

Microbiological Contamination and Its Association with Physicochemical Parameters in Artisanal Gold Mining Areas of Siguiri, Guinea

Aly Badara TOURE

Alymosat@yahoo.fr

Centre d'Excellence Africain pour la Prévention et le Contrôle des Maladies Transmissibles

Mariama Sadjo DIALLO

Centre d'Excellence Africain pour la Prévention et le Contrôle des Maladies Transmissibles

Maladho DIABY

Centre de Recherche et de Formation en Infectiologie de Guinée (CERFIG), Campus Hadja Maforé
Bangoura, Donka

Kadio Jean Jacques Olivier KADIO

Centre de Recherche et de Formation en Infectiologie de Guinée (CERFIG), Campus Hadja Maforé
Bangoura, Donka

Soriba CAMARA

Centre d'Excellence Africain pour la Prévention et le Contrôle des Maladies Transmissibles

Djiba KABA

Centre de Recherche et de Formation en Infectiologie de Guinée (CERFIG), Campus Hadja Maforé
Bangoura, Donka

Saidouba Chérif CAMARA

Centre de Recherche et de Formation en Infectiologie de Guinée (CERFIG), Campus Hadja Maforé
Bangoura, Donka

Sahar TRAORE

Institut de Recherche en Biologie Appliquée de Guinée (IRBAG)

Amadou SYLLA

Laboratoire de l'Office National de Contrôle Qualité

Aboubacar KABA

Laboratoire d'Analyses Environnementales (LAE), Ministère de l'Environnement et du Développement
Durable

Foromo timothée BEAVOGUI

Centre d'Excellence Africain pour la Prévention et le Contrôle des Maladies Transmissibles

Alioune CAMARA

Gamal Abdel Nasser University of Conakry

Abdoulaye TOURE

Centre de Recherche et de Formation en Infectiologie de Guinée (CERFIG), Campus Hadja Maforé
Bangoura, Donka

Sidikiba SIDIBE

Gamal Abdel Nasser University of Conakry

Alexandre DELAMOU

Centre d'Excellence Africain pour la Prévention et le Contrôle des Maladies Transmissibles

Research Article

Keywords: Microbial water quality, fecal contamination, artisanal gold mining, borehole and river water, Guinea

Posted Date: July 17th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10292496/v1>

License:  This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

Background

Water quality degradation in artisanal gold mining areas is a major public health concern because of the co-occurrence of chemical and microbiological contamination. This study assessed the microbiological indicators in borehole and river water from the artisanal mining area of Doko, Siguiri, Guinea.

Methods

An analytical cross-sectional study was conducted on 36 water samples, including 12 borehole and 24 river samples, collected during the dry and rainy seasons in three localities. Five microbiological indicators were enumerated by colony counting on culture media and expressed as colony-forming units per source-specific volume. Comparisons were performed using Mann-Whitney tests and seasonal analyses stratified by source; associations were assessed using Spearman correlations with Benjamini-Hochberg adjustment, followed by exploratory multivariable linear models for total coliforms, fecal coliforms, and total mesophilic flora.

Results

River water was significantly more contaminated than borehole water for all five microbiological indicators (all $p < 0.001$). Total coliforms were non-compliant in 100% of river samples. Turbidity showed the strongest positive associations with microbial contamination (total coliforms: $\rho = 0.81$; total mesophilic flora: $\rho = 0.75$; fecal coliforms: $\rho = 0.66$). In the main exploratory model, river water was associated with approximately 56-fold higher total coliform concentrations than borehole water.

Conclusion

Water sources in the Siguiri mining area showed substantial microbiological contamination, particularly river water. Turbidity may serve as a simple operational warning indicator but should not replace microbiological testing. These findings support integrated water quality monitoring, point-of-use water treatment and improved sanitation around water sources.

