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*Original Article*

# Assessment of the Impacts of Climate Variability on Surface Water Quality of Nyabarongo River, Rwanda

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*Climate Change, Micro-Bacterial, Nyabarongo River, Physicochemical.*

## ABSTRACT

The study aimed to investigate the impact of climatic variability on the surface water quality of the Nyabarongo River over the 2019 – 2024 period. The research sought to identify how seasonal changes in rainfall and temperature influence various physicochemical and microbial water quality parameters. Key findings revealed significant seasonal variations in water quality, closely linked to climatic factors. During the rainy seasons, water quality parameters such as nitrate and total coliform counts were notably elevated. For example, average nitrate concentrations were highest during these periods, reaching 132.39 mg/L in March-April-May and 77.33 mg/L in January-February, compared to much lower levels of 15.41 mg/L in June-July-August. Similarly, total coliform counts peaked at 189,597.22 MPN/100 mL in March-April-May and 164,799.08 MPN/100 mL in January-February, while they dropped to 65,537.11 MPN/100 mL in June-July-August. This pattern suggested that increased rainfall leads to higher runoff and potential contamination sources entering the river, adversely affecting microbial water quality. Temperature also played a role in influencing water quality, albeit less dramatically than rainfall. The study noted relatively stable temperature ranges across the seasons, but with slight variations that could affect biological activity in the water. Overall, the findings underscore a clear relationship between climatic variability, specifically rainfall patterns, and the surface water quality of the Nyabarongo River, indicating that periods of heavy rainfall can lead to deteriorating water quality due to increased nutrient loading and contamination. This study recommended the need for effective water quality management strategies, particularly during the rainy season when the river is more susceptible to pollution.

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## INTRODUCTION

Climate variability significantly impacts surface water quality, primarily through alterations in temperature and precipitation patterns. The Intergovernmental Panel on Climate Change (IPCC, 2014) predicted that the global temperature will rise from 1.8°C to 4.0 °C by 2100, affecting various physicochemical parameters that define water quality, including dissolved oxygen levels and nutrient concentration. As temperatures increase, the kinetic energy for chemical reactions in water also rises, leading to a more pronounced dissolution of various substances, potentially culminating in higher concentrations of contaminants and nutrients in surface waters (Bates et al., 2008). For instance, a 1 °C increase in temperature can lead to a decrease of 10% in dissolved oxygen saturation levels (Bates et al., 2008). Furthermore, extreme weather events such as floods and droughts are projected to intensify, with flood frequency expected to increase by 10-20% in many regions of the globe, compounding the challenges of managing water quality through dilution and concentration effects (Klasic et al., 2017) (Delpla et al., 2009).

In sub-Saharan Africa, the direct impacts of climate change on surface water quality are exacerbated by agricultural activities and inadequate infrastructure (Ayanlade et al., 2022). Studies have indicated that the effects of prolonged droughts and unexpected rainfall lead to a 30% increase in water pollution, primarily through increased runoff that transports sediments, pesticides, and heavy metals into local water bodies (Van Vliet & Zwolsman, 2008). In particular, regions with limited governance and poor resource management are facing heightened vulnerability to climate variability, leading to a potential increase of up to 50% in waterborne diseases such as cholera and dysentery (Kathleen et al., 2018). The complex interplay between climatic shocks and anthropogenic factors raises significant concerns for water quality across the African continent, calling for improved localized management strategies (GoR, 2017).

Rwanda is particularly vulnerable to the effects of climate variability on its water resources (RoR, 2018). The Nyabarongo River, the country's main water source, faces several stressors linked to climate change, including pollution from agricultural runoff and sedimentation from deforestation (Manikuze & Nyongesah, 2023). Recent research shows that rising temperatures in Rwanda lead to increased decomposition rates of organic matter, resulting in higher levels of physicochemical parameters, which can harm aquatic ecosystems by promoting harmful algal blooms (Delpla et al., 2009). This degradation threatens the river's ability to provide safe drinking water to over 60%, highlighting the urgent need for improved monitoring and management practices (Manikuze & Nyongesah, 2023).

The impact of climate variability on water quality in Rwanda also poses significant public health risks (GoR, 2021). Higher temperatures and changing precipitation patterns can enhance the survival and spread of pathogens in water systems (Solheim et al., 2010). A study found that for every 1°C increase in temperature, the incidence of waterborne diseases can rise by approximately 5% (Kathleen et al., 2018). Communities that depend on untreated river water face increased exposure to waterborne diseases due to declining water quality (Whitehead et al., 2009). This situation emphasizes the necessity for integrated water quality assessments, particularly in Rwanda, where health and water management systems are under pressure from climate challenges (Ahmed et al., 2023).

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Globally, surface water quality, a cornerstone of environmental and public health, faces mounting threats from climate variability and human activities ( Graham et al., 2024). Climate variability alters hydrological cycles through irregular precipitation, rising temperatures, and extreme weather events, disrupting water quality (Nguyen & Lee, 2020). These disruptions manifest as eutrophication, sedimentation, and increased pathogen prevalence, which compromise water usability for domestic and industrial purposes (Kundzewicz, 2008). The global scientific community recognizes the urgency of addressing these challenges, yet the complex interplay between climatic factors and surface water quality remains underexplored (Delpla et al., 2009).

The climatic drivers, such as temperature increases and altered precipitation patterns, exacerbate water quality deterioration (Solheim et al., 2010). Rising temperatures intensify microbial activity, accelerate nutrient cycling, and reduce dissolved oxygen levels, while heavy rains amplify sediment and pollutant transport (Klasic et al., 2017). Simultaneously, prolonged droughts concentrate pollutants, such as nitrates and heavy metals, in rivers (Kundzewicz, 2008). Climate variability presents unique challenges to water resource management in Rwanda, particularly due to the country's reliance on rain-fed agriculture and vulnerability to extreme weather events (Recha et al., 2012). Research highlights that climate-driven shifts in rainfall intensity contribute to nutrient enrichment and algal blooms in the Nyabarongo River basin, adversely affecting aquatic ecosystems and water usability (Kundzewicz, 2008). The studies on water quality assessments revealed that bacterial levels in the river sometimes exceed safe limits, with total coliforms measured at over 1,000 CFU/100 mL in certain stretches during peak rainfall periods (Francis Wasswa et al., 2013). Simultaneously, the rainy seasons transport pesticides, nutrients, and sediments from sloping areas into the river, further degrading water quality and threatening aquatic ecosystems (Van & Zwolsman, 2008). Additionally, changing rainfall patterns enhance the survival and transportation of pathogens, significantly escalating public health risks for communities reliant on this surface water for drinking and other uses (Thornton et al., 2014).

The ecological repercussions of these dynamics are particularly pronounced for the Nyabarongo River, which serves densely populated catchments while also grappling with its limited capacity to manage increasing pollution loads (Jabi et al., 2014). Furthermore, there are gaps in localized studies on how climate variability interacts with surface water quality, this presents a significant gap in knowledge. This article aimed to assess the seasonal trends and patterns in rainfall and temperature, to analyze the surface water quality status in the Nyabarongo River, and to determine the relationship between climate variability and surface water quality status in the Nyabarongo River using the data from 2019 to 2024 to significantly provide benefits to researcher and future researchers through knowledge provision and serving as a vital reference for future researchers in the same field providing a robust foundation for comparative studies and the development of innovative methodologies for assessing climate-related impacts on aquatic ecosystems. The academic institutions would benefit from inspired research projects that promote interdisciplinary collaboration among students and faculty working on climate change, water quality management, and sustainability issues. The industries relying on water resources for production could benefit from the study’s findings, and the stakeholders and local communities would be empowered to adopt sustainable practices, participate in conservation efforts, and advocate for initiatives that protect and improve water quality in the Nyabarongo River.

