biodiversity and recreation provision.

To monitor and manage adaptively, we suggest that regularly and standardized monitoring program should be established that measures a minimum of core indicators (TN, TP, COD, BOD or validated surrogates with clear methodology, dissolved oxygen, TSS, and chlorophyll-a) at sentinel inflow-midstream-outflow point. A sample must occur sufficiently often to measure seasonal processes (monthly sampling at least one hydrological year as control group) and to measure biological indicators (macroinvertebrate indices or vegetation cover) to reveal ecological change otherwise not reflected by chemistry. Monitoring information must be integrated into an adaptive management framework-causing specific management interventions when individual indicators reach pre-established thresholds, and must be communicated to local stakeholders so as to foster awareness and stewardship.

Lastly, consider the limitations of the work and areas of future research: the current study is limited by the sampling time, the proxy/estimation methodology of BOD (where appropriate), and the spatial coverage of potential point sources (septic systems, drainage outfalls) is not detailed. Future studies could be enhanced with more long-term data, more detailed spatial resolutions of pollutant sources, controlled tracer or hydrological experiments to estimate the residence times and storage capacity, and socio-economic evaluation to develop practical community-based interventions. Such complementary studies would help to narrow down management priorities and enhance the ability of Rubirizi to remain viable in terms of its provision of key ecosystem services.

Rubirizi, in short, is a still useful urban wetland that counters pollution and promotes biodiversity, although nutrient flow and occasional organic pollution are undermining its strength. Short-term local interventions along with long-term monitoring, involvement of the community and combining the watershed planning will be needed to stop the eutrophication pattern and to save the ecological and social processes of the wetland in the future.

Abbreviations

BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
WHO	World Health Organization
pH	Potential of Hydrogen
UNILAK	University of Lay Adventists of Kigali

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Conflicts of Interest

The authors declare no conflicts of interest.

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