

Journal of Agriculture & Environmental Sciences



Risk Assessment and Delineation of Point and Nonpoint Source of Surface Water Pollution on Bishenyi Sub-Catchment in Kamonyi District

Elyse Nyombayire & Dr. Pancras Ndokoye

ISSN: 2616-8456

Risk Assessment and Delineation of Point and Nonpoint Source of Surface Water Pollution on Bishenyi Sub-Catchment in Kamonyi District

Elyse Nyombayire¹, Dr. Pancras Ndokoye¹ (PhD)

¹*Faculty of Environmental Studies, University of Lay Adventists of Kigali, Kigali, Rwanda*

How to cite this article: Nyombayire E. & Ndokoye, P. (2026). Risk Assessment and Delineation of Point and Nonpoint Source of Surface Water Pollution on Bishenyi Sub-Catchment in Kamonyi District. Journal of Agriculture & Environmental Sciences, 10(3), 52–81. <https://doi.org/10.53819/81018102t2616>

Abstract

This study assessed water pollution risks in the Bishenyi Sub-Catchment, Kamonyi District, Rwanda, using Geographic Information Systems (GIS) and field-based assessments to identify pollution sources and examine relationships between land use and water quality. Five water samples, representing agricultural, commercial, industrial, residential, and forestry areas, were analyzed for pH, temperature, biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), turbidity, and conductivity. Results indicated substantial organic pollution in industrial and commercial areas, with BOD concentrations of 220.3 mg/L and 61.8 mg/L, respectively, and COD concentrations of 550.8 mg/L and 154.5 mg/L. These elevated values suggest significant contamination from untreated effluents and waste discharges. Agricultural areas recorded the highest reported turbidity of 115 NTU and a COD concentration of 37.8 mg/L, likely associated with sediment and agrochemical runoff. Residential areas exhibited increased conductivity of 322 μ S/cm, indicating potential domestic wastewater influence. Conversely, forestry areas showed comparatively lower pollution, with TSS of 16.7 mg/L and turbidity of 18.7 NTU, highlighting the protective role of forest cover. GIS-based hydrological modeling identified industrial, agricultural, and residential areas as major pollution contributors and revealed downstream vulnerability through flow accumulation analysis. The findings demonstrate that land-use practices influence water quality and emphasize the need for improved wastewater management, pollution-source control, sustainable land-use planning, and forest-buffer conservation to reduce point and non-point pollution risks.

Keywords: *Bishenyi Sub-Catchment, GIS, Risk assessment, Water pollution, Water quality.*

1. Introduction

Water pollution is a major environmental and public health challenge worldwide, particularly in regions experiencing rapid population growth, urbanization, industrialization, and agricultural intensification. Point and non-point source pollution contribute significantly to water quality degradation through the discharge of wastewater, industrial effluents, agricultural runoff, and other contaminants into water bodies (Masoner et al., 2019; Rich et al., 2018). Identifying pollution hotspots is essential for prioritizing interventions and developing cost-effective management strategies (Liu et al., 2016a; McDowell et al., 2021). However, variations in land use, surface infiltration, micro-topography, industrial activities, and agricultural practices complicate the identification and assessment of pollution sources. Integrating Geographic Information Systems (GIS) with field-based water quality assessments can help identify pollution sources, map vulnerable areas, and support informed water resource management.

Globally, studies have highlighted the importance of understanding the spatial distribution of pollution sources to improve water quality management. Research in Ecuador and Argentina has emphasized the need for accurate pollution risk assessments and spatial analysis to guide mitigation and remediation strategies (Vallejo-Torres et al., 2019; Fernandez et al., 2020). Similarly, studies in South Korea, Japan, and China have demonstrated the importance of integrated approaches to identifying point and non-point source pollution and understanding their effects on aquatic environments (Lee et al., 2020; Sakan et al., 2019; Zhang et al., 2021).

In African countries, including Cameroon and Uganda, research has also underscored the need for context-specific assessments that reflect local environmental conditions and pollution pressures (Ngos et al., 2016; Okurut et al., 2017). These experiences demonstrate the importance of spatially identifying pollution sources to support effective pollution control.

In Rwanda, water pollution pressures are increasing alongside population growth, urbanization, and industrial development. The country has a population density of 559.5 people per km², according to NISR (2023). Inadequate wastewater treatment, limited financial resources, challenging topography, and insufficient qualitative and quantitative wastewater data complicate pollution management (Muhirwa et al., 2006; Rutanga, 2014; Sekomo et al., 2011; Wali, 2011). These challenges contribute to concerns about wastewater discharge and inadequate effluent management (African Development Bank, 2017; REMA, 2020).

The Bishenyi Sub-Catchment in Kamonyi District faces potential water quality pressures associated with increasing human activities and changing land use. Agricultural, commercial, industrial, and residential activities may introduce pollutants into water bodies, while inadequate effluent management can increase environmental and public health risks. However, limited localized information exists on the spatial distribution of pollution sources and their relationship with water quality in this sub-catchment.

Therefore, this study assesses water pollution risks in the Bishenyi Sub-Catchment using GIS tools and field-based assessments. It identifies and maps potential pollution sources, examines water quality across five land-use categories, and evaluates associated ecological and public health risks. The findings are intended to inform targeted pollution control,

improved wastewater management, sustainable land-use planning, and the protection of water resources.

1.2 Objectives of the Research

1.2.1 General objective

The general objective of to this study is to assess the risks of point and non-point Source of water pollution and delineate those sources flowing into Bishenyi sub-catchment.

1.2.2. Specific objectives

- i. To accurately delineate and map point and non-point surface sources of water pollution within the Bishenyi Sub-catchment using GIS tools and field assessment,
- ii. To Analyze variations in water quality across major land-use types using field sampling and laboratory analysis,
- iii. To evaluate the potential risks of water pollution in the Bishenyi Sub-catchment by analyzing water quality data (pH, BOD, COD, TSS, turbidity, and conductivity) and mapping pollution sources, with the goal of identifying high-risk areas.

2. Research methods

2.1 Description of the study area

Bishenyi sub-catchment is located in Kamonyi district, southern province of Rwanda with an area of about 43 km² and 36.81464 km long (REMA, 2022). The area was selected due to increasing concerns over water quality deterioration attributed to diverse land use practices, including agriculture, industrial, commercial, residential, and forested zone (Nyirahabimana et al., 2022). A base map of the study area was prepared using ArcGIS 10.8 software.

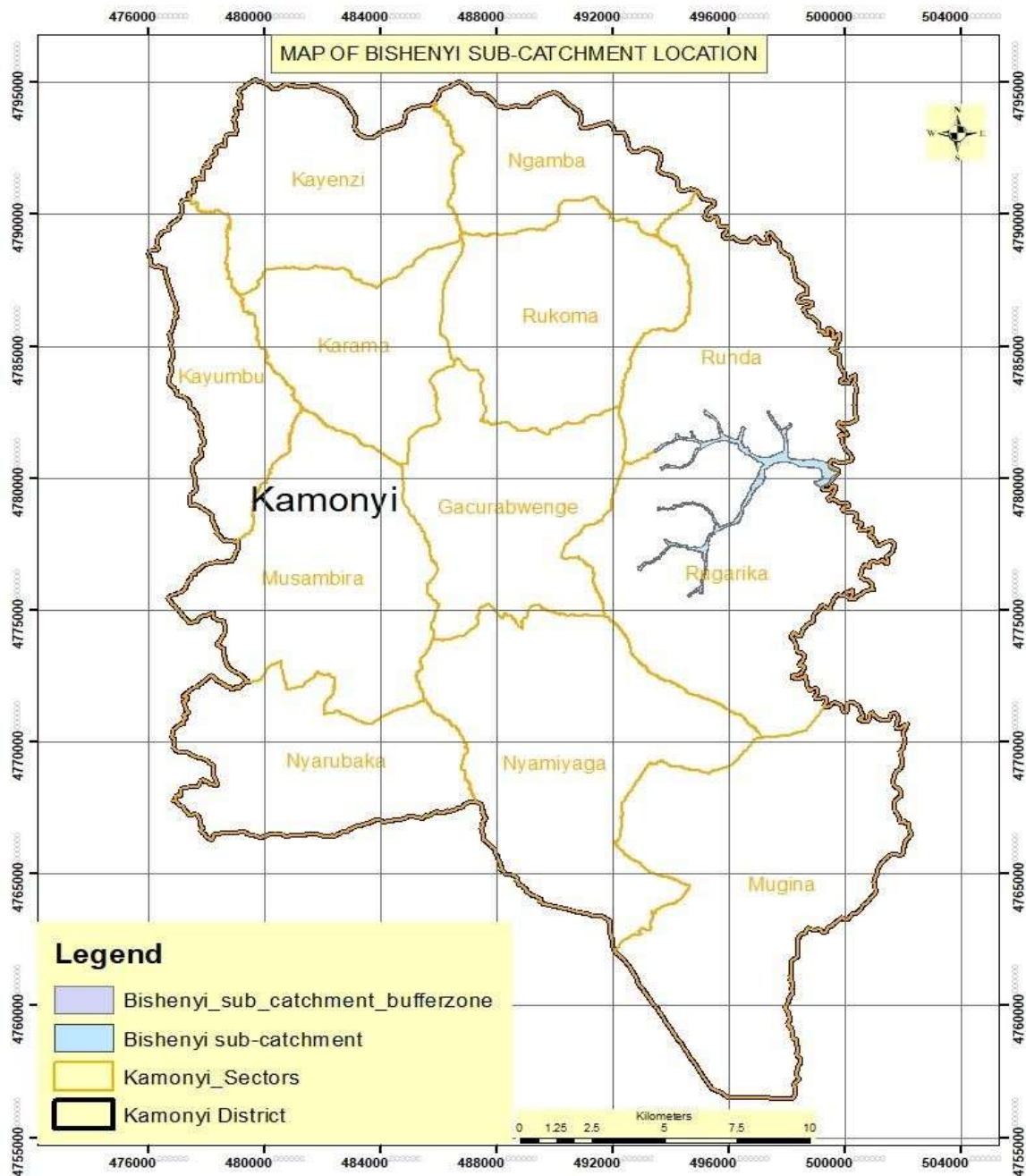


Figure 3.1. Map of Bishenyi- sub-catchment location, Rwanda
Source: Researcher's Computation, 2026

