



THE EFFECT OF MINING ON THE PAMPANA RIVER BASIN, SIERRA LEONE

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Abstract: Mining activities within the Pampana River Basin in Sierra Leone have intensified over recent decades, raising concerns regarding the degradation of surface and groundwater quality and the sustainability of water resources for domestic and agricultural use. This study evaluates the impact of artisanal and small-scale mining on the physicochemical, microbiological, and hydrochemical characteristics of the Pampana River and adjacent groundwater sources. Water samples were collected from upstream, midstream, downstream, and borehole locations within the basin and analyzed using field measurements, laboratory investigations, hydrochemical assessment techniques, and spatial analysis tools. Physicochemical parameters, microbial indicators, Water Quality Index (WQI), irrigation suitability indices, and hydrochemical facies were evaluated to determine the extent of mining-related contamination and water usability. The results indicate significant spatial variations in water quality across the river basin. Elevated turbidity, total dissolved solids, color, and microbial contamination were observed, particularly in the midstream and downstream sections where mining activities are concentrated. Upstream and borehole samples generally exhibited better water quality conditions and lower contaminant levels. Hydrochemical analysis revealed bicarbonate (HCO_3^-) as the dominant anion, while sodium (Na^+) was identified as the dominant cation within the basin. Piper and Schoeller diagrams classified the river water predominantly within sodium-bicarbonate hydrochemical facies. Water Quality Index analysis classified upstream water as excellent for drinking purposes. In contrast, midstream and downstream waters were categorized as unsuitable for potable use due to microbial contamination and elevated pollution levels. Irrigation suitability assessment showed that most samples remained within acceptable irrigation classes despite varying salinity and sodicity conditions. The study demonstrates that uncontrolled mining activities are contributing to the deterioration of water quality within the Pampana River Basin and pose increasing environmental and public health risks to surrounding communities. The findings provide important baseline information for sustainable water resource management, environmental monitoring, and policy formulation in mining-affected river basins in Sierra Leone.

Keywords: Artisanal mining; Water quality index; Hydrochemical facies; Pampana River Basin; Irrigation suitability; Microbial contamination

1. Introduction

Water resources are essential for environmental sustainability, ecosystem stability, economic development, and human survival [1, 2, 3]. However, increasing anthropogenic activities such as mining, industrialization, agriculture, and rapid urbanization continue to place significant pressure on both surface and groundwater systems worldwide [4, 5, 6]. Among these activities, mining has emerged as a major contributor to water quality degradation, particularly in developing countries where environmental regulations and monitoring systems are often limited [5, 7, 8]. Mining operations can introduce large quantities of suspended sediments, heavy metals, chemical pollutants, and microbial contaminants into nearby water bodies, thereby altering natural hydrochemical conditions and threatening aquatic ecosystems and public health [5, 9, 10].

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In many parts of Sub-Saharan Africa, artisanal and small-scale mining (ASM) has become an important source of livelihood and economic survival for rural populations [5, 11]. Despite its economic significance, ASM activities are frequently associated with poor environmental management practices, including uncontrolled excavation, sediment discharge, vegetation removal, and direct disturbance of river systems [7, 12, 13]. These activities often accelerate water pollution, increase turbidity, and reduce the availability of safe water for domestic and agricultural purposes [8, 14, 15]. Sierra Leone, which possesses abundant mineral resources including gold, diamonds, rutile, and bauxite, has experienced substantial expansion in artisanal mining activities over the past decades [11, 16, 17]. While the mining sector contributes significantly to national economic development, its environmental consequences remain a growing concern [5, 17].

The Pampana River Basin represents one of the major river systems affected by artisanal gold mining activities in Sierra Leone [17]. The river traverses several mining communities and serves as an important source of drinking water, domestic use, irrigation, fishing, and other socioeconomic activities [2, 18]. Extensive alluvial gold mining along river channels and floodplains has led to increased sedimentation, water discoloration, and ecosystem disturbance [5, 8, 10]. Communities located downstream of mining zones are particularly vulnerable to deteriorating water quality conditions due to continuous exposure to contaminated water sources [3, 9].

Previous studies conducted in mining environments have documented the relationship between mining activities and water-quality deterioration, characterized by elevated concentrations of suspended solids, dissolved ions, nutrients, and microbial pollutants [7, 8, 12, 19]. However, few studies have comprehensively evaluated the combined physicochemical, microbiological, hydrochemical, and irrigation-suitability characteristics of the Pampana River Basin under active mining conditions [17, 20, 21]. In addition, there remains an insufficient spatial assessment of water quality variations across the upstream, midstream, and downstream sections of the river system. This knowledge gap limits the development of effective environmental monitoring strategies and sustainable water resource management policies for mining-impacted communities in Sierra Leone [3, 16].

Therefore, this study aims to evaluate the effects of mining activities on the Pampana River Basin by assessing the physicochemical and microbiological quality of surface and groundwater sources and determining their suitability for drinking and irrigation purposes. Specifically, the study seeks to: (1) determine the physicochemical and microbial characteristics of water within the river basin; (2) evaluate the Water Quality Index (WQI) of the river system [14]; (3) assess spatial variations in pollution load and water quality along the river course; and (4) determine the suitability of the water resources for irrigation use through hydrochemical and salinity assessments [22, 23, 24].