The researcher has benchmarked the theories to play a fundamental and multifaceted role in guiding and shaping the present research by providing a framework and foundation and identifying the research gaps.

**Hydrological response theory:** The theoretical basis for this study lies in understanding the

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relationships between climatic factors and surface water quality dynamics. Climate variability directly influences hydrological processes such as runoff, evaporation, and sediment transport, which in turn alter the physical, chemical, and biological characteristics of surface water (Delpla et al., 2009). Theories on climate-water interactions emphasize the feedback loops between temperature changes, precipitation patterns, and water quality degradation, particularly in regions experiencing intense anthropogenic pressures (IPCC, 2022). The theory is linked with response to surface water issues, surface water quality contents, and biological cycling prototypes.

**Ecological threshold theory:** The theory posited that ecosystems did not respond linearly to environmental changes; rather, they exhibited sudden shifts when key variables reached certain tipping points (Folke et al., 2004). In the context of the Nyabarongo River, which served as a vital water source for both human and ecological communities, the influence of climate variability, such as alterations in precipitation patterns and temperature, was found to push the river's ecological state beyond critical thresholds (Folke et al., 2004). For instance, an increase in surface water temperature due to climate change could have exacerbated eutrophication, the over-enrichment of water with nutrients, prompting drastic shifts in phytoplankton communities and leading to significant declines in dissolved oxygen (Smith et al., 2016). Given its diverse aquatic life, the Nyabarongo River was particularly vulnerable to such shifts, making it essential to understand the levels of disturbance that it could tolerate before crossing these ecological thresholds (Smith et al., 2016). In this context, understanding the ecological thresholds associated with the Nyabarongo River, the ecological threshold theory guided stakeholders in monitoring river conditions and implementing early intervention strategies to mitigate the adverse effects of climate variability (Twahirwa et al., 2019). In Rwanda, where communities heavily relied on the Nyabarongo River for irrigation, fishing, and domestic purposes, recognizing these thresholds became critical to ensuring sustainable water quality and conserving the biodiversity that underpinned the river's ecological integrity (Twahirwa et al., 2019).

Empirical studies have demonstrated the significant impacts of climate variability and human activities on surface water quality. Globally, studies on river basins, such as the Nile and Congo, have underscored the interplay between deforestation, urbanization, and climate variability in influencing surface water quality. These findings emphasize the need for integrated approaches to manage water resources sustainably, particularly in regions with high climate vulnerability (Alahacoon et al., 2022). Research conducted in Rwanda has shown a direct correlation between rainfall intensity and nutrient runoff into the Nyabarongo River, highlighting the role of extreme weather events in water quality degradation (Ndayisaba et al., 2015).

Suzanne et al., (2023) conducted a study in East African catchments and indicated that communities relying on untreated river water face higher risks of diarrheal diseases, particularly during the rainy season when pathogen loads are elevated due to runoff.

Wayne & Wendy, (2016) revealed that polluted surface water is a primary vector for waterborne diseases, including cholera, dysentery, and typhoid. These diseases are caused by pathogens such as *Escherichia coli* and *Vibrio cholerae*, which thrive in contaminated water systems, where the Nyabarongo River, affected by untreated sewage and agricultural runoff, serves as a hotspot for these public health concerns (GoR, 2017). Similar patterns are observed in Rwanda, where microbial contamination of the Nyabarongo River has led to recurrent disease outbreaks (Manikuze & Nyongesah, 2023). The economic burden of waterborne diseases is significant, impacting healthcare systems and reducing workforce productivity. Addressing these challenges requires urgent action to improve water quality and provide safe drinking water alternatives (Amit et al., 2024).

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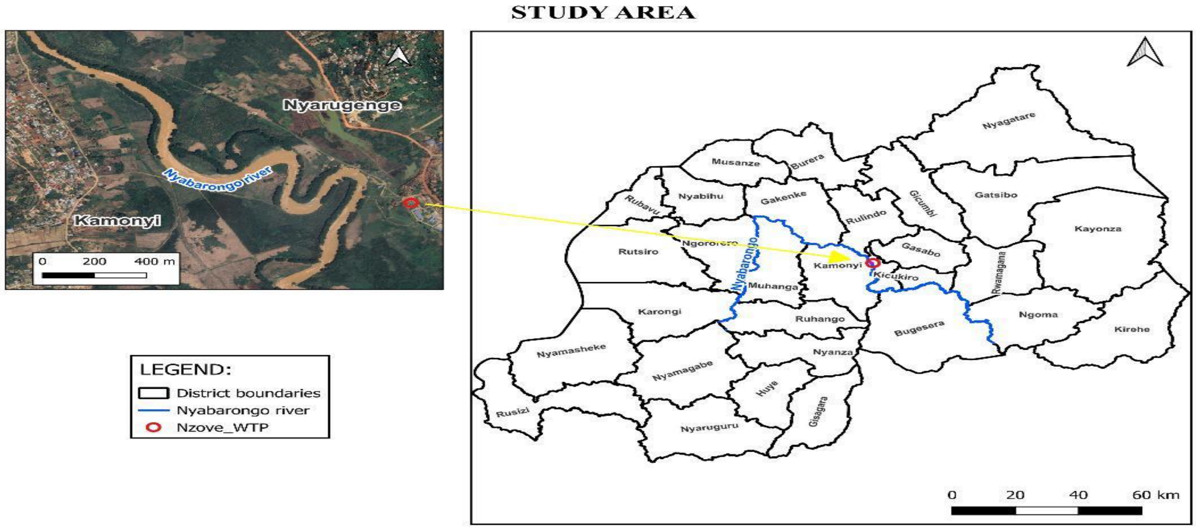
## MATERIALS AND METHODS

Study Area DescriptionNyabarongo River, the largest and most critical waterway supporting diverse socioeconomic activities, including agriculture, industry, and domestic use in Rwanda, is in the Nyabarongo catchment, where varying land-use practices significantly influence its water quality. The region experiences a tropical climate with distinct rainy and dry seasons, which play a critical role in determining the river's hydrological and ecological dynamics.

**Figure 1: Location of Nyabarongo River.**




### Research Design

This study employed a quantitative analysis method to evaluate surface water quality in the Nyabarongo River. The quantitative component focused on analyzing key physicochemical (pH, nitrate levels, total phosphate, heavy metals, etc.) and microbiological parameters (total coliforms), which are essential indicators of water quality. These measurements have provided a comprehensive understanding of the river's water quality across different seasons and over time. The research has adopted a longitudinal design, analyzing data spanning six years. This timeframe allows for the detection of seasonal variability, helping to identify both short-term variations and long-term patterns. Data from Meteo-Rwanda on rainfall and temperature variability have been correlated with water quality data from the WASAC/NZOVE WTP, ensuring a robust analysis of the potential effects of climate variability on water quality. By correlating both climate data and water quality indicators, this approach provided a complete evaluation of how climatic factors, such as temperature fluctuations and precipitation patterns, influence the Nyabarongo River's water quality.

### Data Analysis

Descriptive statistics were employed to comprehensively summarize and interpret the characteristics of the physicochemical and microbial indicators influencing the water quality of the Nyabarongo River. This approach involved calculating the mean (the key measures of central tendency) to represent typical concentrations of each indicator during the rainy (MAM and SOND) and dry (JF and JJA) seasons for the period 2019 to 2024, and the standard deviation (measures of dispersion), which was used to assess the extent of variability in these indicators across different seasons. This analysis provided valuable insights into the consistency and distribution of various indicators between the rainy and dry seasons. The descriptive analysis was crucial in establishing a foundational understanding of the data distribution and identifying any prominent patterns or anomalies that might exist between different seasons.