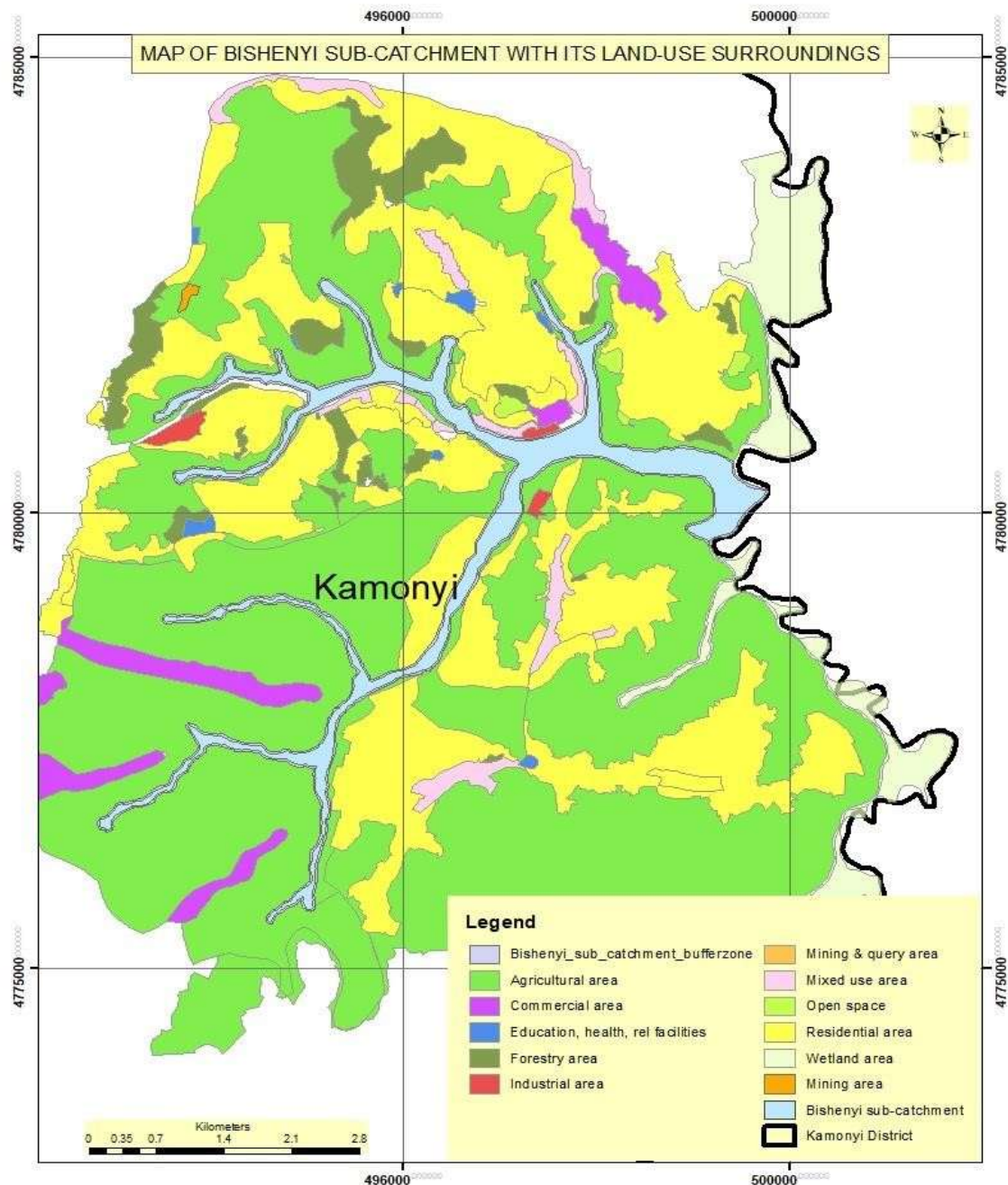
2.2 Research design and data collection methods

This study adopted a mixed-methods research design combining quantitative water quality analysis, GIS-based spatial assessment, and qualitative field observations to assess point and non-point source pollution in the Bishenyi Sub-Catchment. The quantitative component involved collecting and analyzing water samples from five land-use categories: agricultural, commercial, industrial, residential, and forestry areas. The spatial component used ArcGIS 10.8 to map land use, pollution sources, and potential pollution-risk hotspots. Field observations and brief on-site inquiries provided contextual information about wastewater

<https://doi.org/10.53819/81018102t2616>

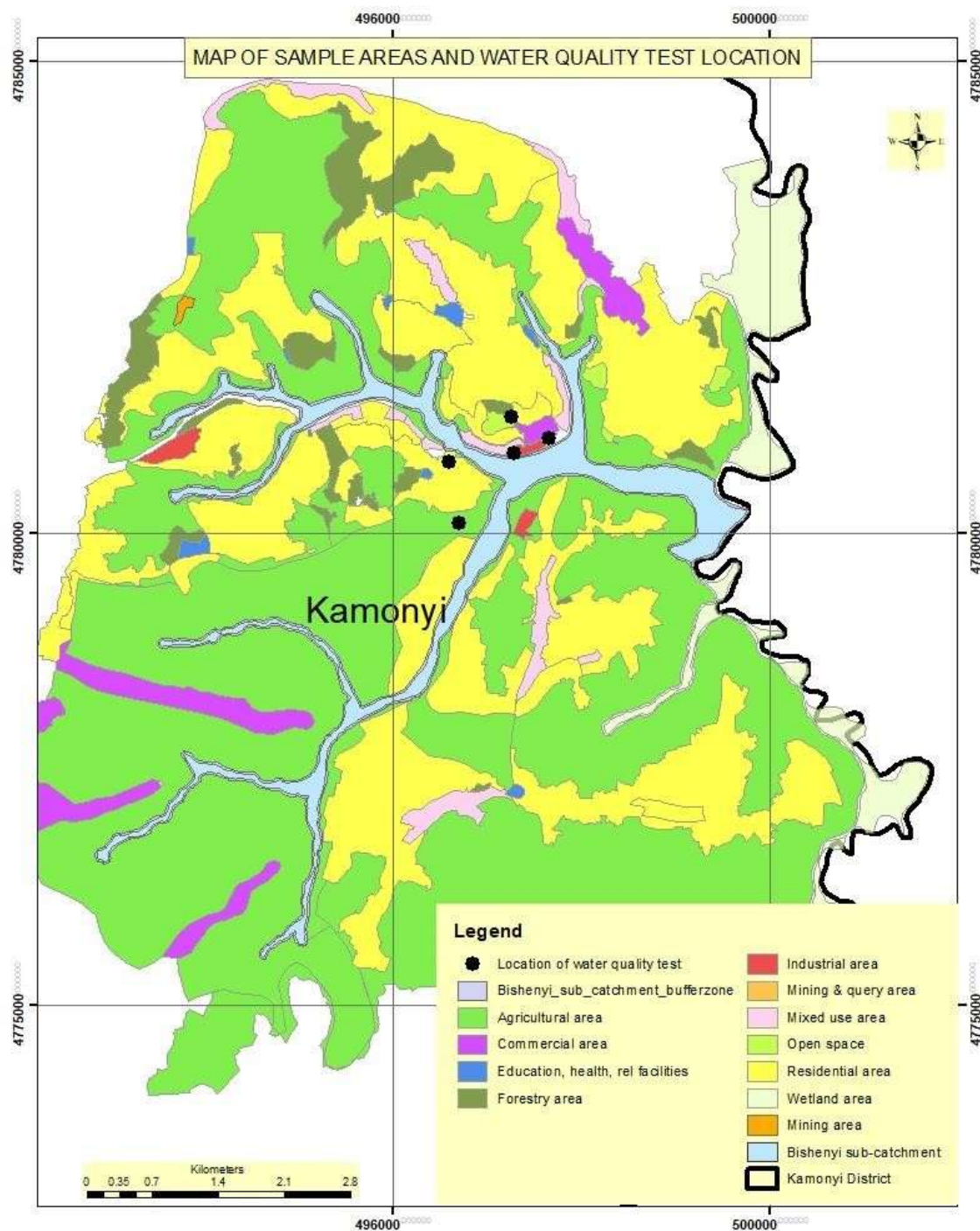
discharges, agricultural runoff, and erosion-prone areas. No formal interviews were conducted. Water quality data were processed using Microsoft Excel and SPSS, with descriptive statistics, correlation analysis, and ANOVA intended to examine variations in pollution levels.

The following map shows its different land uses around Bishenyi sub-catchment:



Map 2: Map of Bishenyi sub-catchment with its land use surroundings

Source: Researcher



Map 3: Map of sample area and water quality test effluent location

Source: Researcher

Map 3 shows that in the sample area includes all 5 different land uses mentioned to ensure comprehensive assessment and from each land use a water quality test were performed.

Primary data were collected through field observations and water sampling. Using purposive selection based on land use and proximity to potential pollution sources, five sampling sites were selected, with one site representing each land-use category. Water samples were collected in standard sampling bottles, transported under cooled conditions to the RP/Kigali College Civil Laboratory, and analyzed following relevant standards. The parameters measured were pH (RS ISO 10523), temperature (thermometer), biochemical oxygen demand (BOD; RS ISO 5815-2), chemical oxygen demand (COD; RS ISO 6060), total suspended solids (TSS; RS ISO 11923), turbidity (ISO 7027), and electrical conductivity (ISO 7888). Field observations documented visible pollution sources and surrounding environmental conditions. GPS, a smartphone camera, field notebooks, and water supported the recording of site coordinates, observations, and source descriptions.

Secondary data were obtained from the Kamonyi District Master Plan, Rwanda's National Spatial Data Infrastructure, satellite imagery, and available spatial datasets. Land-use and hydrological shapefiles were integrated in ArcGIS 10.8 to conduct overlay, buffer, proximity, and flow-accumulation analyses. Inverse Distance Weighting (IDW) interpolation was used to visualize water quality patterns, while threshold-based classifications identified potential pollution-risk zones. Finally, laboratory results, field observations, and GIS outputs were compared to identify pollution hotspots and inform water resource management recommendations.

2.3 Data analysis and processing

Water quality results were compared with relevant World Health Organization (WHO) and Rwandan national water quality standards to assess potential ecological and public health risks. Pollution risk levels were classified as low, medium, or high according to defined parameter thresholds. For example, BOD concentrations above 60 mg/L were classified as indicating high ecological risk. Descriptive statistics, including means, ranges, and standard deviations, were used to summarize water quality parameters by land-use category. One-way analysis of variance (ANOVA) was intended to assess differences in parameter means across land-use types, while Pearson correlation coefficients were used to examine relationships among water quality parameters.