Introduction

Access to drinking water free from microbiological contamination is a fundamental prerequisite for public health and human development. Even when a water source has acceptable chemical characteristics, its direct consumption may be unsafe if it carries pathogenic microorganisms, often indicated by fecal indicator bacteria (Bain et al., 2014; Baudart & Paniel, 2014; Sikder et al., 2021; World Health Organization, 2022). Conversely, the apparent clarity of water does not guarantee microbiological

safety, because critical bacterial loads may persist when source-protection barriers or treatment systems are absent or poorly maintained. The WHO emphasizes that drinking-water safety depends on continuous operational monitoring and a preventive risk-management approach, requirements that are difficult to maintain in rural communities with limited resource (World Health Organization, 2022).

Globally, progress toward the Sustainable Development Goals masks persistent geographic and socioeconomic inequalities. The WHO/UNICEF Joint Monitoring Programme shows that a substantial share of the world population still lacks safely managed drinking-water services, forcing many communities to rely on unprotected surface-water sources (Bain et al., 2014; World Health Organization, 2025). This infrastructure deficit contributes to a substantial disease burden. Diarrhoeal diseases and acute enteric infections remain major causes of preventable morbidity and mortality in low- and middle-income countries, disproportionately affecting children under five years of age (GBD 2021 Diarrhoeal Diseases Collaborators, 2025).

This environmental burden is particularly complex in ecosystems affected by artisanal and small-scale gold mining. Although artisanal mining provides an important livelihood for many rural communities, it can severely alter watersheds. Excavation, intensive ore washing, deforestation, and uncontrolled sediment discharge increase soil erosion and the resuspension of particles (Amidu et al., 2026; Nunoo et al., 2022). In parallel, mining areas frequently face limited water, sanitation, and hygiene infrastructure. Inadequate latrine coverage, open defecation, unsafe household water storage, and multiple uses of rivers may create favourable conditions for the introduction and spread of enteric microorganisms (Amidu et al., 2026).

In sub-Saharan Africa, and particularly in West Africa, studies from Ghana and Nigeria have documented severe degradation of surface-water quality near mining sites, where high sediment loads and metal contamination can complicate treatment processes (Akindele et al., 2023; Armah, 2014). In Burkina Faso, water quality index approaches have also confirmed the close overlap of chemical and biological contamination in areas under strong anthropogenic pressure (Nacanabo et al., 2025).

The characterization of these risks relies on bacterial indicators with complementary meanings. Total coliforms indicate general vulnerability of a water source or failure of protection systems, whereas fecal coliforms are operational tracers of intestinal contamination (Bain et al., 2014; Sikder et al., 2021; World Health Organization, 2025). Total mesophilic flora reflects the overall culturable microbial load and the general biological deterioration of the water matrix. Fecal streptococci, or enterococci, can provide information on environmental persistence, whereas sulfite-reducing anaerobes, mainly in spore-forming forms, may indicate old, persistent, or sediment-associated contamination.

The survival, transport, and persistence of these microorganisms are strongly shaped by physicochemical conditions. Turbidity is of particular relevance because suspended particles provide attachment sites, protect bacteria from ultraviolet radiation and disinfectants, and reduce chlorination efficiency (LeChevallier et al., 1981; Shawon et al., 2026; Volf et al., 2025). pH may influence bacterial viability as well as the solubility and speciation of trace metals. In mining environments, heavy metals

derived from mining inputs or geologic leaching can exert selective pressures on microbial communities, raising increasing concern about the co-selection of heavy-metal and antimicrobial resistance in environmental bacteria (Gillieatt & Coleman, 2024; Seiler & Berendonk, 2012; Tchounwou et al., 2012).