The findings of this study are expected to contribute to a better understanding of mining-induced water quality degradation in Sierra Leone and to provide scientific evidence to support environmental regulation, water resource protection, and the sustainable management of mining-affected river basins [3, 5, 17].

2. Literature Review

2.1. Mining and Water Quality Degradation

Mining activities are widely recognized as major contributors to surface and groundwater degradation globally [5, 7, 8]. Both large-scale and artisanal mining operations alter natural hydrological systems through excavation, sediment mobilization, chemical discharge, and land disturbance [5, 13]. Mining-related activities introduce suspended solids, heavy metals, nutrients, and other contaminants into nearby water bodies, thereby affecting aquatic ecosystems and reducing the availability of safe water resources for domestic and agricultural use [1, 9, 10].

In many developing countries, artisanal and small-scale mining (ASM) has expanded rapidly due to increasing economic pressures, unemployment, and the growing demand for mineral resources [5, 11]. Although ASM contributes significantly to rural livelihoods and national economies, poor environmental management practices often lead to severe ecological degradation [5, 8]. Previous studies have linked artisanal mining to increased turbidity, sedimentation, acidification, and microbial contamination of river systems, particularly in regions where mining activities occur directly within river channels and floodplains [7, 12, 13].

Several researchers have documented the relationship between mining and declining water quality in Sub-Saharan Africa. Donkor et al. [12] reported significant surface-water contamination associated with gold-mining activities in Ghana, while Thorslund et al. [10] identified mining-induced acidification and heavy-metal pollution in downstream aquatic systems. Similar observations have been reported in Sierra Leone, where artisanal gold mining has intensified environmental pressures on river basins and surrounding communities [16, 17, 21].

2.2. Mining and Water Resources in Sierra Leone

Sierra Leone possesses abundant mineral resources, including gold, diamonds, rutile, bauxite, and iron ore, making mining one of the country's major economic sectors [11, 16, 17]. However, mining operations have also generated increasing environmental concerns, particularly regarding land degradation and water pollution [5, 8]. Artisanal mining activities are widespread in mineral-rich regions and are often conducted with limited environmental oversight and inadequate waste management practices [12, 13].

The Pampana River Basin is among the major river systems affected by artisanal gold mining activities in Sierra Leone [17]. The river serves as an important source of drinking water, domestic use, irrigation, fishing, and other socioeconomic activities for surrounding communities [2, 18]. Uncontrolled dredging, excavation, and sediment discharge into the river have contributed to increased turbidity, ecosystem disturbance, and deterioration of water quality [5, 8, 15].

Despite growing concerns regarding mining-related environmental degradation in Sierra Leone, relatively few hydrochemical and microbiological investigations have been conducted within the Pampana River Basin [17, 20, 21]. Most available studies focus on the socioeconomic impacts of mining, with fewer comprehensive assessments that integrate physicochemical, microbial, hydrochemical, and irrigation-suitability analyses. This knowledge gap limits effective environmental monitoring and sustainable water-resource management in mining-affected river basins in Sierra Leone [3, 16].

2.3. Water Quality Assessment in Mining Environments

Water quality assessment provides critical information for evaluating the impacts of anthropogenic activities on aquatic systems [1, 3, 19]. Physicochemical parameters such as pH, turbidity, electrical conductivity (EC), total dissolved solids (TDS), hardness, dissolved oxygen, major ions, nutrients, and trace metals are commonly used to determine the condition of surface and groundwater systems affected by mining activities [1, 25, 26].

Microbiological indicators, including total coliforms, fecal coliforms, and *Escherichia coli* (*E. coli*), are also important in assessing the suitability of water for drinking purposes [9, 27, 28]. Elevated microbial contamination in mining communities is often associated with poor sanitation practices, surface runoff, and direct contamination of water bodies [9, 27].

Hydrochemical assessment tools such as Piper diagrams, Gibbs diagrams, Schoeller plots, and correlation analyses are commonly used to evaluate hydrochemical facies, dominant geochemical processes, and ionic relationships within water systems [7, 23, 29, 30]. These approaches provide insight into the geochemical evolution of water and help identify the influence of anthropogenic activities on water chemistry [7, 30, 31].

Water Quality Index (WQI) models have become widely used to simplify complex water quality data into understandable classifications such as excellent, good, poor, or unsuitable [1, 14]. Similarly, irrigation suitability indices, including the Sodium Adsorption Ratio (SAR), Sodium Percentage (Na%), Permeability Index (PI), Kelly's Ratio (KR), and Wilcox classification, are frequently used to assess the suitability of water resources for agricultural use [22, 24, 31, 32, 33].

2.4 Research Gap

Although several studies have investigated mining-related environmental degradation in developing countries, there remains a limited integrated assessment of water quality conditions within the Pampana River Basin in Sierra Leone [5, 7, 8]. Existing studies have rarely combined physicochemical, microbiological, hydrochemical, spatial, and irrigation suitability analyses within a single assessment framework [17, 20, 21].

Furthermore, limited information is available regarding spatial variations in water quality across upstream, midstream, downstream, and groundwater sources within active artisanal mining zones. The absence of comprehensive water quality monitoring data restricts effective environmental management, environmental monitoring, and policy development for mining-affected communities in Sierra Leone [3, 16].