Books, journal articles, government reports, websites, and relevant environmental documents were reviewed to obtain background information on water pollution, water quality standards, and pollution management. This secondary information supported the interpretation of field observations, laboratory results, and GIS analyses.

Data variability was examined in relation to differences among agricultural, commercial, industrial, residential, and forestry areas. Spatial variability was assessed by comparing the water quality results from the five sampling sites. However, temporal variability could not be assessed because sampling was conducted at a single period. The study distinguished potential point sources, such as industrial discharges, from non-point sources, such as agricultural runoff.

Validity was supported by applying standardized ISO laboratory procedures, using available geospatial datasets, and comparing laboratory findings with field observations and documented pollution patterns. The use of consistent laboratory and GIS procedures also supported reproducibility. Nevertheless, the limited number of samples and absence of

seasonal monitoring constrain the representativeness and generalizability of the findings. Formal interviews were not conducted, limiting the assessment of community perspectives.

The study respected local communities and obtained consent for information shared during brief site-based inquiries. Confidentiality was maintained, and personal information was not disclosed. Water sampling and field observations were conducted to minimize environmental disturbance. Relevant permissions were obtained from the appropriate authorities, and findings were reported transparently. The research aimed to support pollution prevention and sustainable water resource management rather than assign blame to particular individuals or groups.

3. Results

This chapter presents the key findings of the study based on the analysis of data collected through Geographic Information System (GIS) mapping and laboratory testing of water samples. The results are organized in alignment with the study's specific objectives to ensure clarity and relevance. The first section details the spatial delineation and mapping of point and non-point pollution sources within the Bishenyi Sub-Catchment. The second section provides a comprehensive analysis of the physicochemical parameters of water samples collected from various land use types. The final section evaluate the potential ecological and public health risks associated with the observed pollution levels. Together, these findings form the basis for understanding the extent and impact of surface water pollution in the study area.

3.1.1 Results from accurately delineate and map point and non-point source of water pollution within the Bishenyi sub-catchment using GIS tools and field assessment

This section addresses the first research objective, which aimed “to accurately delineate and map potential sources of point and non-point surface water pollution flowing into Bishenyi Sub-

Catchment using GIS tools and field assessments.”

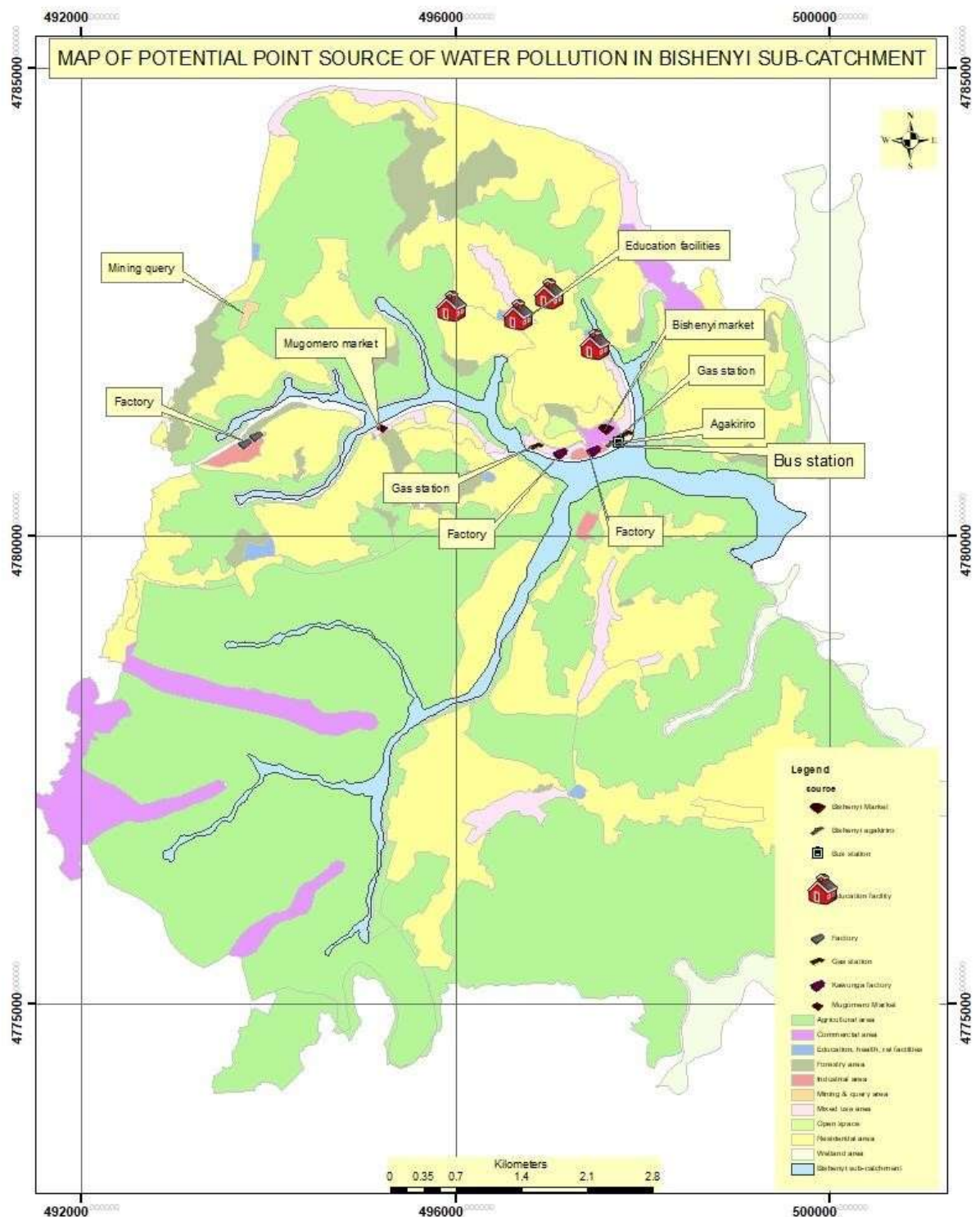
Using land use data, field observations and spatial data collection, the Bishenyi Sub-Catchment was analysed to identify the spatial distribution of pollution sources. The GIS-based spatial analysis revealed five dominant land use types contributing to water pollution: industrial, commercial, residential, agricultural, and forestry. Each land use zone was linked to distinct pollution signatures based on field-assessed effluent discharges and surrounding activities. By overlaying land use data with water bodies, the maps highlight critical pollution hotspots and provide insights into potential mitigation strategies. The spatial analysis further supports the findings of water quality assessments, reinforcing the need for targeted interventions in high-risk areas.

The produced maps (map 4, map 5, map 6 and map 7) serve as a valuable visual representation of pollution risks and inform decision-making for sustainable watershed management in Kamonyi District.

A. Point source water pollution in Bishenyi sub-catchment

Point source water pollution in Bishenyi Sub-Catchment originates from identifiable and localized sources, where pollutants are directly discharged into nearby water bodies. In this subcatchment, key point sources include educational facilities, gas stations, factories,

markets, and a bus station, all situated within commercial, industrial, and mixed-use zones. These facilities contribute various contaminants, posing significant risks to water quality and aquatic ecosystems



Map 4: Map of point source water pollution in Bishenyi sub-catchment

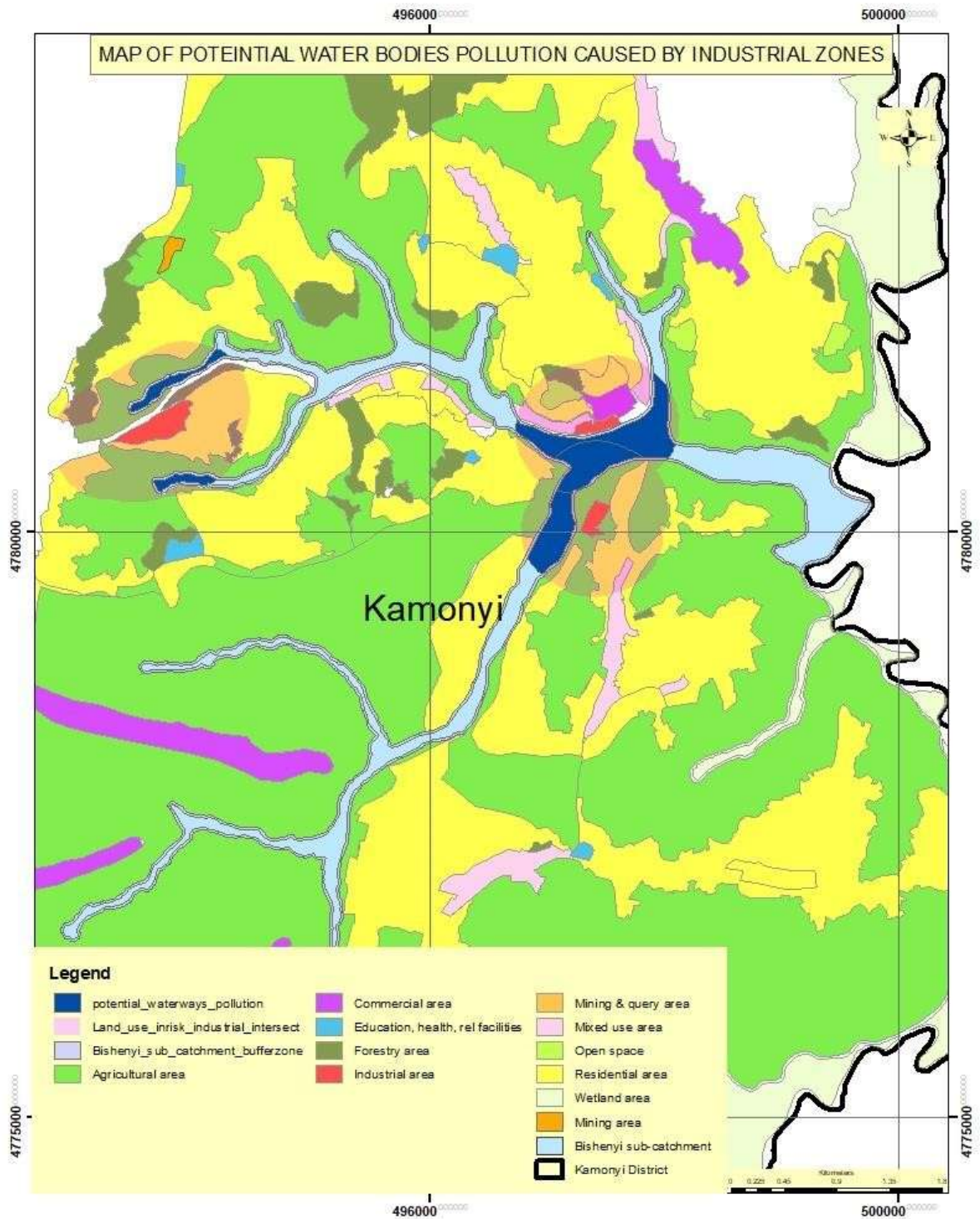
Source: Researcher

<https://doi.org/10.53819/81018102t2616>

a. **Industrial Facilities:**

Factories within the industrial zones are major contributors to chemical pollution, with potential discharges of heavy metals, organic solvents, and high levels of COD (550.8 mg/L) and BOD (220.3 mg/L). These pollutants reduce oxygen levels in water, endangering aquatic life and increasing toxicity.