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The inferential analysis was conducted through one-way ANOVA (analysis of variance), selected for its effectiveness in comparing mean differences across multiple groups, to determine whether the observed variations in the concentration of physicochemical and microbial indicators between the rainy and dry seasons were statistically significant. In this case, the seasonal categories assume that the data for each indicator followed a normal distribution. This Analysis was performed to study the correlation and regression between variables and test the hypotheses. A 95% confidence level ($\alpha = 0.05$) was set as the threshold for statistical significance. A p-value less than 0.05 led to the rejection of the null hypothesis, indicating that seasonal variations had a significant effect on the concentrations of certain indicators. The application of ANOVA, combined with descriptive statistics, provided a robust analytical framework for assessing and interpreting seasonal variations in water quality parameters.

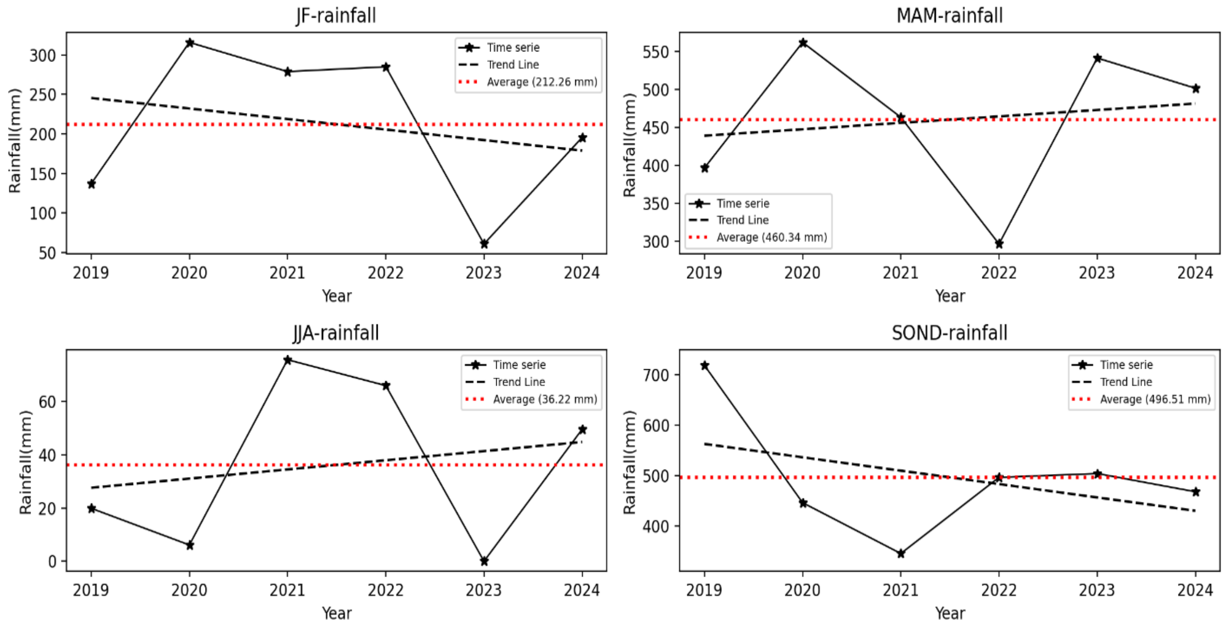
## RESULTS

Seasonal trends and patterns in rainfall and temperature

### Rainfall

Figure 2 shows that seasonal rainfall varies from year to year, with the lowest values in January-February (JF) and June-August found in 2023 and the lowest in 2021 and 2022, September-December and March-May (MAM), respectively. The results also show a positive trend in March-May and June-August, while showing a negative trend in January-February and September-December (SOND) during the study period. The average seasonal rainfall is 212.26 mm, 460.34mm, 36.22mm, and 496.51mm in January-February, March-May, June-August (JJA), and September-December, respectively.

**Figure 2: Seasonal Variation of Rainfall.**




### Temperature

**Minimum Temperature:** The overall average minimum temperature across the study period is 17.02 °C. Analyzing the seasonal trends, the study observed a negative trend in January-February, suggesting cooler conditions during this period. Conversely, minimum temperatures demonstrated a positive trend in the other seasons, March-May, June-August, and SOND, with average values of 17.33 °C, 17.14 °C, and 17.37 °C, respectively.

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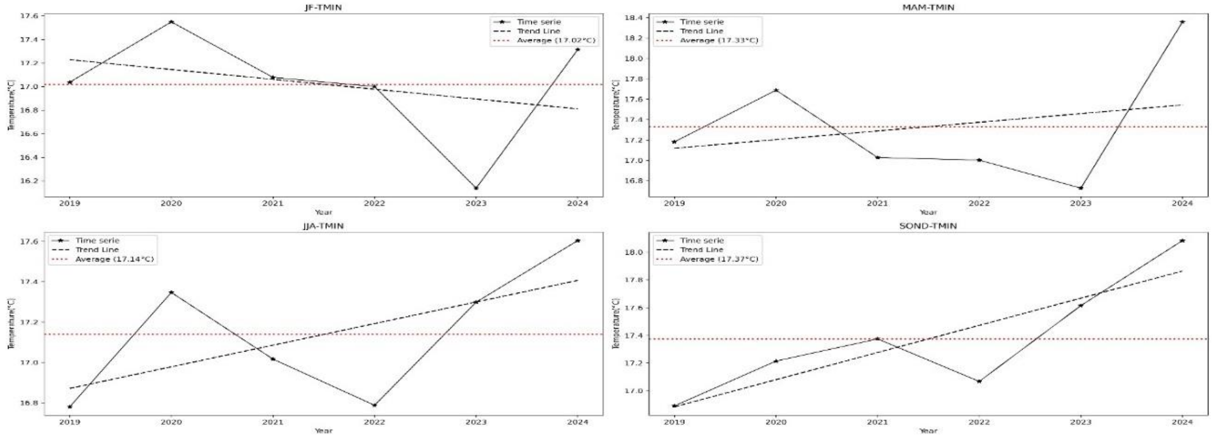
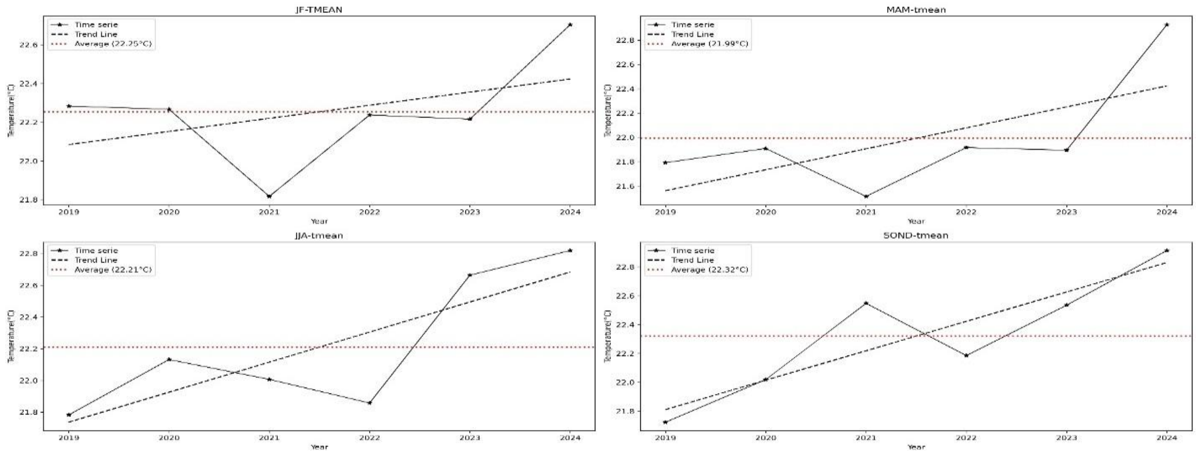
**Figure 3: Seasonal variation and trends of minimum temperature, 2019-2024.**