This study addresses these gaps by integrating physicochemical assessment, microbial analysis, hydrochemical facies interpretation, Water Quality Index (WQI) evaluation, and irrigation suitability assessment to determine the impact of mining activities on the Pampana River Basin.

3. Methodology

3.1. Study Area

The study was conducted within the Pampana River Basin in Sierra Leone. The Pampana River originates from the northeastern region of the country and flows through several mining communities before converging with the Teye River to form the Jong River. The basin is characterized by extensive artisanal and small-scale gold mining, particularly in alluvial deposits associated with the Kangari Hills Greenstone Belt.

The river serves as an important source of water for domestic consumption, irrigation, fishing, and other socioeconomic activities. However, increasing mining activity within the basin has raised concerns about declining water quality and ecosystem degradation.

3.2. Sample Collection and Field Measurements

Water samples were collected from upstream, midstream, downstream, and borehole locations within the Pampana River Basin to evaluate spatial variations in water quality. Sampling locations were selected based on proximity to mining activities, accessibility, and representativeness of river conditions. The spatial distribution of sampling locations within the study area is presented in Figure 1.

Grab sampling techniques were employed at the four sampling stations located along the riverbanks. Sampling was conducted at two-week intervals over a three-month period from December 2020 to February 2021, resulting in a total of 25 water samples [34]. The sampling period primarily represented dry-season conditions within the study area.

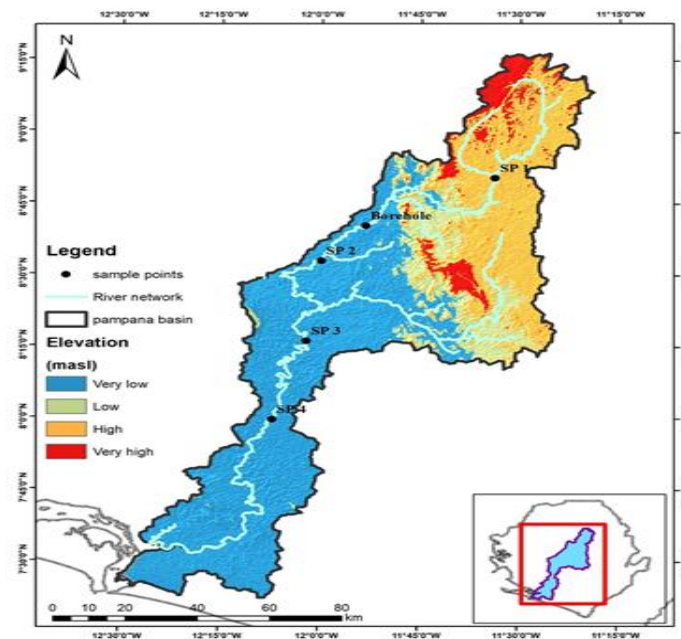


Fig. 1. Study area showing elevations and sample collection points

Table 1. Physicochemical Characteristics of the Pampana River Basin

Parameter	Upstream Mean	Midstream Mean	Downstream Mean	Borehole Mean	WHO Limit
pH	7.30	7.46	7.48	6.94	6.5–8.5
Conductivity ($\mu\text{S}/\text{cm}$)	57.60	30.40	38.60	35.20	1500
Turbidity (NTU)	29.72	342.00	377.00	11.00	5
TDS (mg/L)	28.59	18.24	23.16	21.12	1000
Total Hardness (mg/L)	12.76	11.80	11.12	10.40	500
Bicarbonate (mg/L)	24.98	18.60	17.46	20.80	500
Chloride (mg/L)	5.86	3.44	3.58	4.10	250
Sodium (mg/L)	5.30	2.92	3.54	3.40	200
Fluoride (mg/L)	1.53	1.20	1.57	0.62	1.5
Nitrate (mg/L)	0.38	0.15	0.25	0.06	50
Ammonia (mg/L)	0.05	0.21	0.19	0.02	1.5
Copper (mg/L)	0.42	2.46	3.00	0.23	2.0
Iron (mg/L)	0.64	1.35	1.58	0.02	0.3
Chromium (mg/L)	0.18	1.17	1.28	0.09	0.05

Prior to sample collection, the 500 mL plastic sampling bottles were washed with distilled water and rinsed three times with river water to minimize contamination. Immediately after collection, the samples were preserved in ice-packed containers and transported to the Ministry of Water Resources National Water Quality Laboratory in Freetown, Sierra Leone, for physicochemical and microbiological analyses.

In-situ measurements of pH, dissolved oxygen (DO), electrical conductivity (EC), and temperature were conducted using the Hydro Kit HK1000 and portable multi-meter HC1000.

3.3. Laboratory Analysis

Laboratory analyses were conducted at the Ministry of Water Resources National Water Quality Laboratory in Freetown following standard analytical procedures recommended by APHA and WHO guidelines [25, 35].

A total of thirty physicochemical and microbiological water-quality parameters were analyzed. The physicochemical parameters analyzed included turbidity, total dissolved solids (TDS), total hardness, alkalinity, calcium, magnesium, sodium, potassium, chloride, bicarbonate, sulfate, nitrate, phosphate, ammonia, fluoride, iron, copper, chromium, and lead. Microbiological analysis focused on total coliforms, fecal coliforms, and *Escherichia coli* (*E. coli*) to assess microbial contamination and suitability of water for domestic use [27, 28].