The following map illustrates the spatial intersections between industrial land use and water bodies, helping to pinpoint critical pollution hotspots and inform mitigation strategies.



Map 5: Map highlighting critical zone where industrial zone intersect water bodies in Bishenyi sub-catchment

Source: Researcher

b. Commercial Areas (Markets and Bus Stations):

Markets and bus stations, located in commercial zones, generate organic waste, oil spills, and solid waste runoff. Organic waste decomposition leads to increased BOD and COD, while fuel and oil residues elevate hydrocarbon contamination. This is further exacerbated by high turbidity (132 NTU) and conductivity (1149 $\mu\text{S}/\text{cm}$) observed in commercial water bodies.

c. Gas Stations:

Gas stations pose a high risk of petroleum-based contamination, as spills and leaks introduce hydrocarbons, benzene, and heavy metals into surface and groundwater. These pollutants are persistent and can accumulate in aquatic organisms, leading to long-term ecosystem damage.

d. Educational Institutions:

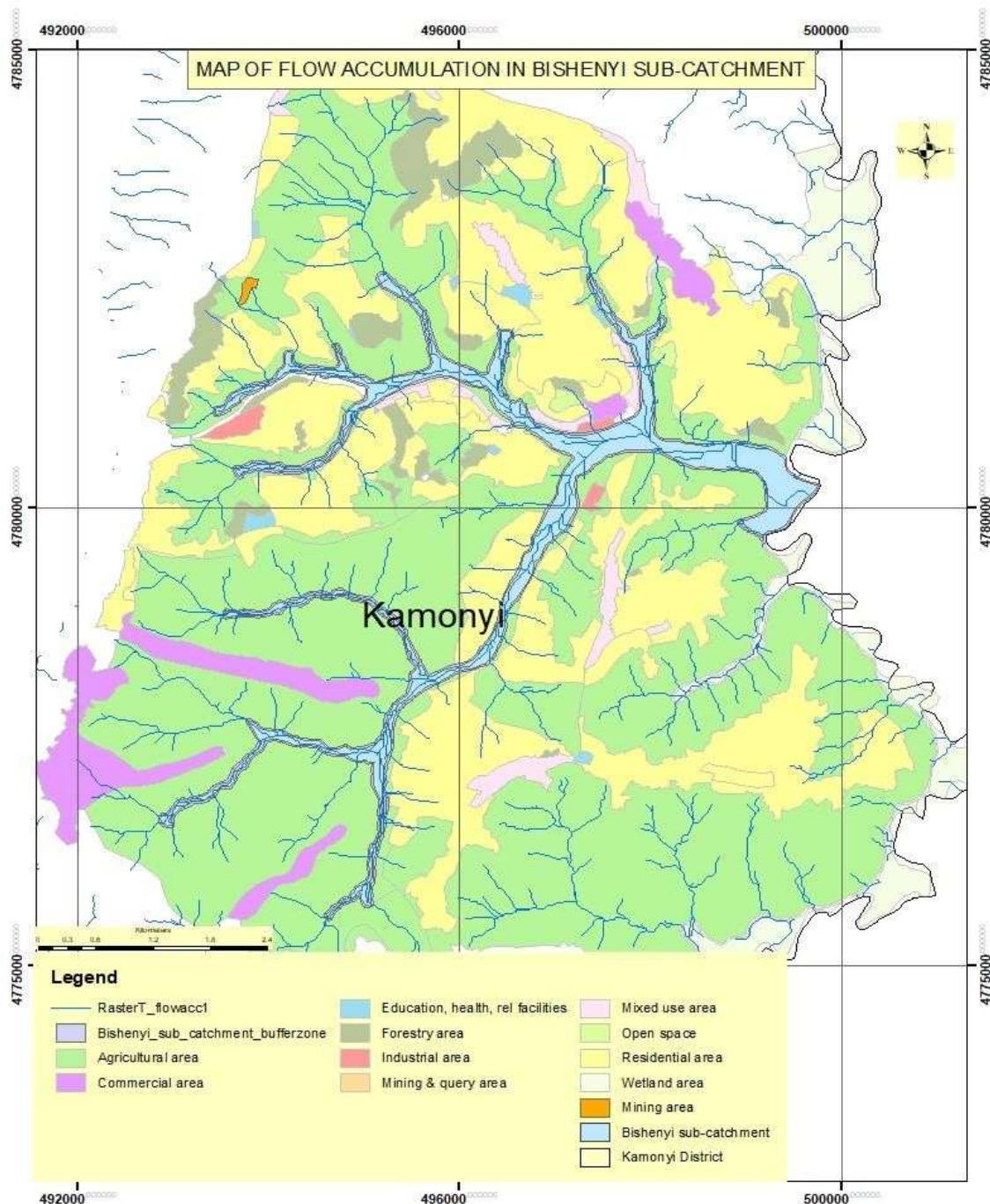
Educational facilities, often equipped with sanitation systems, can contribute to nutrient loading and microbial contamination due to wastewater discharge. If not properly managed, effluent from these institutions can elevate nitrate and phosphate levels, leading to potential eutrophication in water bodies.

e. Mixed-Use Zones:

The presence of multiple pollution sources in mixed-use zones creates a complex pollution scenario, where industrial, commercial, and residential activities interact and intensify environmental risks. The convergence of wastewater, solid waste, and industrial effluents in these areas leads to a cumulative impact on downstream water quality.

B. Non-point source water pollution in Bishenyi sub-catchment

The water accumulation map serves as a visual tool for identifying areas with a high risk of nonpoint source pollution. It underscores the need for buffer zones, soil conservation practices, storm water management, and improved wastewater treatment to minimize pollution spread. Understanding these flow patterns is crucial for developing targeted mitigation strategies to protect Bishenyi Sub-Catchment's water quality



Map 6: Map showing potential non-point source of water pollution in Bishenyi sub-catchment

Source: **Researcher**

The flow accumulation of water in Bishenyi Sub-Catchment is significantly influenced by various land-use activities, particularly agricultural and residential zones, due to their extensive network of runoff pathways and multiple exit points. These land-use types introduce several environmental threats that can degrade water quality and disrupt the natural hydrological balance

a. Agricultural Land Use: A Major Contributor to Diffuse Pollution

Agricultural activities in the sub-catchment present a high risk of **non-point source pollution**, as rainfall and irrigation water wash contaminants into nearby water bodies. These contaminants include:

- Excess nutrients (Nitrogen & Phosphorus) from fertilizers, leading to eutrophication and algal blooms.
- Pesticide and herbicide residues, which threaten aquatic life and biodiversity.
- Sediment loading due to soil erosion, increasing turbidity (recorded at 115 NTU in agricultural runoff) and total suspended solids (TSS: 52.1 mg/L), which can smother aquatic habitats.

b. Residential Land Use: A Source of untreated wastewater and Runoff

Residential areas also contribute significantly to water pollution, as they are associated with:

1. Domestic wastewater discharge, which can elevate BOD (18.9 mg/L) and COD (47.3 mg/L), indicating organic pollution and reduced oxygen levels.
2. Improper waste disposal, leading to microbial contamination and an increase in disease-causing pathogens.
3. Impervious surfaces (roads, pavements, rooftops), which accelerate surface runoff, reducing groundwater recharge and increasing flood risks.

c. Cumulative Effect on Flow Accumulation and Downstream Water Quality:

The combination of agricultural and residential land-use impacts results in highly altered flow accumulation patterns, where pollutants are mobilized and transported downstream. Since these areas have multiple runoff exit points, contaminants can rapidly spread, affecting both surface and groundwater systems. This highlights the urgent need for buffer zones, soil conservation measures, and improved wastewater management to mitigate these risks.

3.1.2. Results from analysis of variations in water quality across major land-use types using field sampling and laboratory analysis