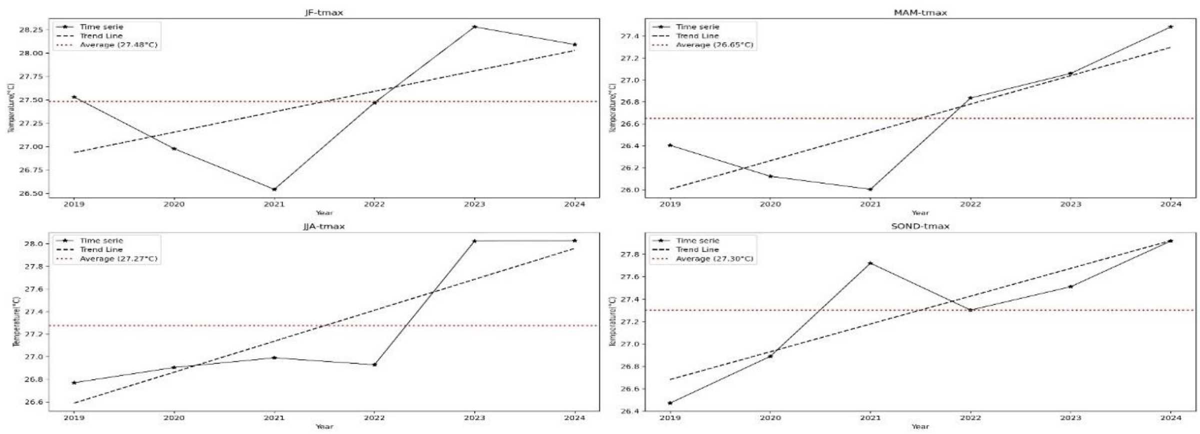

**Mean Temperature:** The average mean temperature across the entire period was recorded at 22.25 °C in JF, 21.99 °C in MAM, 22.10 °C in JJA, and 22.32 °C in SOND. This indicates a slight increase in mean temperatures during the rainy season compared to the dry season.

**Figure 4: Seasonal Variation and Trends of Mean Temperature, 2019-2024.**




**Maximum Temperature:** The maximum temperatures also displayed an increasing trend during the study period, with averages of 27.48 °C in JF, 26.65 °C in MAM, 27.27 °C in JJA, and 27.30 °C SOND. This upward trajectory highlights the potential for more intense heat events particularly during the dry months, reinforcing the overall warming trend in the area.

**Figure 5: Seasonal Variation and Trends of Maximum Temperature, 2019-2024.**



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**Seasonal Surface Water Quality Status in Nyabarongo River**

Table 1 illustrates the Minimum, Maximum, and Mean of physicochemical and microbial water quality parameters of the Nyabarongo River. Rwanda experiences two rainy seasons, MAM and SOND, as well as two dry seasons, JF and JJA. To effectively analyze seasonal variations, the study compared water quality parameters by pairing one dry season with one rainy season: JF-MAM, SOND-JF, MAM-JJA, and JJA-SOND.

The analysis showed no statistically significant difference between JF (dry) and MAM (rainy) for all parameters, including pH with a p-value of 0.17, nitrate with a p-value of 0.11, phosphate p-value of 0.20, total hardness p-value of 0.11, total coliforms with p-value of 0.40, zinc p-value of 0.31, copper p-value of 0.60, and iron p-value of 0.19. This suggests that the transition from the short dry season (JF) to the first rainy season (MAM) does not lead to abrupt changes in water quality. Possible explanations include gradual increases in rainfall, which may not be strong enough to significantly influence pollutant levels, dilution, or sediment transport in the river. Similarly, no significant variation was observed between JF and SOND, reinforcing the idea that the short dry season does not drastically impact water quality parameters compared to rainy periods. This could indicate a more stable water quality regime during these seasonal transitions.

In contrast, a clear and significant difference in water quality was detected between MAM (rainy) and JJA (long dry season). The p-values indicated strong variations for most parameters: nitrate p-value of 0.0007, phosphate p-value of 9.5E-06, total coliforms p-value of 0.0006, zinc p-value of 0.0006, and iron p-value of 0.0014. These results suggest that the shift from heavy rainfall (MAM) to the prolonged dry period (JJA) substantially affects water chemistry and microbial content. During JJA, the decreased river flow contributes to higher concentrations of pollutants, due to reduced dilution and increased retention of contaminants in the water.

A similar trend was observed in the transition from JJA (dry) to SOND (rainy), where significant variations were noted for most parameters except total hardness. The p-values for this transition included total coliforms p-value of 0.0023, nitrate p-value of 0.0415, and zinc p-value of 0.0008. The onset of the rainy season (SOND) seems to enhance surface runoff, introducing sediments, organic matter, and other pollutants into the river, which leads to noticeable changes in water quality. The stability of total hardness between these two seasons suggests that the mineral content of the river remains relatively unchanged, possibly due to the geological consistency or buffering capacity of the water.

**Table 1: Minimum (Min), Maximum (Max) and Average (Mean) of Physicochemical and Microbial Water Quality Parameters of the Nyabarongo River.**

| SEASONS/Parameters | | pH | Nitrate | Phosphate | Total hardness | Total coliforms | Zinc | Copper | Iron |
|---|---|---|---|---|---|---|---|---|---|
| JF | Min | 7.00 | 18.00 | 2.90 | 57.50 | 88885.00 | 0.12 | 0.14 | 9.35 |
| | Max | 7.45 | 156.00 | 13.00 | 150.50 | 213425.00 | 1.40 | 7.30 | 26.45 |
| | Mean | 7.17 | 77.33 | 7.91 | 84.71 | 164799.08 | 0.60 | 2.09 | 16.93 |
| MAM | Min | 6.90 | 84.00 | 4.83 | 49.00 | 116141.00 | 0.11 | 0.37 | 12.17 |
| | Max | 7.17 | 222.67 | 7.67 | 70.00 | 239293.33 | 0.64 | 8.52 | 33.93 |
| | Mean | 7.04 | 132.39 | 5.85 | 59.94 | 189597.22 | 0.37 | 3.03 | 22.77 |
| JJA | Min | 7.47 | 2.43 | 12.94 | 148.33 | 9927.33 | 1.08 | 1.79 | 3.23 |
| | Max | 7.60 | 48.33 | 21.90 | 196.67 | 105449.33 | 2.77 | 25.17 | 10.50 |
| | Mean | 7.50 | 15.41 | 17.18 | 171.83 | 65537.11 | 1.75 | 12.01 | 7.68 |
| SOND | Min | 7.03 | 54.25 | 4.05 | 37.25 | 125005.25 | 0.34 | 0.54 | 12.59 |
| | Max | 7.23 | 309.75 | 10.98 | 105.50 | 196492.75 | 0.54 | 5.05 | 23.08 |
| | Mean | 7.12 | 110.46 | 7.34 | 76.275 | 153895.92 | 0.46 | 2.15 | 17.50 |

**Source:** Field Data, 2025.

 

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**Variation of Concentration of Key Physicochemical and Microbial Indicators**

***pH***

The study found that pH values varied across seasons, indicating slight changes in the acidity and alkalinity of the Nyabarongo River. During the JF (dry) season, pH ranged from 7.00 to 7.45, with an average of 7.17, while in the JJA (dry) season, pH was slightly higher, ranging from 7.47 to 7.60, with an average of 7.50. In contrast, during the MAM (wet) season, pH values ranged from 6.90 to 7.17, with an average of 7.04, and in the SOND (wet) season, pH values ranged from 7.03 to 7.23, with an average of 7.12. The observed pH values indicate that the river water is generally neutral to slightly alkaline across all seasons. However, during the rainy seasons (MAM and SOND), the pH tends to be lower, suggesting a slight increase in acidity. This could be attributed to runoff carrying acidic materials such as organic matter, agricultural residues, and atmospheric deposition. In contrast, during the dry seasons (JF and JJA), the pH is slightly higher, indicating increased alkalinity due to reduced dilution and possible accumulation of dissolved minerals. The lower pH during the rainy seasons may affect aquatic life by altering biological processes and influencing the solubility of nutrients and metals. Slightly acidic conditions can increase the availability of certain heavy metals, potentially impacting water quality. The higher pH in dry seasons suggests that evaporation and reduced river flow may concentrate dissolved substances, potentially leading to increased mineralization.