3.4. Water Quality and Hydrochemical Analysis

Water Quality Index (WQI) analysis was performed to evaluate the suitability of water for drinking purposes using weighted arithmetic methods based on World Health Organization (WHO) guideline standards [14, 35].

Hydrochemical facies and geochemical processes controlling water chemistry were evaluated using Piper diagrams, Schoeller plots, Gibbs diagrams, and ionic relationship analyses [7, 23, 29, 30]. Correlation analysis was conducted using the Statistical Package for Social Sciences (SPSS) to determine relationships among physicochemical parameters and identify potential pollution sources.

3.5. Irrigation Water Quality Assessment

The suitability of river water for irrigation purposes was assessed using standard hydrochemical indices, including Sodium Adsorption Ratio (SAR), Sodium Percentage (Na%), Kelly's Ratio (KR), Magnesium Hazard (MH), Residual Sodium Carbonate (RSC), and Permeability Index (PI) [22, 24, 31, 32, 33].

Wilcox and United States Salinity Laboratory (USSL) diagrams were further used to classify irrigation water quality and evaluate salinity and sodicity hazards [24, 36].

3.6. Spatial Analysis

Spatial distribution of selected water quality parameters was analyzed using ArcGIS software. Water quality maps were developed to illustrate spatial variations in contamination levels and hydrochemical characteristics across the Pampana River Basin. GIS-based spatial interpolation was used to evaluate pollution gradients and identify mining-affected zones within the river basin.

4. Results and Discussion

4.1. Physicochemical Characteristics of the Pampana River Basin

The physicochemical characteristics of water within the Pampana River Basin exhibited considerable spatial variation across upstream, midstream, downstream, and borehole sampling locations. These variations are strongly associated with the intensity of artisanal mining activities occurring along different sections of the river basin.

pH Characteristics

The pH values recorded within the Pampana River Basin generally ranged within the acceptable limits recommended by the World Health Organization (WHO) for drinking water. However, slight spatial variations were observed across the river sections. Upstream water samples exhibited relatively stable pH, whereas fluctuations were more pronounced in the midstream and downstream sections, where mining activities were concentrated.

The observed pH variations may be attributed to sediment disturbance, mineral dissolution, and anthropogenic inputs associated with artisanal mining activities. Although the pH values remained largely within permissible limits, localized deviations indicate potential alteration of the river system's natural hydrochemical balance.

Turbidity

Turbidity values showed significant increases within the midstream and downstream sections of the Pampana River Basin. In several sampling locations, turbidity exceeded WHO guideline values for potable water, indicating severe sediment contamination within mining-affected sections of the river.

Elevated turbidity levels are primarily associated with dredging activities, sediment resuspension, riverbank disturbance, and direct excavation within alluvial mining zones. The continuous disturbance of river sediments by artisanal miners increases suspended particulate matter within the water column, thereby reducing water clarity and overall water quality.

The relatively lower turbidity values observed upstream suggest limited anthropogenic disturbance in comparison with downstream mining zones. These findings demonstrate that mining activities significantly contribute to sediment loading and deterioration of surface water quality within the basin.

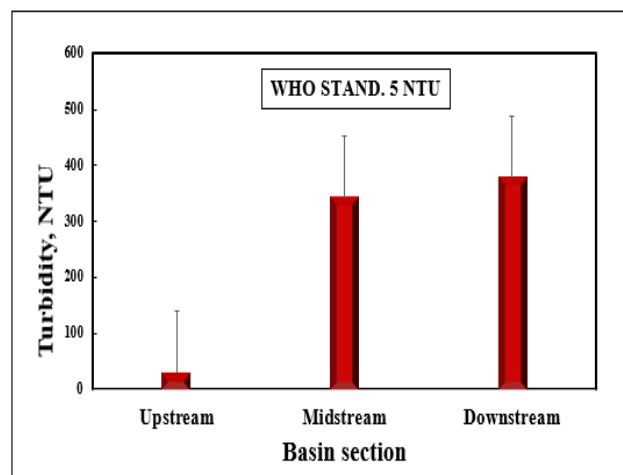


Fig. 2. Turbidity values across the Pampana River basin with a WHO guideline value of 5.00 NTU

The spatial variation of turbidity within the Pampana River Basin is illustrated in Figure 3

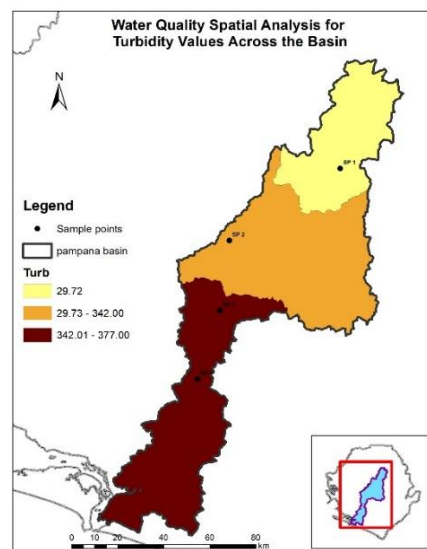


Fig. 3. Spatial distribution of turbidity levels across the Pampana River Basin

Electrical Conductivity and Total Dissolved Solids

Electrical Conductivity (EC) and Total Dissolved Solids (TDS) exhibited spatial variations across the Pampana River Basin. Although downstream sections generally reflected increased anthropogenic influence associated with mining activities, the upstream section recorded relatively elevated EC values compared to the midstream section. This may be attributed to localized geological conditions, natural mineral dissolution, and baseline hydrochemical characteristics within the upstream catchment area. Elevated EC and TDS values observed within mining-intensive areas suggest increased ion mobilization and sediment-water interaction associated with artisanal mining disturbances.