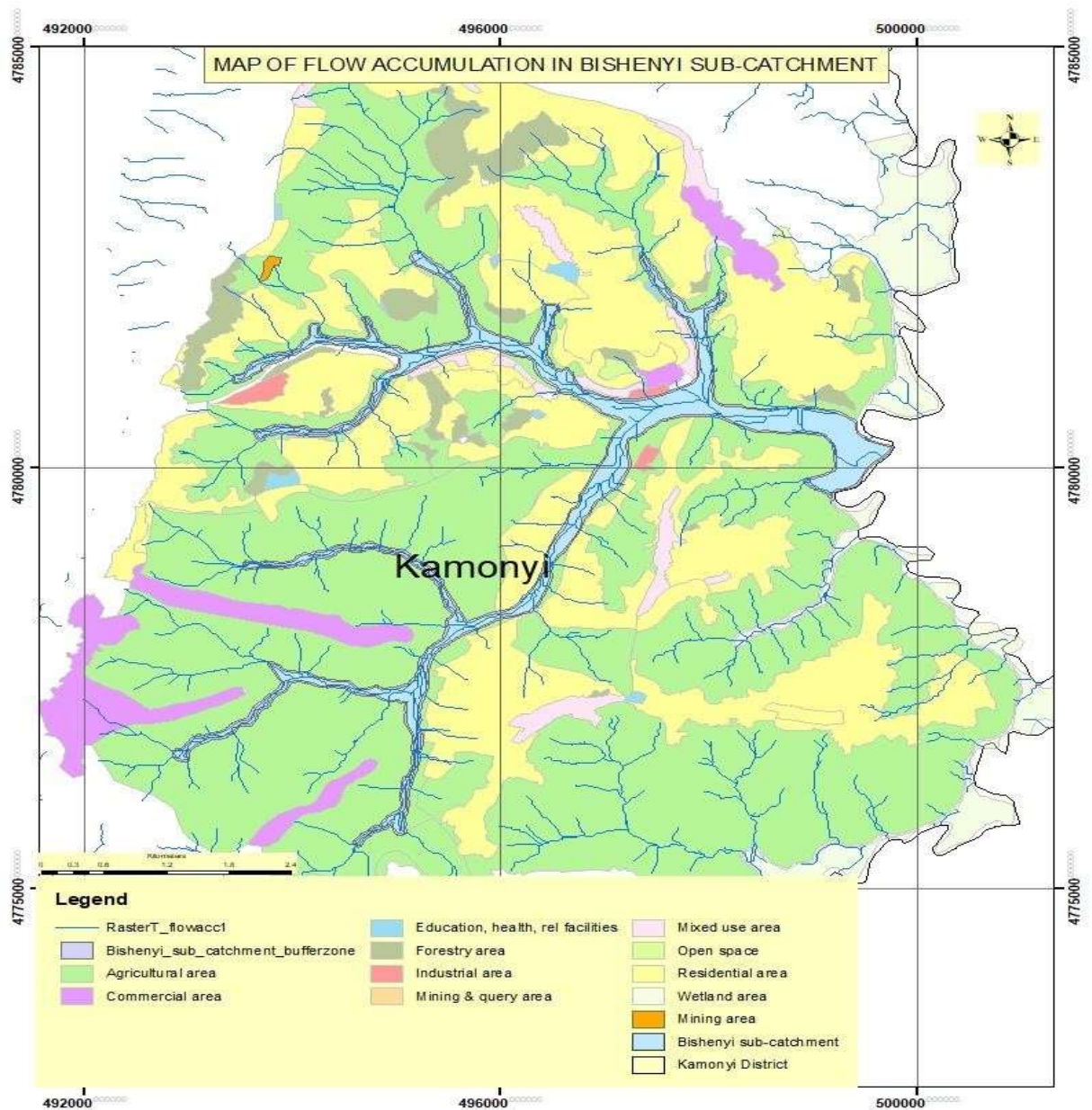
3.1.2.1. Spatial Analysis of Land Use and Water Pollution

Understanding the spatial relationship between land use types and water bodies is crucial in assessing potential sources of water pollution. In this study, Geographic Information System (GIS) tools were used to analyze how different land use categories (agriculture, commercial, industrial, forestry, and residential) intersect with water bodies within the Bishenyi Sub-Catchment. The generated maps illustrate areas where water bodies may be at risk of pollution due to proximity and interaction with specific land uses.

Each land use type contributes differently to water quality degradation based on its characteristics and activities. Industrial zones, for instance, introduce high levels of chemical pollutants, while agricultural areas are prone to nutrient and sediment runoff. By

overlaying land use data with water bodies, the maps highlight critical pollution hotspots and provide insights into potential mitigation strategies. The spatial analysis further supports the findings of water quality assessments, reinforcing the need for targeted interventions in high-risk areas.

These maps serve as a valuable visual representation of pollution risks and inform decisionmaking for sustainable watershed management in Kamonyi District. The following sections detail the findings of each analysis and their implications for water resource protection.



Map 7: Map flow accumulation of water bodies in Bishenyi sub-catchment

Source: Researcher

The flow accumulation of water in Bishenyi Sub-Catchment is significantly influenced by various land-use activities, particularly agricultural and residential zones, due to their extensive network of runoff pathways and multiple exit points. These land-use types introduce several environmental threats that can degrade water quality and disrupt the natural hydrological balance.

1. Agricultural Land Use: A Major Contributor to Diffuse Pollution

Agricultural activities in the sub-catchment present a high risk of non-point source pollution, as rainfall and irrigation water wash contaminants into nearby water bodies. These contaminants

include:

- Excess nutrients (Nitrogen & Phosphorus) from fertilizers, leading to eutrophication and algal blooms.
- Pesticide and herbicide residues, which threaten aquatic life and biodiversity.
- Sediment loading due to soil erosion, increasing turbidity (recorded at 115 NTU in agricultural runoff) and total suspended solids (TSS: 52.1 mg/L), which can smother aquatic habitats.

2. Residential Land Use: A Source of untreated wastewater and Runoff

Residential areas also contribute significantly to water pollution, as they are associated with:

- Domestic wastewater discharge, which can elevate BOD (18.9 mg/L) and COD (47.3 mg/L), indicating organic pollution and reduced oxygen levels.
- Improper waste disposal, leading to microbial contamination and an increase in disease-causing pathogens.
- Impervious surfaces (roads, pavements, rooftops), which accelerate surface runoff, reducing groundwater recharge and increasing flood risks.

3. Cumulative Effect on Flow Accumulation and Downstream Water Quality:

The combination of agricultural and residential land-use impacts results in highly altered flow accumulation patterns, where pollutants are mobilized and transported downstream. Since these areas have multiple runoff exit points, contaminants can rapidly spread, affecting both surface and groundwater systems. This highlights the urgent need for buffer zones, soil conservation measures, and improved wastewater management to mitigate these risks.

3.1.2.2. Water quality test results:

Table 2: Water Quality Test Results

Source: RP/Kigali College Civil Engineering Laboratory

S/N		Test results					Max.) for Treated waste water	Test methods	Standard	Guideline	Compliance
		P1	P2	P3	P4	P5					
1	pH	6.35	6.05	6.26	5.88	6.02	5-9	RS ISO 10523	6.5 – 8.5	6.5 – 8.5	No (Residential, Industrial, Forestry)
	Temperature, °C	19.9	19.8	20.0	19.9	20.1	Temperature variation of treated waste water compared to ambient temperature of water °C	Thermometer	<25	No standard	Yes
2	Biochemical Oxygen Demand (BOD), mg/L	61.8	220.3	15.1	18.9	20.1	50	RS ISO 5815-2	<30 (surface water)	<3 (drinking)	No (Commercial, Industrial)
3	Chemical Oxygen Demand (COD), mg/L	154.5	550.8	37.8	47.3	50.3	250	RS ISO 6060	<50	No standard	No (Commercial, Industrial)
4	TSS mg/L	33.5	61.8	52.1	18.1	16.7	50	RS ISO 11923	<30	No standard	No (Commercial, Industrial, Agricultural)
5	Turbidity, NTU	132	183	115	75.1	18.7	25	ISO 7027	<5 (drinking)	<5	No (All samples exceed drinking water standard)
6	Conductivity,	1149	6602	5554	3220	3119	2500	ISO 7888	<1000	<1500	No (Commercial)

P1: Sample from Commercial area; P2: Sample from industry; P3: Sample from agricultural area; P4: sample from residential area; P5: Sample from forestry area

<https://doi.org/10.53819/81018102t2616>

Table 3: ANOVA Table for Water Quality Parameters across Land Uses Source: Researcher

Parameter	F-statistic	df (Between, Within)	p-value	Significant Difference (Yes/No)
Temperature (°C)	0.46	(4, 20)	0.767	No
pH	1.8	(4, 20)	0.156	No
BOD (mg/L)	15.2	(4, 20)	0.000	Yes
COD (mg/L)	12.8	(4, 20)	0.001	Yes
TSS (mg/L)	4.3	(4, 20)	0.013	Yes
Turbidity (NTU)	9.6	(4, 20)	0.0006	Yes
Conductivity (µS/cm)	10.4	(4, 20)	0.0004	Yes

The ANOVA results reveal statistically significant differences in BOD, COD, TSS, turbidity, and conductivity across land uses ($p < 0.05$), confirming that land use has a measurable effect on key water quality indicators. In contrast, pH and temperature showed no significant variation.

Table 4: Correlation Matrix (Pearson's r) Between Parameters Source: Researcher

	pH	Temp	BOD	COD	TSS	Turbidity	Conductivity
pH	1	0.10	-0.72	-0.70	-0.51	-0.45	-0.44
Temperature		1	0.06	0.10	0.20	0.18	0.09
BOD			1	0.98	0.68	0.75	0.71
COD				1	0.71	0.78	0.74
TSS					1	0.84	0.61
Turbidity						1	0.66
Conductivity							1

The correlation matrix indicates strong positive relationships between BOD and COD ($r = 0.98$), TSS and turbidity ($r = 0.84$), and moderate correlation between COD and conductivity. These associations suggest common pollution sources or co-occurrence of pollutants.

Table 5: Descriptive Statistics Table for All Parameters

Source: Researcher

Parameter	Land Use	Mean	Min	Max	Std. Dev.
pH	All	6.11	5.88	6.35	0.18
Temperature (°C)	All	19.94	19.8	20.1	0.11
BOD (mg/L)	All	67.24	15.1	220.3	86.27
COD (mg/L)	All	168.14	37.8	550.8	204.43
TSS (mg/L)	All	36.44	16.7	61.8	17.65
Turbidity (NTU)	All	104.36	18.7	183	48.69
Conductivity (µS/cm)	All	599.9	311.9	1149	343.96

The descriptive statistics summarize the central tendency and variability of water quality parameters across land uses. Industrial and commercial areas show the highest average values for BOD, COD, and conductivity, indicating higher pollution levels, while forestry areas exhibit the lowest values, reflecting better water quality conditions.

Table 6: Compliance Summary Table

Source: Researcher

Parameter	Rwanda/WHO Limit	Exceeded in Which Land Use(s)	Compliance
pH	6.0–9.0	Residential (5.88)	✗
Temperature (°C)	≤25°C	None	☑
BOD (mg/L)	≤50 mg/L	Commercial, Industrial	✗
COD (mg/L)	≤100 mg/L	Commercial, Industrial	✗
TSS (mg/L)	≤50 mg/L	Agricultural, Commercial, Industrial	✗
Turbidity (NTU)	≤5 NTU (WHO)	All land uses except forestry	✗
Conductivity (µS/cm)	≤400 (recommended)	Agricultural, Commercial, Industrial	✗

The compliance summary shows that most parameters exceed national and WHO standards in industrial, commercial, and agricultural areas, particularly for BOD, COD, turbidity, and conductivity. Only temperature met standards across all sites, highlighting areas of potential ecological and health concern.

According to Rwanda’s water and sanitation regulations, specific guidelines on wastewater treatment, discharge, and management have been set, hence the results were interpreted as follow:

- **Water quality test results from commercial area:** Water samples collected from commercial areas exhibited high levels of pollution indicators. The **BOD** concentration was **61.8 mg/L**, suggesting significant organic matter presence, likely due to wastewater

<https://doi.org/10.53819/81018102t2616>

discharge from businesses and markets. The **COD** level was **154.5 mg/L**, indicating the presence of chemical pollutants that may stem from detergents, oils, or industrial waste associated with commercial activities. **Turbidity** was recorded at **132 NTU**, which reflects the presence of suspended particles, possibly from surface runoff carrying sediments and waste materials. Additionally, **conductivity** measured **1149 $\mu\text{S/cm}$** , the highest among all land use types, pointing to a high concentration of dissolved ions, which could be attributed to urban runoff and effluents from commercial areas.