While the values remain within acceptable limits for most aquatic ecosystems and human use, prolonged shifts in pH could indicate environmental changes requiring monitoring. Maintaining pH stability is crucial for the ecological balance of the Nyabarongo River. The findings highlight the need for seasonal monitoring of pH levels, particularly during rainy seasons when runoff and acidification risks are higher. Implementing measures to reduce agricultural and industrial runoff can help prevent excessive fluctuations in water acidity and alkalinity.

***Nitrate***

The study found that nitrate concentrations varied across seasons, indicating slight seasonal fluctuations. During the JF (dry) season, nitrate levels ranged from 18 mg/L to 156 mg/L, with an average of 77 mg/L. In the JJA (dry) season, nitrate concentrations were notably lower, ranging from 2.43 mg/L to 48.55 mg/L, with an average of 15.41 mg/L. In contrast, during the MAM (wet) season, nitrate levels were significantly higher, ranging from 22.67 mg/L to 84.00 mg/L, with an average of 132.39 mg/L. Similarly, in the SOND (wet) season, nitrate concentrations ranged from 54.25 mg/L to 309.75 mg/L, with an average of 110.46 mg/L.

Higher nitrate concentrations during rainy seasons (MAM and SOND) suggest increased runoff from agricultural land, urban areas, and natural sources. Heavy rainfall likely washes fertilizers, decomposing organic matter, and other nitrogen sources into the river. Lower nitrate levels during dry seasons (JF and JJA) may be attributed to reduced surface runoff and lower agricultural activity, leading to decreased nitrogen input into the river system. Additionally, slower water flow during dry periods may facilitate denitrification, a natural process that reduces nitrate levels. Elevated nitrate concentrations, especially in the rainy seasons, can pose risks to aquatic ecosystems, promoting eutrophication, which leads to excessive algal growth and reduced oxygen levels, potentially harming fish and other aquatic life. High nitrate levels in drinking water sources can pose human health risks, particularly in causing methemoglobinemia (blue baby syndrome) in infants and other health issues when consumed at excessive levels. Extremely low nitrate levels in the JJA season could indicate minimal nutrient availability, potentially affecting aquatic organisms that rely on nitrogen for biological processes. Enhanced monitoring during rainy seasons is crucial to track nitrate spikes and mitigate pollution risks. Implementing the best agricultural practices, such as controlled fertilizer

 

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application and buffer zones along riverbanks, can help reduce nitrate runoff. Promoting sustainable land-use management can help balance nutrient levels and prevent extreme fluctuations that could disrupt the aquatic ecosystem.

***Phosphate***

The study found that phosphate concentrations varied across seasons, reflecting slight seasonal fluctuations. During the JF (dry) season, phosphate levels ranged from 2.9 mg/L to 13.00 mg/L, with an average of 7.91 mg/L. In the JJA (dry) season, phosphate concentrations were slightly higher, ranging from 12.94 mg/L to 21.9 mg/L, with an average of 17.18 mg/L. In contrast, during the MAM (wet) season, phosphate levels were significantly lower, ranging from 4.83 mg/L to 7.67 mg/L, with an average of 5.85 mg/L. Similarly, in the SOND (wet) season, phosphate concentrations ranged from 4.05 mg/L to 10.98 mg/L, with an average of 7.34 mg/L. Higher phosphate levels in dry seasons suggest a concentration effect due to reduced river flow, possibly influenced by sediment resuspension or localized pollution sources and lower phosphate levels in wet seasons may be due to dilution from increased water volume, though runoff from agricultural and urban areas could still contribute to phosphate inputs. Excessive phosphate can lead to eutrophication, causing algal blooms and oxygen depletion, which negatively impacts aquatic life.

***Total Hardness, and Coliform***

The study found that during the JF (dry) season, total hardness ranged from 57.50 mg/L to 150.50 mg/L, with an average of 84.71 mg/L. In the JJA (dry) season, total hardness increased, ranging from 148.33 mg/L to 196.67 mg/L, with an average of 171.83 mg/L. Conversely, during the MAM (wet) season, total hardness was significantly lower, ranging from 49.00 mg/L to 70.00 mg/L, with an average of 59.94 mg/L. Similarly, in the SOND (wet) season, total hardness ranged from 37.25 mg/L to 105.5 mg/L, with an average of 76.28 mg/L. Higher total hardness in dry seasons may result from reduced water levels leading to increased mineral concentration and lower total hardness in wet seasons is likely due to rainfall-induced dilution, reducing mineral concentration in the river. Water with excessive hardness can affect industrial and domestic use by increasing scaling in pipes and appliances.

The study found that total coliform concentrations fluctuated across seasons, suggesting seasonal microbial contamination dynamics. During the JF (dry) season, total coliforms ranged from 88,885 MPN/100ML to 213,425 MPN/100ML, with an average of 164,799.08 MPN/100ML. In the JJA (dry) season, concentrations were lower, ranging from 9,927.33 MPN/100ML to 105,449.33 MPN/100ML, with an average of 65,537.11 MPN/100ML. In contrast, during the MAM (wet) season, total coliforms were significantly higher, ranging from 116,141.00 MPN/100ML to 239,293.33 MPN/100ML, with an average of 189,597.22 MPN/100ML. Similarly, in the SOND (wet) season, coliform levels ranged from 125,005.25 MPN/100ML to 196,492.75 MPN/100ML, with an average of 153,895.92 MPN/100ML. Higher coliform levels in rainy seasons indicate contamination from runoff carrying sewage, animal waste, and other microbial pollutants into the river and lower levels in dry seasons suggest reduced surface water contamination due to limited runoff. High coliform levels pose serious public health risks, increasing the likelihood of waterborne diseases such as cholera and dysentery.

***Zinc, and Copper***

Zinc concentrations also exhibited seasonal fluctuations. During the JF (dry) season, zinc levels ranged from 0.12 mg/L to 1.40 mg/L, with an average of 0.60 mg/L. In the JJA (dry) season, concentrations were notably higher, ranging from 1.08 mg/L to 2.77 mg/L, with an average of 1.75 mg/L. Conversely, during the MAM (wet) season, zinc levels were lower, ranging from 0.11 mg/L to 0.64 mg/L, with an average of 0.37 mg/L. Similarly, in the SOND (wet) season, concentrations ranged from 0.34 mg/L to 0.54 mg/L, with an average of 0.46 mg/L. Higher zinc levels in dry seasons could be due to reduced water

 