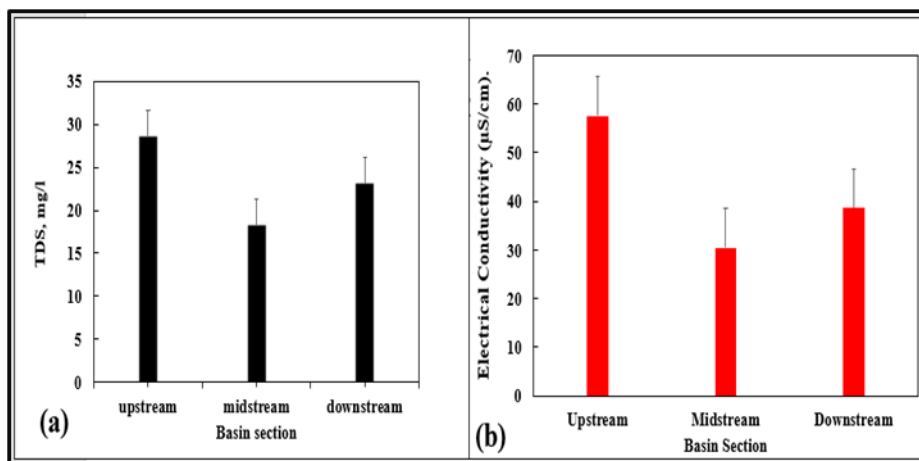


Fig. 4. Physical parameters along the river basin. (a) Total Dissolved Solids; (b) Electrical Conductivity

The spatial distributions of TDS and EC across the Pampana River Basin are presented in Figure 5.

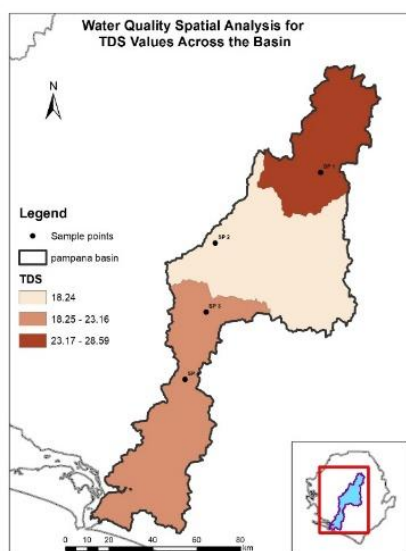


Fig. 5. The spatial distribution of Total Dissolved Solids (TDS) across the Pampana River Basin

Total Hardness and Alkalinity

Total hardness and alkalinity values showed moderate variations across the sampling locations. Calcium and magnesium ions contributed significantly to hardness levels within the basin, while bicarbonate ions largely influenced alkalinity conditions.

The relatively elevated alkalinity observed within some river sections indicates the buffering capacity of the water against rapid pH fluctuations. This may be linked to the dissolution of carbonate-bearing minerals and weathering processes occurring within the basin geology.

Although hardness values generally remained within acceptable drinking water standards, continued mining activities may influence long-term hydrochemical evolution of the river system through enhanced mineral weathering and sediment interaction.

4.2. Major Ions and Nutrient Characteristics

Calcium, Magnesium, Sodium, and Potassium

Among the major cations analyzed, sodium (Na^+) was the dominant ion in the river basin, followed by calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+). The dominance of sodium in river water suggests strong mineral dissolution and possible anthropogenic contributions associated with mining activities.

The elevated sodium concentrations observed within downstream sections may indicate increased interaction between surface water and disturbed geological formations resulting from excavation and sediment exposure. Calcium and magnesium concentrations remained relatively moderate, suggesting limited carbonate mineral enrichment within the basin.

Bicarbonate, Chloride, and Fluoride

Bicarbonate (HCO_3^-) was identified as the dominant anion across the Pampana River Basin, indicating that carbonate weathering processes strongly influence the hydrochemistry of the river system. Chloride and fluoride concentrations remained generally within WHO permissible limits across most sampling locations.

The hydrochemical dominance of bicarbonate ions is consistent with natural geochemical interactions between water and surrounding geological materials within the basin. However, localized increases in chloride concentrations within some downstream locations may reflect anthropogenic inputs and increased mineral dissolution associated with mining disturbances.

4.3. Nutrient and Trace Metal Distribution

Nitrate, phosphate, sulfate, and ammonia concentrations generally remained within acceptable guideline limits. However, localized increases in nutrient concentrations were observed in mining-intensive sections of the river, potentially due to surface runoff, domestic activities, and sediment disturbance.