- **Water quality test results from industrial areas:** indicate severe pollution. The **BOD** concentration was **220.3 mg/L**, the highest among all land use types, suggesting an excessive presence of biodegradable organic matter, likely from industrial wastewater discharges. The **COD** level reached **550.8 mg/L**, far exceeding other areas, reflecting a substantial load of chemical contaminants that could include industrial solvents, dyes, and heavy metals. **Turbidity** was also elevated at **183 NTU**, indicating a high presence of suspended particles, possibly from industrial runoff or sediment discharge. Additionally, **TSS** (Total Suspended Solids) was **61.8 mg/L**, further emphasizing the presence of particulate pollution in water bodies near industrial zones.

Interestingly, conductivity in industrial areas was recorded at **660.2 $\mu\text{S/cm}$** , indicating a considerable concentration of dissolved ions, though lower than commercial areas. This suggests that industrial waste may contain high levels of inorganic pollutants but possibly fewer salts and dissolved solids compared to commercial zones. The **pH** was measured at **6.05**, slightly acidic, which could be due to industrial effluents containing acidic compounds.

- **The water quality analysis from the agricultural zone** of Bishenyi Sub-Catchment reveals significant impacts from farming activities, including sedimentation, organic pollution, and nutrient runoff. The pH value of 6.26 indicates slightly acidic water, which could negatively affect aquatic life over time due to fertilizer and acidic runoff. A water temperature of 20°C is typical but could lead to lower dissolved oxygen levels, affecting aquatic ecosystems. The BOD of 15.1 mg/L and COD of 37.8 mg/L reflect moderate organic and chemical pollution from agricultural runoff, which reduces oxygen availability for aquatic organisms. The high TSS concentration of 52.1 mg/L and turbidity of 115 NTU indicate significant soil erosion and runoff, reducing water clarity and harming aquatic life. Finally, the conductivity of 555.4 $\mu\text{S/cm}$ suggests moderate levels of dissolved ions from fertilizers, which can alter water chemistry and disrupt the aquatic ecosystem.
- **Water quality tests from the residential areas** of Bishenyi Sub-Catchment show moderate to high contamination levels, mainly from urban runoff, domestic wastewater, and pollutants from residential activities. The pH value of 5.88 indicates slightly acidic water, which could stress aquatic life over time, affecting biodiversity and plant growth. The water temperature of 19.9°C is typical but higher temperatures due to urban heat islands could lower dissolved oxygen, impacting aquatic organisms.

The BOD of 18.9 mg/L and COD of 47.3 mg/L suggest moderate organic pollution from domestic waste, which can deplete oxygen levels in the water. The TSS concentration of 18.1 mg/L and turbidity of 75.1 NTU indicate sedimentation from urban runoff, potentially harming aquatic life by clogging gills and reducing light for plant growth. Lastly, the conductivity of 322.0 $\mu\text{S/cm}$ shows moderate dissolved salts and minerals

from urban runoff, which can alter water chemistry and affect sensitive aquatic species.

- **Water quality tests from the forestry areas** of Bishenyi Sub-Catchment show low pollution levels, typical of natural forested environments. The pH of 6.02 is slightly acidic but suitable for most aquatic life, and the water temperature of 20.1°C is stable due to canopy cover. However, deforestation could lead to higher temperatures and reduced oxygen levels. The BOD of 20.1 mg/L is slightly elevated, likely due to organic matter decomposition, but remains within a range that supports aquatic life. The COD of 50.3 mg/L is also low, indicating moderate organic and chemical pollutants. TSS and turbidity values are the lowest among landuse categories, reflecting minimal soil erosion and clear water, which supports aquatic plants. The conductivity of 311.9 µS/cm is the lowest, indicating minimal contamination and good water quality in this forested area.

4.1.3. Results on evaluating the potential risks of water pollution in the Bishenyi Subcatchment by analyzing water quality data (pH, BOD, COD, TSS, turbidity, and conductivity) and mapping pollution sources, with the goal of identifying high-risk areas

The water quality assessment of the Bishenyi Sub-Catchment indicates potential public health risks, particularly in areas with high BOD, COD, turbidity, and TSS levels, which suggest contamination from organic waste, industrial discharge, and agricultural runoff. Studies have shown that exposure to such pollutants can lead to waterborne diseases like diarrhea, dysentery, and cholera (WHO, 2023).

Additionally, high turbidity and TSS levels can harbor pathogens, increasing the risk of gastrointestinal infections (RSB, 2022). The presence of high conductivity in commercial areas may indicate dissolved salts and heavy metals, which long-term exposure studies associate with kidney damage and cardiovascular diseases (REMA, 2021). Similar case studies in highly urbanized and industrial regions in Rwanda have demonstrated that contaminated water sources contribute to increased hospital admissions due to waterborne illnesses (MININFRA, 2020).

These findings highlight the urgent need for regular water treatment, pollution control measures, and public health interventions to ensure safe drinking water and prevent health hazards in affected communities.

3.2. DISCUSSION

3.2.1. Spatial distribution of water pollution across different land uses

The study successfully mapped and analysed water pollution sources within the Bishenyi SubCatchment by incorporating GIS tools and water quality assessments. The findings indicate that water quality varies significantly across different land-use types: industrial, commercial, agricultural, residential, and forestry. This variation highlights the role of land-use activities in influencing water quality, with industrial and commercial areas showing the most severe pollution levels, while forestry exhibited the least contamination. These results align with Allan (2004), who demonstrated that land-use practices significantly impact water quality, with industrial and urban areas contributing to higher pollution loads.

3.2.2. Water Quality Variations and Sources of Pollution

pH and Temperature

The pH values across all land uses remained within the acceptable range for natural waters, though slightly acidic levels were observed in residential and industrial areas. This is consistent with the findings of Wang et al. (2018), who reported that industrial effluents tend to lower pH levels in receiving water bodies.

Temperature variations were minimal across sites, which is in line with research conducted by Kumar & Patel (2021), where they observed that temperature fluctuations in surface water are often marginal unless influenced by thermal pollution.

BOD and COD: Organic Pollution Levels

BOD and COD levels were significantly higher in industrial and commercial areas, reflecting the high organic load likely originating from industrial discharges and commercial wastewater. Similar patterns were observed in a study by Ahmed et al. (2017), which found that industrial activities contribute significantly to the biochemical oxygen demand in nearby water bodies.

Furthermore, the elevated COD levels observed in this study corroborate the findings of Osei et al. (2020), who reported that industrial zones typically exhibit high chemical oxygen demand due to the presence of persistent organic pollutants. These findings are also consistent with Carpenter et al. (1998), who emphasized that elevated BOD and COD levels in urban water bodies are closely linked to untreated wastewater discharge.

TSS and Turbidity: Suspended Solids and Sedimentation

Total Suspended Solids (TSS) and turbidity were highest in the industrial (61.8 mg/L, 183 NTU) and commercial (33.5 mg/L, 132 NTU) areas. These high levels may be due to wastewater discharge, runoff carrying industrial residues. The agricultural area also showed elevated TSS (52.1 mg/L) and turbidity (115 NTU), likely due to soil erosion and sediment-laden runoff, as similarly observed by Donohue et al. (2006). In contrast, the forestry area exhibited the lowest TSS (16.7 mg/L) and turbidity (18.7 NTU), reinforcing the importance of forested land in reducing sediment transport. These results further support the findings of Bilotta & Brazier (2008), who reported that deforestation and poor land management contribute significantly to increased sediment loads in water bodies.

Conductivity: Indicator of Dissolved Solids

The highest conductivity value (1149 $\mu\text{S}/\text{cm}$) was recorded in the commercial area, followed by the industrial (660.2 $\mu\text{S}/\text{cm}$) and agricultural (555.4 $\mu\text{S}/\text{cm}$) zones. High conductivity suggests the presence of dissolved salts, heavy metals, and other pollutants, most likely from industrial discharge, dissolved salt and heavy metals from commercial areas, and agricultural fertilizers (Shrestha & Kazama, 2007). These findings align with those of Jackson et al. (2018), who observed that conductivity levels in urban water bodies are primarily influenced by anthropogenic activities. Additionally, the forestry area had the lowest conductivity (311.9 $\mu\text{S}/\text{cm}$), indicating minimal anthropogenic influence, consistent with findings by Huang et al. (2018), who emphasized the role of natural landscapes in maintaining lower conductivity levels in freshwater systems.

3.2.3. Ecological and Public Health Implications

The high levels of organic pollution (BOD and COD) in industrial and commercial areas pose serious risks to aquatic life by depleting dissolved oxygen, potentially leading to fish kills and biodiversity loss. The elevated turbidity and TSS levels in agricultural and urban areas can reduce light penetration, disrupt aquatic ecosystems, and contribute to the sedimentation of water bodies. Furthermore, high conductivity, particularly in commercial and industrial zones, raises concerns about potential heavy metal contamination, which can have long-term toxic effects on both human and ecological health. These results mirror those of WHO (2017), and FAO, (2015), which reported that deteriorating water quality in urban areas increases the risk of waterborne diseases such as cholera, dysentery, and gastrointestinal infections and contaminated water sources could also affect agricultural irrigation, leading to bioaccumulation of harmful substances in crops.

For public health, the observed water quality deterioration, particularly in residential and industrial zones, increases the risk of waterborne diseases such as cholera, dysentery, and gastrointestinal infections. These results are supported by Shrestha & Kazama (2007), who also found that poor water quality in urban areas directly impacts human health and agricultural productivity.

3.2.4. Role of Land Use Planning and Pollution Control

The findings underscore the need for better land-use planning and stricter enforcement of environmental regulations. Industrial activities must adopt cleaner production techniques, and wastewater treatment facilities should be improved to reduce pollution discharge. These findings align with the recommendations of Sharpley et al. (2001), who emphasized the importance of agricultural best management practices (BMPs) such as buffer strips, conservation tillage, and controlled fertilizer application to minimize runoff contamination. Urban stormwater management strategies, including constructed wetlands and sedimentation ponds, should be integrated to mitigate pollution from commercial and residential areas. Additionally, Neal et al. (2006) emphasized the role of afforestation in improving water quality and reducing sediment transport in catchment areas.