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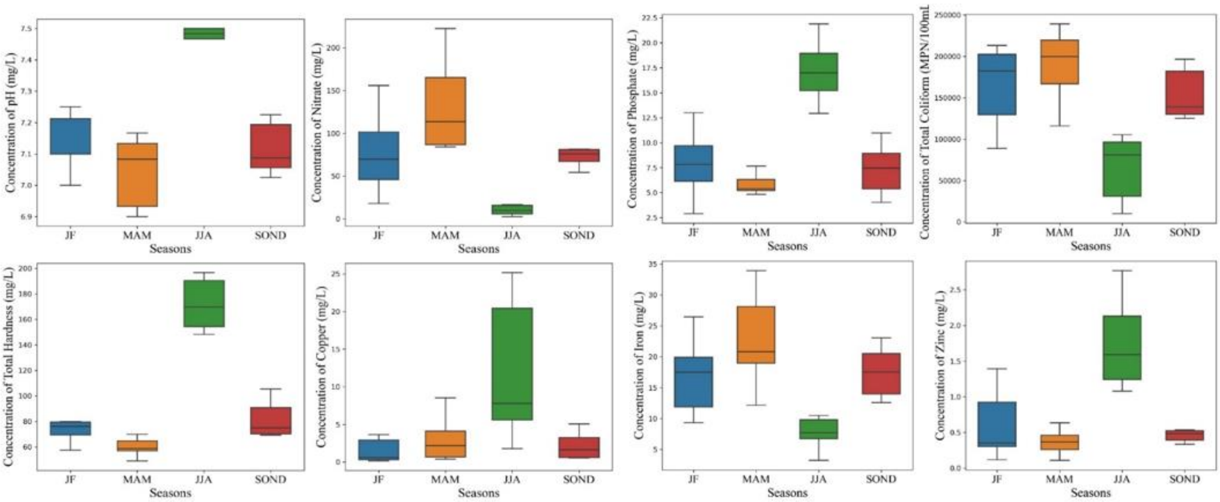
flow concentrating metal contaminants and Lower zinc levels in wet seasons may be due to dilution, although stormwater runoff from industrial and urban areas could still contribute to contamination.

Copper concentrations varied across seasons. During the JF (dry) season, copper levels ranged from 0.14 mg/L to 7.30 mg/L, with an average of 2.09 mg/L. In the JJA (dry) season, copper concentrations were significantly higher, ranging from 1.79 mg/L to 25.17 mg/L, with an average of 12.01 mg/L. In contrast, during the MAM (wet) season, copper levels were lower, ranging from 0.37 mg/L to 8.52 mg/L, with an average of 3.03 mg/L. Similarly, in the SOND (wet) season, concentrations ranged from 0.54 mg/L to 5.05 mg/L, with an average of 2.15 mg/L. Higher copper levels in the JJA (dry) season may indicate industrial discharge and mining activity influence and lower levels in wet seasons could result from dilution, though runoff from agricultural pesticides and urban waste may still introduce copper into the river (Nyamangara et al., 2008), (Gunes, 2022). High copper concentrations can be toxic to aquatic organisms and may affect water quality for human consumption (Malhotra et al., 2020).

***Iron***

Iron concentrations showed seasonal variation. During the JF (dry) season, iron levels ranged from 9.35 mg/L to 26.45 mg/L, with an average of 16.93 mg/L. In the JJA (dry) season, iron levels were notably lower, ranging from 3.23 mg/L to 10.50 mg/L, with an average of 7.68 mg/L. In contrast, during the MAM (wet) season, iron concentrations were significantly higher, ranging from 12.17 mg/L to 33.93 mg/L, with an average of 22.77 mg/L. Similarly, in the SOND (wet) season, iron levels ranged from 12.59 mg/L to 23.08 mg/L, with an average of 17.50 mg/L. Higher iron levels in wet seasons could be due to increased erosion and leaching from soils into the river and lower levels in dry seasons may result from reduced surface water interaction with iron-rich sediments (Maranguit et al., 2017). Elevated iron concentrations can lead to water discolouration, metallic taste, and pipe corrosion, affecting both water quality and infrastructure (Hussein Farh et al., 2023).

**Figure 6: Variation of Physicochemical and Microbial Water Quality Parameters' Values in Nyabarongo River.**




**Correlation Between Temperature, Precipitation, Physicochemical & Microbial Indicators Seasonal Variation**

Table 2 indicates the results of a one-way ANOVA test at a 95% significance level $\alpha = 0.05$. The null hypothesis states that there is no significant seasonal variation in the physicochemical and microbial water quality parameters of the Nyabarongo River between rainy and dry seasons, while the alternative hypothesis suggests otherwise. To effectively analyze seasonal variations, the study compared

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water quality parameters by pairing one dry season with one rainy season: JF with MAM, SOND with JF, MAM with JJA, and JJA with SOND. The analysis showed no statistically significant difference between JF (dry) and MAM (rainy) for all parameters, including pH with a p-value of 0.17, nitrate with a p-value of 0.11, phosphate with a p-value of 0.20, total hardness with a p-value of 0.11, total coliforms with a p-value of 0.40, zinc with a p-value of 0.31, copper with a p-value of 0.60, and iron with a p-value of 0.19. These results suggest that the transition from the short dry season (JF) to the first rainy season (MAM) does not lead to significant changes in water quality, likely due to a gradual increase in rainfall that does not substantially influence pollutant levels or river dynamics.

Similarly, no significant variation was observed between JF and SOND, indicating that the shorter dry season does not drastically impact water quality parameters compared to rainy periods. However, significant differences were noted between MAM (rainy) and JJA (long dry season) for all tested parameters except copper. For instance, nitrate had a p-value of 0.0007 and phosphate had a p-value of 9.5E-06, demonstrating substantial changes and indicating that the shift from heavy rainfall to a prolonged dry period significantly impacts water chemistry. The increased nutrient loads during MAM lead to enhanced microbial growth, evidenced by total coliforms with a p-value of 0.0006. In contrast, the decrease in river flow during JJA likely results in higher concentrations of pollutants due to reduced dilution and accumulation of contaminants, further corroborating the significant changes in water quality during this transition. This trend is evident in the findings for zinc, which had a p-value of 0.0006, and iron, with a p-value of 0.0014, suggesting increased concentrations of these elements in the water during the prolonged dry season.

A similar pattern emerged in the transition from JJA to SOND, where significant variations were noted for several parameters, including total coliforms with a p-value of 0.0023 and nitrate with a p-value of 0.0415. The onset of SOND likely causes increased surface runoff, resulting in the introduction of sediments, organic matter, and nutrients into the river. This reflects the strong correlation between seasonal precipitation and surface water quality indicators, as increased rainfall enhances sediment transport and nutrient loading in the river system.

The stability of total hardness was noted with a p-value of 0.3439 between JJA and SOND, suggesting geological consistency, while the lack of significant variation in copper was indicated by a p-value of 0.0653, suggesting that its levels remain stable across seasons, potentially due to consistent natural sources or low anthropogenic inputs. Overall, the transitions between MAM-JJA and JJA-SOND, underscore the intricate relationship between climate factors such as precipitation and temperature and water quality parameters in the Nyabarongo River. The significant changes in nutrient concentrations and microbial indicators emphasize the need for continuous monitoring and robust management strategies to sustain water quality considering climatic fluctuations.