Trace metal analysis detected iron, copper, chromium, and lead across the basin. Although most concentrations remained within permissible limits, elevated iron concentrations were recorded in some mining-affected sections. These elevated concentrations may be associated with the weathering of iron-bearing minerals and the mobilization of sediment during mining operations.

The presence of trace metals in the river system highlights the need for continuous environmental monitoring, given the potential long-term ecological and human health implications of metal accumulation.

The spatial distribution of iron concentrations within the Pampana River Basin is presented in Figure 6.

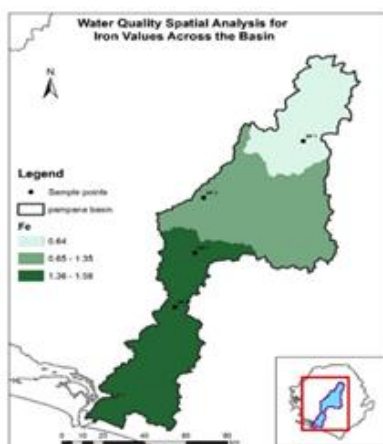


Fig. 6. The Spatial distribution of iron concentration within the Pampana River basin

4.4. Water Quality Index (WQI) Assessment

Table 2. Water Quality Index (WQI) classification of water samples within the Pampana River Basin

Sampling Location	WQI Value	Water Quality Classification
Upstream	10.19	Excellent water quality
Midstream	51.0	Poor water quality
Downstream	54.2	Poor water quality
Borehole	5.69	Excellent water quality

The Water Quality Index (WQI) analysis revealed clear spatial variation in water quality conditions across the Pampana River Basin. Upstream water samples and borehole sources were generally classified as “excellent” for drinking purposes, indicating relatively low levels of contamination and better hydrochemical conditions.

In contrast, the midstream and downstream sections exhibited significantly poorer water quality, with elevated turbidity, dissolved solids, and microbial contamination. These sections were classified as unsuitable for drinking in several sampling locations.

The deterioration in WQI values downstream strongly reflects the cumulative environmental impacts of artisanal mining activities occurring within the basin. The findings indicate that mining operations are contributing significantly to declining water quality and increasing risks to communities dependent on the river for domestic use.

4.5 Microbial Water Quality Assessment

Microbial assessment of the Pampana River Basin revealed significant contamination at several sampling locations, particularly in the midstream and downstream sections, where artisanal mining and human settlements are concentrated. The presence of *Escherichia coli* (E-coli), fecal coliforms, and non-fecal coliforms indicates substantial microbial pollution and possible fecal contamination of the river system.

Upstream water samples generally exhibited comparatively lower microbial concentrations, suggesting reduced anthropogenic disturbance within those sections of the basin. However, microbial contamination increased considerably downstream, reflecting cumulative impacts from mining activities, surface runoff, direct human interaction with the river, and inadequate sanitation practices within surrounding communities.

The high microbial loads recorded in several locations render portions of the river unsuitable for direct domestic consumption without adequate treatment. These findings raise important public health concerns for communities that rely heavily on the Pampana River for drinking, cooking, bathing, and other household activities.

The elevated microbial contamination observed in the study area may also be associated with the direct use of river water by mining operators, open defecation, poor waste disposal systems, and disturbance of river sediments during dredging activities. Similar relationships between artisanal mining activities and microbial deterioration of water quality have been reported in several developing countries where environmental monitoring and sanitation infrastructure remain limited.

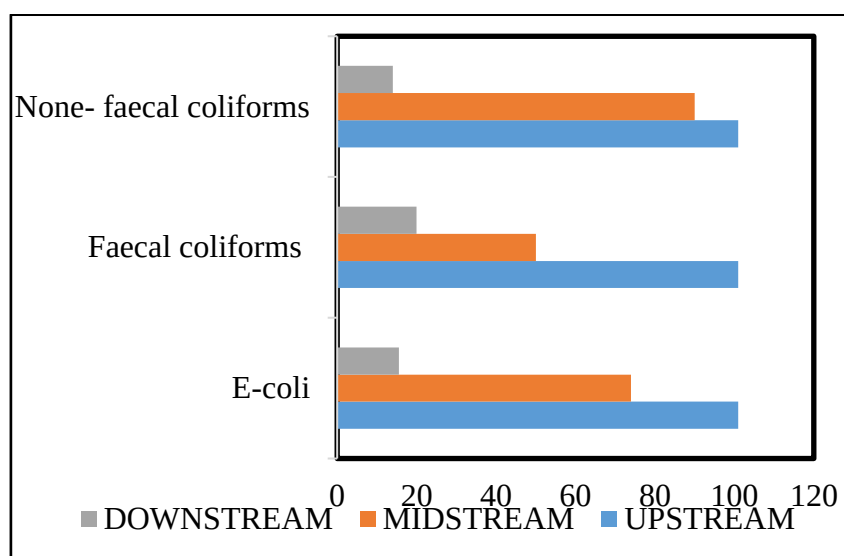


Fig 7. Microbial Contaminant across the Pampana River Basin

4.6. Correlation Analysis of Physicochemical Parameters

Pearson correlation analysis revealed varying relationships among the physicochemical parameters across upstream, midstream, downstream, and borehole samples. The observed correlations indicate that multiple hydrochemical and anthropogenic processes influence water chemistry within the Pampana River Basin.