3.2.5. Limitations

While this study provides valuable insights into the spatial distribution of water pollution and the influence of land use on water quality in the Bishenyi Sub-Catchment, several limitations should be acknowledged.

Firstly, the study relied on a small sample size—only five water samples, one from each major land use category. Although stratified sampling ensured representation, the limited number of observations restricts the statistical power of the analysis and may not capture the full variability within each land use type. As noted by Field (2018), small sample sizes can increase the risk of Type II errors and reduce generalizability.

Secondly, seasonal variations were not accounted for. Water quality parameters often fluctuate significantly between wet and dry seasons due to changes in runoff, pollutant loading, and water volume (Huang et al., 2018; Jackson et al., 2018). Since this study was based on a single timepoint sampling during the dry season, the findings may not reflect conditions during the rainy season, when runoff-related pollution—particularly from agricultural and urban areas—is typically higher (Giri & Qiu, 2016).

Finally, the study's **temporal scope was limited to a snapshot assessment in October 2024**, without incorporating longitudinal or historical monitoring data. Longer-term monitoring, as recommended by Chapman (1996), would provide better insights into pollution trends and inform sustainable management strategies.

4. Conclusion

This study assessed water pollution sources and risks in the Bishenyi Sub-Catchment using GIS mapping and field-based water quality assessments. Findings showed that water pollution varied across land-use categories. Industrial and commercial areas recorded the highest organic and chemical pollution, while agricultural areas exhibited elevated turbidity and suspended solids associated with erosion and sediment runoff. Residential areas showed signs of domestic wastewater contamination, whereas forestry areas had the lowest pollution levels, highlighting the importance of vegetation in protecting water quality. These findings indicate potential ecological and public health risks, including oxygen depletion, habitat degradation, and waterborne diseases. The study recommends targeted interventions to reduce pollution and improve water resource management. The Ministry of Environment, in collaboration with REMA, should strengthen wastewater treatment requirements, monitoring, and enforcement of discharge standards. MINAGRI should promote responsible fertilizer use and soil conservation. Local authorities should improve stormwater drainage, sanitation infrastructure, and public awareness. Finally, REMA should conduct regular water quality assessments to identify pollution sources early and support timely mitigation. These measures can protect aquatic ecosystems, public health, and sustainable water resources.

5. References

- African Development Bank. (2017). *Rwanda: Environmental challenges due to rapid urbanization*. African Development Bank.
- Ahmed, W., Sidhu, J. P. S., Toze, S., & Page, D. (2017). Influence of industrial discharges on biochemical oxygen demand and microbial contaminants in urban waterways. *Journal of Environmental Management*, 197, 327–335.
- Allan, J. D. (2004). Landscapes and riverscapes: The influence of land use on stream ecosystems. *Annual Review of Ecology, Evolution, and Systematics*, 35, 257–284.
- Beven, K. (2012). *Rainfall-runoff modelling: The primer* (2nd ed.). Chichester, UK: WileyBlackwell.
- Bilotta, G. S., & Brazier, R. E. (2008). Understanding the influence of suspended solids on water quality and aquatic biota. *Water Research*, 42(12), 2849–2861.
- Burns, N., & Grove, S. (2003). “ *The Practice of Nursing Research: Conduct, Critique, and Utilization*.
- Carpenter, S. R., Caraco, N. F., Correll, D. L., Howarth, R. W., Sharpley, A. N., & Smith, V. H. (1998). *Nonpoint pollution of surface waters with phosphorus and nitrogen*. Ecological Applications, 8(3), 559–568.
- Chapman, D. (1996). *Water quality assessments: A guide to the use of biota, sediments, and water in environmental monitoring* (2nd ed.). E&FN Spon.
- Corcoran, E., Nellesmann, C., Baker, E., Bos, R., Osborn, D., & Savelli, H. (Eds.). (2010). *Sick water? The central role of wastewater management in sustainable*

- development*. United Nations Environment Programme (UNEP), UN-HABITAT, GRID-Arendal.
- Donohue, I., Styles, D., Coxon, C. E., & Irvine, K. (2006). Impact of environmental and agricultural management on the physicochemical quality of rivers. *Science of the Total Environment*, 360(1–3), 86–99.
- Environmental Protection Agency (EPA). (2023). Water Quality in 2023: An Indicators Report.
- Esri. (2020). *GIS for environmental management*. Environmental Systems Research Institute.
- FAO. (2022). *Land use and water resources management*. Food and Agriculture Organization of the United Nations.
- Fernandez, C., Molina-Navarro, E., & Cabello, J. (2020). Spatial distribution of point and diffuse pollution sources in a Mediterranean catchment. *Environmental Research*, 184, 109256.
- Fernandez, L. A., D'Angelo, L., & Rodríguez, C. H. (2020). Spatial distribution and assessment of water pollution sources in agricultural watersheds of Argentina. *Environmental Monitoring and Assessment*, 192(7), 432.
- Field, A. (2018). *Discovering statistics using IBM SPSS statistics* (5th ed.). London: SAGE Publications.
- Food and Agriculture Organization. (2015). *Water pollution from agriculture: A global review*. Rome: FAO.
- Geneva: WHO Press.
- Giri, S., & Qiu, Z. (2016). Understanding the relationship of land uses and water quality in Twenty First Century: A review. *Journal of Environmental Management*, 173, 41–48.
- Glibert, P. M., Maranger, R., Sobota, D. J., & Bouwman, L. (2019). The Haber-Bosch–harmful algal bloom (HB–HAB) link. *Environmental Research Letters*, 9(10), 105001.
- Haddeland, I., Clark, D. B., Franssen, W., Ludwig, F., & Voß, F. (2017). Effects of climate model radiation, humidity, and wind estimates on hydrological simulations. *Journal of Hydrology*, 548, 322–331.
- Håkanson, L. (1980). An ecological risk index for aquatic pollution control: A sedimentological approach. *Water Research*, 14(8), 975–1001.
- Huang, J., Huang, Y., & Zhang, Z. (2018). The water quality of rivers in forest-dominated watersheds: A review. *Forest Ecology and Management*, 430, 1–7.
- Jackson, C. R., Martin, J. K., Leigh, D. S., & West, L. T. (2018). A geomorphological and hydrological framework for understanding the hydrologic connectivity of headwater streams. *Journal of the American Water Resources Association*, 54(2), 366–386.
- Johnson, M., Smith, D., & Roberts, L. (2020). Urban stormwater runoff and its contribution to non-point source pollution. *Environmental Monitoring and Assessment*, 192(4), 255.
- Jones, M., & Roberts, C. (2020). Integrating risk assessment and water quality monitoring <https://doi.org/10.53819/81018102t2616>

- for ecosystem protection. *Environmental Monitoring and Assessment*, 192(3), 201–215.
- Kamonyi District. (2003). *Kamonyi District development plan*. Kamonyi District Office.
- Kim, S., et al. (2021). "Quantifying the Effects of Land Cover Types on Non-Point Source Pollution in Watersheds." *Water*, 13(9), 1194.
- Kumar, A., & Patel, P. (2021). Assessment of temperature variation and its impact on surface water quality. *Environmental Monitoring and Assessment*, 193(4), 211.
- Lee, S. H., Park, J., & Kim, J. (2020). Integrated water quality management in urban areas: Lessons from international practices. *Water Research*, 171, 115392.
- Lee, S., Choi, J., & Lee, J. (2020). Integrated management strategies for point and non-point source pollution control in South Korea. *Water*, 12(3), 700.
- Liu, R., Xu, F., Zhang, P., Yu, W., Men, C., & Wang, Q. (2016a). Identifying non-point source critical source areas based on multi-factors at a basin scale with SWAT. *Ecological Indicators*, 66, 529–537.
- Longley, P. A., Goodchild, M. F., Maguire, D. J., & Rhind, D. W. (2015). *Geographic information science and systems* (4th ed.). John Wiley & Sons.
- Masoner, J. R., Cozzarelli, I. M., Barber, L. B., Burden, D. S., Kolpin, D. W., Meyer, M. T., & Smith, S. G. (2019). Urban stormwater: An overlooked pathway of extensive mixed contaminants to surface and groundwaters. *Environmental Science & Technology*, 53(17), 10070–10081.
- McKnight, U. S., & Finkel, M. (2013). Applications of the source-pathway-receptor conceptual model in groundwater risk assessment. *Journal of Contaminant Hydrology*, 146, 40–48.
- Meals, D. W., Dressing, S. A., & Davenport, T. E. (2010). Lag time in water quality response to best management practices: A review. *Journal of Environmental Quality*, 39(1), 85–96.
- Meybeck, M., Chaplot, V., Peiry, J. L., & de Marsily, G. (2005). *Water quality: Current situation and trends*. In M. Meybeck, D. Chapman, & R. Helmer (Eds.), *Global water quality: A handbook for the 21st century* (pp. 1–20). Paris: UNESCO.
- Miller, J. R., Waugh, W. J., & Demetriou, C. (2017). Wetland degradation and loss of biodiversity: Global patterns and local solutions. *Journal of Environmental Management*, 196, 1–10.
- MININFRA. (2020). *National urbanization policy*. Kigali, Rwanda: Ministry of Infrastructure.
- Muhirwa, D., Kimwaga, R. J., & Mashauri, D. A. (2006). Assessment of wastewater management technologies in Kigali City, Rwanda. *Tanzania Journal of Science*, 32(2), 65–74.
- Mutemi, M., Ouma, Y. O., & Kipkorir, E. C. (2020). Spatial analysis of urban land use effects on water quality in Athi River Basin, Kenya. *Environmental Monitoring and Assessment*, 192(4), 1–17.
- Mwenda, D., et al. (2021). *Assessment of water pollution in Rwanda: A case study of the Bishenyi sub-catchment*. *Journal of Water Research*, 48(3), 102-115.
- Mwenda, F. A., Murwira, A., & Magombo, Z. (2021). Water pollution trends and