**Table 2: ANOVA Test Results**

| **SEASONS** | **JF-MAM** | | **SOND-JF** | | **MAM-JJA** | | **JJA-SOND** | |
|---|---|---|---|---|---|---|---|---|
| **PARAMETERS** | **F** | **P-value** | **F** | **P-value** | **F** | **P-value** | **F** | **P-value** |
| pH | 2.23 | 0.17 | 0.45 | 0.52 | 72.46 | 6.8E-06 | 85.32 | 3.3E-06 |
| Nitrate | 3.15 | 0.11 | 0.54 | 0.48 | 23.06 | 0.0007 | 5.46 | 0.0415 |
| Phosphate | 1.89 | 0.20 | 0.10 | 0.76 | 67.27 | 9.5E-06 | 33.80 | 0.0002 |
| Total hardness | 3.17 | 0.11 | 1.00 | 0.34 | 143.23 | 3E-07 | 0.99 | 0.3439 |
| Total coliforms | 0.78 | 0.40 | 0.19 | 0.67 | 23.94 | 0.0006 | 16.40 | 0.0023 |
| Zinc | 1.12 | 0.31 | 0.47 | 0.51 | 24.38 | 0.0006 | 22.59 | 0.0008 |
| Copper | 0.30 | 0.60 | 0.00 | 0.96 | 4.28 | 0.0653 | 5.46 | 0.0415 |
| Iron | 1.95 | 0.19 | 0.03 | 0.86 | 19.20 | 0.0014 | 22.64 | 0.0008 |

**Source:** Field Data, 2025.

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***Correlation with Rainfall***

Table 3 indicates that pH exhibited a strong negative correlation with rainfall during the dry seasons, with correlation coefficients of -0.94 in JF and -0.77 in JJA. In contrast, during the wet seasons, the correlation was moderately negative in MAM (-0.65) but became weakly negative in SOND (-0.49). This suggests that higher rainfall dilutes alkaline components, lowering pH values more significantly in dry seasons. Nitrate showed a positive correlation with rainfall in all seasons, with strong positive correlations in JF and SOND, which implies that increased precipitation enhanced nitrate runoffs from agricultural and urban sources.

Phosphate demonstrated a negative correlation across all seasons, with a strong negative correlation observed in JF and SOND, suggesting that increased rainfall dilutes mineral content in the water. Zinc exhibited a negative correlation with rainfall, with a strong negative relationship in JF, indicating dilution effects during high rainfall periods. Copper also showed a negative correlation with rainfall across all seasons except SOND, with a strong negative relationship in JF, suggesting that rainfall reduces copper concentrations in most cases. In contrast, iron demonstrated a positive correlation with rainfall in all seasons except SOND, suggesting that increased runoff may transport iron-rich sediments into the river during higher precipitation periods (Sonone et al., 2021).

**Table 3: Seasonal Correlation between Physicochemical, Microbial Water Quality Parameters, and Rainfall**

| SEASON | pH | Nitrate | Phosphate | Total hardness | Total coliforms | Zinc | Copper | Iron |
|---|---|---|---|---|---|---|---|---|
| JF | -0.94 | 0.82 | -0.97 | -0.83 | 0.80 | -0.84 | -0.73 | 0.73 |
| MAM | -0.65 | 0.37 | -0.67 | -0.37 | 0.32 | -0.40 | -0.16 | 0.57 |
| JJA | -0.77 | 0.68 | -0.50 | -0.55 | 0.73 | -0.49 | -0.63 | 0.67 |
| SOND | -0.49 | 0.86 | -0.75 | -0.96 | 0.63 | -0.18 | 0.37 | -0.20 |

**Source:** Field Data, 2025.

***Correlation with Maximum Temperature***

Table 4 indicates that pH exhibited a weak positive correlation with maximum temperature in JF and JJA, while a very weak positive correlation was observed in SOND, and no correlation was detected in MAM. Nitrate showed a strong negative correlation with maximum temperature in JF, MAM, and SOND, whereas a weak negative trend was observed in JJA. Phosphate exhibited a strong positive correlation in JF and SOND, a moderate positive correlation in MAM, and a weak negative correlation in JJA. Total hardness displayed a weak positive correlation in JF, JJA, and SOND but showed a very weak negative correlation in MAM.

Total coliforms exhibited a weak positive correlation in MAM and JJA but showed a weak negative correlation in JF and SOND. Among heavy metals, zinc showed a weak positive correlation in JF but a weak negative correlation in JJA, with very weak negative correlations in MAM and SOND. Copper demonstrated a strong positive correlation in SOND, a weak positive correlation in MAM and JJA, and a very weak positive correlation in JF. In contrast, iron showed a strong positive correlation in MAM, a weak positive correlation in SOND, a very weak positive correlation in JJA, and a very weak negative correlation in JF.

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**Table 4: Correlation of Physicochemical and Microbial Water Quality Parameters with Maximum Temperature.**

| SEASONS | pH | Nitrate | Phosphate | Total hardness | Total coliforms | Zinc | Copper | Iron |
|---|---|---|---|---|---|---|---|---|
| JF | 0.64 | -0.91 | 0.74 | 0.64 | -0.44 | 0.53 | 0.36 | -0.20 |
| MAM | 0.00 | -0.86 | 0.61 | -0.48 | 0.49 | -0.10 | -0.63 | 0.70 |
| JJA | 0.47 | -0.20 | -0.45 | 0.58 | 0.37 | -0.57 | -0.54 | 0.36 |
| SOND | 0.24 | -0.78 | 0.89 | 0.55 | -0.43 | -0.38 | -0.83 | 0.64 |

Source: Field Data, 2025.

***Correlation with Minimum Temperature***

Table 5 indicates that pH exhibited a strong negative correlation with minimum temperature in JF and MAM, a weak negative correlation in SOND, but a weak positive correlation in JJA. Nitrate showed a weak positive correlation in JF and MAM, while a moderate negative correlation was observed in SOND, and a weak negative correlation in JJA. Phosphate demonstrated a strong negative correlation in JF, a weak negative correlation in JJA, a moderate positive correlation in SOND, and a very weak positive correlation in MAM. The total hardness had a strong negative correlation in JF and a weak negative correlation in MAM.t exhibited a weak positive correlation in JJA and SOND. Total coliforms displayed a weak positive correlation in JF and MAM, no correlation in JJA, and a weak negative correlation in SOND. Regarding heavy metals, Zinc exhibited a weak negative correlation in JF and SOND, along with very weak negative correlations in MAM and JJA. Copper showed a moderate negative correlation in SOND, a weak negative correlation in JF and JJA, and a very weak correlation in MAM. Lastly, iron demonstrated a strong positive correlation in SOND, a weak positive correlation in JF and JJA, and a very weak positive correlation in MAM.

**Table 5: Correlation of Physicochemical and Microbial Water Quality Parameters with Minimum Temperature.**

| SEASON | pH | Nitrate | Phosphate | Total hardness | Total coliforms | Zinc | Copper | Iron |
|---|---|---|---|---|---|---|---|---|
| JF | -0.93 | 0.44 | -0.81 | -0.83 | 0.47 | -0.54 | -0.38 | 0.47 |
| MAM | -0.85 | 0.10 | 0.09 | -0.46 | 0.21 | -0.07 | -0.08 | 0.18 |
| JJA | 0.19 | -0.41 | -0.19 | 0.24 | 0.00 | -0.05 | -0.19 | 0.46 |
| SOND | -0.34 | -0.63 | 0.53 | 0.31 | -0.29 | -0.69 | -0.66 | 0.74 |

**Source:** Field Data, 2025.

***Correlation with Mean Temperature***

Table 6 indicates that pH exhibited a moderate negative correlation in MAM, a very weak negative correlation in JF, a weak positive correlation in JJA, and a very weak positive correlation in SOND. Nitrate showed a strong negative correlation in SOND, a moderate negative correlation in JF, and a weak negative correlation in MAM and JJA. Phosphate demonstrated a strong positive correlation in SOND, a weak positive correlation in MAM, and a very weak positive correlation in JF. Total hardness exhibited a weak positive correlation in JJA and SOND, and a very weak correlation in JF. Total coliforms displayed a weak positive correlation in MAM and JJA but a weak negative correlation in JF and SOND. Among heavy metals, zinc demonstrated a moderate negative correlation in SOND, a weak negative correlation in MAM and JJA, and a weak positive correlation in JF. Copper exhibited a strong negative correlation in SOND, a weak negative correlation in JJA, a weak positive correlation in MAM, and a very weak correlation in JF. Finally, iron showed a strong positive correlation in SOND, a moderate positive correlation in MAM, a weak positive correlation in JJA, and a very weak positive correlation in JF.