Strong positive relationships between Electrical Conductivity (EC), Total Dissolved Solids (TDS), sodium, chloride, and alkalinity suggest that dissolved ionic constituents in the river are largely controlled by mineral dissolution and sediment-water interactions. The correlation between turbidity and several trace elements further indicates that suspended sediments associated with mining activities may contribute to the transport of dissolved and particulate contaminants within the river system.

The distinct correlation patterns observed between upstream and downstream sections demonstrate the progressive influence of mining activities along the river course. In relatively undisturbed upstream sections, natural geochemical processes appear to dominate water chemistry, whereas downstream sections exhibit stronger anthropogenic signatures associated with mining disturbances and human activities.

4.7. Hydrochemical Facies Assessment

Piper Diagram Interpretation

Hydrochemical facies analysis using the Piper diagram revealed that bicarbonate (HCO_3^-) is the dominant anion within the Pampana River Basin, while sodium (Na^+) represents the dominant cation. The hydrochemical composition of the river water is therefore characterized predominantly by sodium-bicarbonate (Na-HCO_3) water types.

The dominance of sodium and bicarbonate ions suggests that water chemistry within the basin is strongly influenced by rock-weathering processes, mineral dissolution, and ion exchange reactions occurring within the geological formations surrounding the river system. These hydrochemical characteristics also indicate substantial interaction between surface water and weathered geological materials mobilized during mining activities.

The hydrochemical evolution observed across the river sections further demonstrates increasing ionic enrichment within mining-affected downstream locations. The downstream migration of dissolved ions may be associated with sediment mobilization, excavation processes, and enhanced water-rock interaction caused by artisanal mining operations.

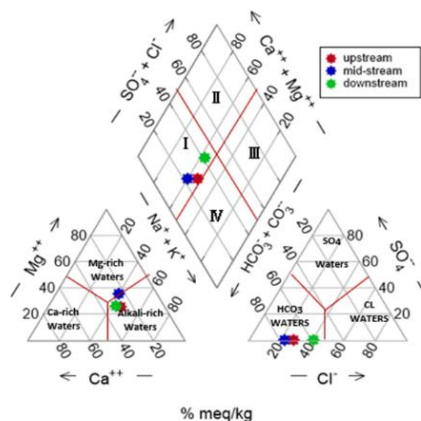


Fig. 8. Piper diagram showing Hydro chemical facies for the Pampana River Basin

Schoeller Diagram Interpretation

The Schoeller diagram further confirmed the dominance of sodium among the cations and bicarbonate among the anions within the river basin. The general ionic abundance trend observed in the study area followed the order:

$$\text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+$$

and

$$\text{HCO}_3^- > \text{Cl}^- > \text{SO}_4^{2-}$$

This ionic distribution indicates a relatively strong mineral weathering influence on the hydrochemistry of the basin. The relatively elevated sodium concentrations observed in several downstream locations may also reflect anthropogenic influences associated with mining activities and sediment disturbance.

The similarity in ionic trends across different river sections suggests that the basin shares common hydrogeochemical controls despite localized anthropogenic impacts.

The ionic distribution and hydrochemical relationships among upstream, midstream, and downstream water samples are illustrated in Figure 9.

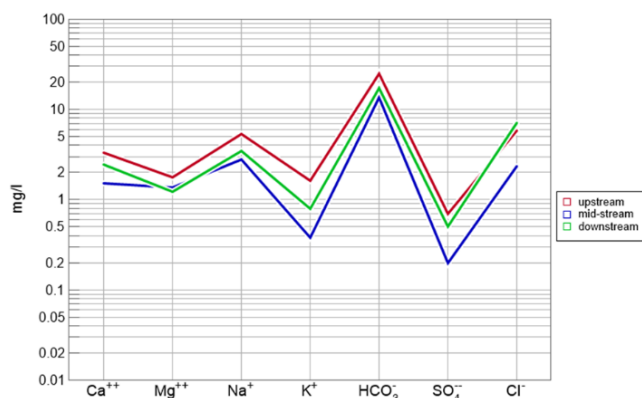


Fig. 9. Schoeller diagram using average concentrations of major ions for the Pampana river basin

Gibbs Diagram Interpretation

Gibbs diagram analysis demonstrated that rock weathering represents the principal mechanism controlling water chemistry within the Pampana River Basin. Most of the water samples plotted within the rock dominance field, indicating that the hydrochemical composition of the river is strongly influenced by geological interactions and mineral dissolution processes.

Although precipitation and evaporation processes contribute to water chemistry variations to some extent, the dominant hydrogeochemical control remains water-rock interaction. However, mining activities may accelerate these natural geochemical processes through excavation, sediment exposure, and increased contact between water and freshly exposed geological materials.

The Gibbs analysis therefore confirms that both natural geological processes and anthropogenic mining disturbances collectively influence the hydrochemical characteristics of the Pampana River Basin.

The hydrogeochemical control mechanisms identified through Gibbs diagram analysis are illustrated in Figure 10.