- associated risks to ecosystem health in Lake Muhazi catchment, Rwanda. *Environmental Monitoring and Assessment*, 193(2), 70.
- National Institute of Statistics of Rwanda (NISR). (2023). *RPHC5 Thematic Report: Population Projection*. Retrieved April 17, 2025.
- Neal, C., Wickham, H., & Jenkins, A. (2006). Afforestation and water quality: Managing forested catchments. *Environmental Science & Technology*, 40(4), 1101–1111.
- Ngeruka, R., Mucyo, N. A., & Shima, L. (2019). *Assessment of flood causes and provision of control measures to prevent its effects* (Undergraduate dissertation). College of Science and Technology, University of Rwanda
- Ngos, S., Ndjama, J., & Ngnikam, E. (2016). Urban sanitation management in Cameroon: Status and constraints. *Journal of Water, Sanitation and Hygiene for Development*, 6(2), 270–278.
- NISR (National Institute of Statistics of Rwanda). (2023). *Population data and urban growth in Rwanda: Statistical report 2023*. National Institute of Statistics of Rwanda.
- Novotny, V. (2003). *Water quality: Diffuse pollution and watershed management*. New York, NY: John Wiley & Sons.
- Nyirahabimana, C., Uwizeyimana, D., & Mugiraneza, T. (2022). Impact of land use patterns on water quality in Rwandan catchments: A case of Bishenyi sub-catchment. *Rwandan Journal of Environmental Studies*, 6(2), 44–53.
- Okurut, T. O., Kansime, F., & Nhapi, I. (2017). *Pollution of water sources in developing countries: Case studies from Uganda*. Kampala: Makerere University Press.
- Osei, J., Biney, C. A., & Asomaning, J. (2020). Chemical oxygen demand as an indicator of pollution from industrial effluents: A Ghanaian case study. *Environmental Monitoring and Assessment*, 192, 550.
- Owens, P. N., Batalla, R. J., Collins, A. J., Gomez, B., Hicks, D. M., Horowitz, A. J., ... & Wasson, R. J. (2005). Fine-grained sediment in river systems: Environmental significance and management issues. *River Research and Applications*, 21(7), 693–717.
- Oyebamiji, O., Owoade, O., & Fagbeja, M. (2025). *Pollution transport and receptor modeling in urban catchments*. *Water Research*, 246, 119071.
- Patton, M. Q. (2015). *Qualitative research & evaluation methods* (4th ed.). Thousand Oaks, CA:
- Persson, J., Futter, M., Köhler, S., & Bishop, K. (2018). Local scale impacts of industrial point source discharges into aquatic ecosystems: A review. *Science of The Total Environment*, 621, 1035-1044.
- Persson, J., Nilsson, P. A., & Andersson, M. G. (2018). Nutrient pollution and hypoxia: Long-term threats to aquatic biodiversity. *Aquatic Ecology*, 52(2), 129–142.
- Qian, Y., Migliaccio, K. W., Wan, Y., & Li, Y. (2019). Application of remote sensing and GIS for non-point source pollution modeling: A review. *Environmental Pollution*, 251, 630–641.
- Rai, P. K., & Singh, M. M. (2016). *Spatial and seasonal variation of water quality using GIS techniques: A case study of river Gomti, India*. *Journal of Environmental*

- Science and Technology, 9(2), 118–126.
- Ravindra, K., et al. (2020). "Air pollution and health." *Environmental Science and Pollution Research*, 27(1), 1011-1016.
- REMA. (2022). *Rwanda State of Environment and Outlook Report 2022*. Kigali: Rwanda Environment Management Authority.
- Rich, B. A., Schilling, K. E., & Schultz, R. C. (2018). Nonpoint source pollution and water quality monitoring in agricultural watersheds. *Water*, 10(6), 718.
- Rogers, E. M. (2003). *Diffusion of innovations* (5th ed.). Free Press.
- RSB. (2022). *National standards on drinking water quality*. Kigali, Rwanda: Rwanda Standards Board.
- Rutanga, M. (2014). Challenges of wastewater management in Rwanda: A case study of Kigali City. Kigali: University of Rwanda.
- Rwanda Standards Board (RS ISO). " Rwanda Standards for Wastewater Treatment and Quality Management." Government of Rwanda.
- National Spatial Data Infrastructure (NSDI). " Kamonyi District Master Plan: GIS Data on Environmental and Land Use Management." Government of Rwanda.
- McKnight, U. S., & Finkel, M. (2013). A system dynamics approach for the assessment and prediction of risks and risk-reduction options at contaminated sites. [Environmental Modelling&Software]40,2.https://www.researchgate.net/publication/239573214_A_System_Dynamics_Approach_for_the_Assessment_and_Prediction_of_Risks_and_RiskReduction_Options_at_Contaminated_Sites.
- DEFRA. (2012). Environmental Protection Act 1990: *Part 2A - Contaminated Land Statutory Guidance*. Department for Environment, Food & Rural Affairs.
- EMS. (2016). What is the Source, Pathway, Receptor model? Environmental Monitoring Solutions.
- Owens, P. N., Batalla, R. J., Collins, A. J., Gómez, B., Hicks, D. M., Horowitz, A. J., ... & Wasson, J. G. (2005). Fine-grained sediment in river systems: Environmental significance and management issues. *River Research and Applications*, 21(7), 693-717.
- Oyebamiji, A. R., Hoque, M. A., & Whitworth, M. (2025). Regional assessment of groundwater contamination risk from crude oil spillages in the Niger Delta: A novel application of the source-pathway-receptor model. *Earth Systems and Environment*, 9, 117-133.
- Waldschläger, K., Lechthaler, S., Stauch, G., & Schüttrumpf, H. (2020). The way of microplastic through the environment – Application of the source-pathway-receptor model (review). *Science of the Total Environment*, 713, 136584.
- Tong, S. T. Y., & Chen, W. (2002). Modeling the relationship between land use and surface water quality. *Journal of Environmental Management*, 66(4), 377-393.
- Nyirahabimana, M., Habimana, S., & Ndayisaba, F. (2022). Assessment of industrial wastewater impact on surface water quality in Rwanda. *Journal of Water and Environment*, 45(2), 113125.
- Rwanda Environment Management Authority (REMA). (2020). State of Environment and <https://doi.org/10.53819/81018102t2616>

Outlook Report. Retrieved April 17, 2025.

- Sahu, O., Mazumder, D., & Chaudhari, P. K. (2019). Treatment of industrial effluent using advanced oxidation process: A review. *Journal of Industrial and Engineering Chemistry*, 73, 1–12.
- Sakan, S. M., Đorđević, D. S., & Relić, D. J. (2019). Multidisciplinary approach in the assessment of water pollution: Integrating geospatial and chemical risk indicators. *Science of the Total Environment*, 667, 1181–1193.
- Sekomo, C. B., Rousseau, D. P. L., & Lens, P. N. L. (2011). Use of constructed wetlands for urban wastewater treatment in Rwanda. *Environmental Technology*, 32(9), 963–970.
- Sharpley, A. N., Williams, J. R., & Huggins, D. R. (2001). Agricultural phosphorus management and water quality protection. *Agricultural Water Management*, 47(2), 91–121.
- Shrestha, S., & Kazama, F. (2007). Assessment of surface water quality using multivariate statistical techniques: A case study of the Fuji river basin, Japan. *Environmental Modelling & Software*, 22(4), 464–475.
- Singh, V. P., & Woolhiser, D. A. (2002). Mathematical modeling of watershed hydrology. *Journal of Hydrologic Engineering*, 7(4), 270–292.
- Smith, A., Turner, B., & Wang, H. (2020). Evaluating the sustainability of pollution prevention in manufacturing industries. *Journal of Cleaner Production*, 252, 119809.
- Smith, V. H., Tilman, G. D., & Nekola, J. C. (2021). Eutrophication: Impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. *Environmental Pollution*, 281, 116988.
- Tong, S. T. Y., & Chen, W. (2002). Modeling the relationship between land use and surface water quality. *Journal of Environmental Management*, 66(4), 377–393.
- UNESCO. (2021). *Water quality monitoring and assessment: A global overview*. United Nations Educational, Scientific and Cultural Organization.
- United Nations Educational, Scientific and Cultural Organization.
- United Nations Environment Programme. (2021). *Wastewater management and water quality*. Nairobi, Kenya: UNEP.
- United States Environmental Protection Agency. (2021). *Clean Water Act overview*. Washington, DC: USEPA.
- Vallejo-Torres, G., García-Álvarez, A., & Ordóñez, A. (2019). Assessment of water pollution sources and risks in agricultural and industrial regions: A case study from Ecuador. *Science of the Total Environment*, 651, 2325–2337.
- Waldschläger, K., Schüttrumpf, H., & Hering, D. (2020). *Concepts and limitations of the SourcePathway-Receptor model in water pollution*. *Environmental Science: Processes & Impacts*, 22(9), 1775–1789.
- Wali, A., Waqas, M., Alibakhshi, M., & Waseem, A. (2019). A review on pollution source identification and water quality modeling techniques. *Water Practice and Technology*, 14(4), 930–944.
- Wali, F. (2011). *The status of wastewater treatment in Rwanda: Current challenges and* <https://doi.org/10.53819/81018102t2616>

- opportunities*. Water Research Journal, 15(4), 120-135.
- Wang, X., Liu, J., Zhang, Y., & Xu, J. (2018). Influence of industrial effluents on pH and water quality in aquatic ecosystems. *Water Science and Technology*, 77(7), 1901–1910.
- Wang, Y., Zhang, H., & Zhao, X. (2020). Advances in wastewater treatment processes: A review. *Science of the Total Environment*, 731, 139081.
- WHO. (2017). *Guidelines for drinking-water quality* (4th ed.). World Health Organization.
- World Health Organization (WHO). (2021). *Water, sanitation and hygiene: Strategy 2021–2025*.
- World Health Organization. (2019). *WHO guidelines on sanitation and health*. Geneva: World Health Organization.
- Zhang, H., Zhang, X., & Zhao, Y. (2022). Recent advancements in integrated wastewater treatment technologies for enhanced removal of emerging contaminants. *Science of The Total Environment*, 821, 153340.
- Zhang, L., Wu, J., & Li, Y. (2022). Performance evaluation of advanced wastewater treatment technologies for water pollution control. *Journal of Environmental Management*, 305, 114367.
- Zhang, S., Wang, Y., & Ding, Y. (2021). Integrated assessment of urban water pollution based on fuzzy comprehensive evaluation and geographic information system. *Science of The Total Environment*, 750, 141571.
- Zhang, Y., Gao, J., & Chen, M. (2020). Agricultural nutrient runoff and harmful algal blooms: A growing concern for water bodies. *Water Science and Technology*, 82(6), 1251–1262.
- Zhu, B., et al. (2020). "Effects of land use and land cover changes on non-point source pollution: A case study in the Kuye River Watershed, China." *Sustainability*, 12(7), 2707. <https://mapcarta.com/12751990/Map>