 

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**Table 6: Correlation of Physicochemical and Microbial Water Quality Parameters with Mean Temperature.**

| SEASONS | pH | Nitrate | Phosphate | Total hardness | Total coliforms | Zinc | Copper | Iron |
|---|---|---|---|---|---|---|---|---|
| JF | -0.05 | -0.68 | 0.17 | 0.04 | -0.11 | 0.16 | 0.08 | 0.16 |
| MAM | -0.53 | -0.45 | 0.41 | -0.58 | 0.42 | -0.10 | 0.43 | 0.53 |
| JJA | 0.39 | -0.30 | -0.37 | 0.49 | 0.24 | -0.40 | -0.43 | 0.42 |
| SOND | 0.02 | -0.73 | 0.79 | 0.46 | -0.36 | -0.54 | -0.82 | 0.70 |

**Source:** Field Data, 2025.

## DISCUSSION

The study found that the pH ranged from 7.00 to 7.45 in JF and was slightly lower during rainy seasons (MAM and SOND), averaging around 7.04 and 7.12, respectively. This pattern aligns with findings from Zhou et al. (2016), who reported similar seasonal pH variations in rivers influenced by rainfall and runoff. However, for this study, the lower pH in wet seasons reflects more pronounced acidic inputs from surface runoff, which aligns with the conclusions of Kauffman et al. (2016) who noted that rain events could wash away organic material and fertilizers, contributing to increased acidity. The increase in pH during dry seasons could indicate the accumulation of alkaline substances due to reduced runoff, supported by Smith et al. (2019), who documented enhanced mineral concentrations due to evaporation during dry months.

The findings of the current study, which recorded nitrate averages of 132.39 mg/L and 110.46 mg/L during MAM and SOND, respectively, are consistent with previous research by Casado et al. (2017), who observed elevated nitrate levels in river systems due to agricultural runoff during rainy periods. This increase is likely attributed to fertilizer leaching, with the heavy rains washing nitrates from agricultural fields into nearby water bodies, as noted by Baird et al. (2020). Conversely, the sharp decline in nitrate levels during dry seasons may reflect reduced agricultural activity and slower water flow, leading to natural denitrification processes, aligning with the findings of Zhang et al. (2018).

Phosphate concentrations varied significantly across seasons, showing elevated levels during dry seasons and lower concentrations during wet seasons. These trends align with the observations by Al-Maqdisi et al. (2019), who noted that dry periods often lead to increased phosphate concentrations owing to nutrient accumulation in reduced water volumes. The lower phosphate levels during rainy seasons observed in this study suggest effective dilution from increased flow and runoff, mirroring findings by Sorensen et al. (2020), indicating that heavy rainfall could significantly reduce nutrient concentrations through runoff dilution.

Total hardness was generally observed to be lower in wet seasons compared to dry seasons, with study averages of 59.94 mg/L and 76.28 mg/L in MAM and SOND, respectively, indicating dilution effects from precipitation, similar to findings by Amador et al. (2018). Such patterns suggest that rainfall-induced dilution effectively reduces the mineral concentration in surface waters. Conversely, the higher hardness values in dry seasons align with the observations made by Kim (2017), who attributed increased mineralization and limited water volume due to evaporation as causes for heightened hardness levels during arid periods.

Total coliform counts were significantly higher during the rainy seasons, with averages of 189,597.22 MPN/100ML in MAM and 153,895.92 MPN/100ML in SOND, correlating with patterns identified by Wanjiru et al. (2020), who reported increased microbial contamination associated with runoff in similarly impacted river systems during periods of heavy rainfall. The apparent increase in coliform levels could be attributed to runoff from agricultural and urban landscapes, as highlighted by Mara et al. (2018). In dry seasons, total coliform levels tended to be

 

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lower, correlating with reduced runoff and a decrease in microbial loading from surrounding areas, consistent with findings from Dhananjay et al. (2021).

Zinc concentrations were observed to be elevated in dry seasons, aligning with studies by Mullen and Wilsey (2019), which indicated that reduced flow rates lead to increased metal contamination due to concentration effects. In contrast, the findings of lower zinc levels during the rainy season in this study reflect dilution from increased flow, consistent with Simmons et al. (2020), who noted that stormwater runoff reduces metal concentrations in rivers. Copper levels exhibited a similar trend but were particularly high during the JJA dry season, reflecting potential industrial inputs or urban runoff, as documented by Nkengili et al. (2020).

## CONCLUSION

This study's aims were achieved with the findings indicating significant variations in both climate and water quality parameters, highlighting critical interconnections that warrant ongoing management. The analysis revealed distinct seasonal patterns in both rainfall and temperature over the study period. Rainfall data showed variability, with the lowest values recorded in the dry seasons (JF and JJA) and higher averages during the rainy seasons (MAM and SOND). Temperature trends demonstrated an overall warming trajectory, particularly in dry months. Minimum temperature measurements in JF showed a slight cooling, while mean and maximum temperatures exhibited gradual increases across the years.

The investigation into the physicochemical and microbial parameters illustrated marked seasonal variations in water quality. Higher concentrations of nutrients (nitrate and phosphate) and total coliforms were noted during wet seasons, likely influenced by agricultural runoff and increased erosion. Dry seasons, while showing lower nutrient levels, indicated a concerning accumulation of contaminants, including heavy metals like zinc and copper. The overall assessment points to significant quality challenges in the river, particularly during rainy periods when runoff inflates pollutant levels. The findings suggest a strong correlation between climatic factors, specifically rainfall and temperature, and surface water quality indicators in the Nyabarongo River. Increased rainfall was associated with higher nutrient concentrations and microbial contamination due to runoff, while temperature changes influenced the solubility and dynamics of various water quality parameters. The study highlights the importance of understanding these relationships to develop robust water management practices.

## RECOMMENDATIONS

Based on the findings of this study, the researcher has recommended the Researchers, to comprehensively assess the long-term impacts of climate variability on water quality. It is recommended to incorporate more extensive sampling intervals and include additional parameters, such as metals and pollutants from various anthropogenic sources. This comprehensive approach would deepen the understanding of watershed dynamics and pollution sources over time. Additionally, researchers should engage in collaborative studies with other institutions to expand the data set and refine methodologies using innovative techniques, such as remote sensing and ecological modelling. These advanced methods can help predict the impacts of climate variability on water quality more accurately, enabling better-informed management strategies.

UNILAK, to strengthen its research capabilities, is crucial. This can be achieved by providing more training programs focused on water management and climate studies, which will equip students and researchers with essential skills. Collaborative projects between different academic departments can foster interdisciplinary approaches to water quality monitoring and management. Furthermore, establishing partnerships with governmental and non-governmental organizations would facilitate the implementation of community awareness and educational programs concerning water quality and climate issues, thereby enhancing outreach efforts and promoting a culture of environmental stewardship.

The government and policymakers play a critical role in addressing water quality challenges. They should implement robust policies aimed at managing agricultural runoff, including promoting sustainable farming practices and improved land management to minimize nutrient loading into the Nyabarongo River. Allocating resources for the continuous monitoring of water quality and climate patterns is essential, supporting the establishment of a dedicated water quality management body responsible for overseeing regular sampling and analysis. Additionally, developing regulations to better control industrial discharges into the river is necessary, ensuring that heavy metal levels and other contaminants are regularly tested and adequately managed to protect public health and ecosystem integrity.

The community, to engage and promote awareness of the importance of water quality and the impacts of climate change on local water resources. Educational workshops can provide essential information about sustainable practices that individuals can adopt to reduce contamination. Encouraging community participation in local conservation initiatives and clean-up campaigns is equally important, as such efforts can significantly reduce litter and pollutants entering the river, contributing to overall improvements in water quality.

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