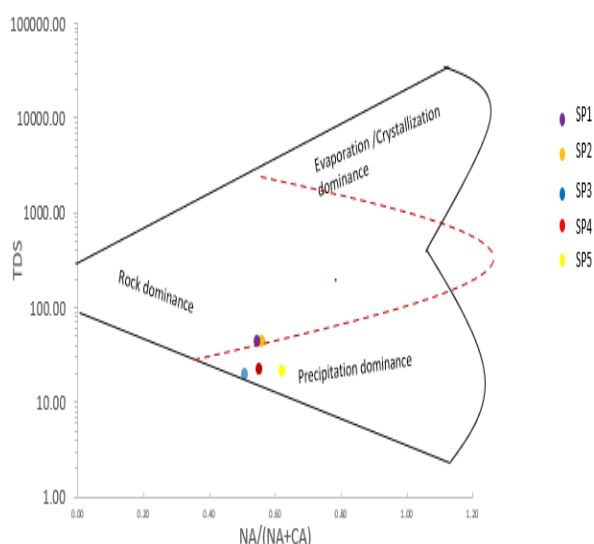


Fig. 10. Gibb's diagram showing upstream data of the Pampana River basin for irrigation

4.8. Irrigation Water Quality Assessment

Table 3. Irrigation suitability assessment of water samples within the Pampana River Basin

Sampling Location	EC Class	SAR Value	USSL Class	Irrigation Suitability
Upstream	Excellent	0.663	C1S1	Suitable
Midstream	Excellent	0.339	C1S1	Suitable
Downstream	Excellent	0.446	C1S1	Suitable
Borehole	Excellent	0.366	C1S1	Suitable

Sodium Adsorption Ratio and USSL Classification

Assessment of irrigation suitability using Sodium Adsorption Ratio (SAR) and United States Salinity Laboratory (USSL) diagrams indicated varying salinity and sodicity conditions across the river basin. Most samples ranged from low to very high salinity hazard classes depending on location and season.

Despite the observed variations, the majority of water samples remained generally suitable for irrigation purposes. The relatively low SAR values observed in several locations indicate limited sodium hazard for agricultural soils. However, continued accumulation of dissolved salts may pose long-term risks to soil permeability and crop productivity if mining activities intensify within the basin.

Wilcox and Permeability Index Assessment

Wilcox classification indicated that most upstream, midstream, and downstream water samples fall within the “excellent to good” category for irrigation suitability. Similarly, Permeability Index (PI) assessment classified most samples within Class II water types, suggesting acceptable permeability conditions for agricultural use.

The results demonstrate that although sections of the Pampana River Basin may be unsuitable for direct drinking purposes due to microbial contamination and elevated turbidity, much of the river water remains usable for irrigation under current conditions.

These findings highlight the importance of differentiating between potable water suitability and irrigation suitability in mining-affected river systems.

5. Conclusion and Recommendations

5.1 Conclusion

This study evaluated the impact of artisanal mining activities on the physicochemical, microbiological, hydrochemical, and irrigation quality characteristics of the Pampana River Basin in Sierra Leone. The integrated assessment revealed clear spatial variations in water quality across upstream, midstream, downstream, and borehole sampling locations, demonstrating the significant influence of mining activities on the river system.

The physicochemical assessment showed that several water quality parameters remained within World Health Organization (WHO) permissible limits; however, elevated turbidity, total dissolved solids, color, and microbial contamination were observed, particularly within the midstream and downstream sections of the river where mining activities are concentrated. These findings indicate substantial sediment mobilization and increasing anthropogenic disturbance associated with artisanal mining operations.

Water Quality Index (WQI) analysis classified upstream and borehole water samples as excellent for drinking purposes, whereas several midstream and downstream samples were classified as unsuitable for potable use due to elevated contamination levels and microbial pollution. The microbial assessment further confirmed the presence of *Escherichia coli*, fecal coliforms, and non-fecal coliforms, highlighting potential public health risks for communities dependent on untreated river water.

Hydrochemical facies analysis revealed sodium (Na^+) and bicarbonate (HCO_3^-) as the dominant ions within the basin, with most samples characterized by sodium-bicarbonate (Na-HCO_3) water types. Gibbs diagram interpretation indicated that rock weathering represents the dominant hydrogeochemical process controlling water chemistry within the basin, while mining activities accelerate sediment-water interactions and ionic mobilization.

Irrigation suitability assessment showed that most river water samples remain generally suitable for agricultural use despite localized salinity and sodicity concerns. Wilcox, USSL, and Permeability Index classifications indicated that most samples fall within acceptable water-quality categories.

Overall, the study demonstrates that uncontrolled artisanal mining activities are contributing significantly to water quality deterioration within the Pampana River Basin. The findings provide important baseline information for environmental monitoring, sustainable water resource management, and the development of regulatory strategies to protect mining-affected river systems in Sierra Leone.

5.2 Recommendations

Based on the findings of this study, the following recommendations are proposed:

1. Continuous water quality monitoring programs should be established within the Pampana River Basin to evaluate long-term environmental changes associated with mining activities.
2. Environmental regulations governing artisanal and small-scale mining activities should be strengthened and effectively enforced to minimize sediment discharge and water contamination.
3. Community education and awareness programs should be implemented to improve public understanding of water pollution risks and promote sustainable environmental practices.
4. Alternative and safer drinking water sources should be developed for communities relying directly on contaminated river water for domestic use.
5. Further studies should investigate seasonal variations, heavy metal accumulation in sediments and aquatic organisms, and long-term ecological impacts associated with mining activities within the basin.

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