Guinea has major gold resources, and Siguiri Prefecture is one of the country's densest artisanal gold mining areas. In the mining localities of Doko, Kodiarani, and Oudoula, communities rely heavily on boreholes and rivers for domestic water needs. Previous work in this area documented concerning concentrations of heavy metals that exceeded WHO guideline values and were associated with elevated non-carcinogenic and carcinogenic health risks, especially among children (Toure et al., 2026). A related knowledge, attitudes, and practices study showed important gaps in risk perception and prevention practices among local communities despite general awareness of environmental pollution (Toure et al., 2025). Although these studies documented chemical and behavioural vulnerabilities in Siguiri, the microbiological quality of the same water resources remains insufficiently characterized.

Addressing this gap is important for designing context-specific environmental health strategies, prioritizing surveillance indicators, and targeting interventions for source protection and household water safety. However, the extent to which microbiological contamination co-occurs with physicochemical degradation in these same water sources remains poorly understood. Identifying simple environmental parameters associated with microbial indicators, such as turbidity, could help prioritize surveillance and prevention measures in resource-limited mining communities. The objective of this study was to assess microbiological contamination of borehole and river water in the artisanal gold mining areas of Siguiri and to examine its associations with key physicochemical parameters in order to identify practical indicators for integrated water quality monitoring.

Materials and Methods

Study area

The study was conducted in the Republic of Guinea, a West African country covering approximately 245,857 km², with a population estimated at more than 17.5 million inhabitants according to the preliminary results of the fourth General Population and Housing Census (Institut National de la Statistique (INS), 2025). Guinea has substantial mineral resources and an economy strongly dependent on the mining sector, which accounts for more than 85% of national exports. Despite this potential, a large share of the population lives in rural areas and relies heavily on natural resources, including water (Guinea-ASGM-NAP, 2021). The study took place in Siguiri Prefecture, located in Upper Guinea, approximately 850 km from Conakry. This region is one of the country's main artisanal gold mining areas, with a high density of mining sites and a long history of gold extraction. The climate is Sudanian-Sahelian, with a long dry season and a shorter rainy season (Cissé, 2019). The study sites included Doko Centre, Oudoula Damafè, and Kodiarani. These sites were selected because of the intensity of artisanal mining activities, the proximity of water sources to mining areas, and the strong dependence of local populations on both surface and groundwater for domestic uses. Previous studies in this area reported

significant heavy-metal contamination of water resources and substantial community exposure to water-pollution risks (Toure et al., 2025, 2026). Making it a relevant setting for assessing the joint microbiological and physicochemical quality of water under strong anthropogenic pressure.

Study design and period

This was a cross-sectional analytical study conducted in the artisanal gold mining area of Siguiri Prefecture, Guinea. Sampling was carried out in 2023 during two seasonal campaigns: the dry season in April and the rainy season in August.

Water sample Collection

Water samples were collected in three mining localities in the Siguiri area: Doko Centre, Kodiarani, and Oudoula Damafè. Two types of water sources were considered: borehole water, representing groundwater used by local populations, and river water, representing surface water exposed to mining and domestic activities. A total of 36 water samples were collected, including 12 borehole samples and 24 river samples, distributed between the dry and rainy seasons.

Samples intended for microbiological analysis were collected in sterile bottles and handled under aseptic conditions. River samples were taken by submerging the bottle to about 50 cm and filling it completely, after pre-rinsing with the source water. Borehole samples were taken only after the tap had been left running for five minutes or more, so that water standing in the pipes was cleared beforehand. Each sample was labelled, stored at 4 °C in coolers protected from light, and transported to the National Office for Quality Control laboratory for analysis.

Sample analyses

Microbiological analyses

Microbiological analyses were performed at the laboratory of the National Office for Quality Control according to its standard procedures for microbiological control of water. The indicators analysed included total aerobic mesophilic flora, total coliforms, fecal or thermotolerant coliforms, fecal streptococci or enterococci, and sulfite-reducing anaerobic bacteria. Fecal coliforms were used as operational indicators of recent fecal contamination, whereas total coliforms were interpreted as indicators of source vulnerability and sanitary integrity rather than as specific evidence of fecal contamination. (International Organization for Standardization., 1999, 2018; Rodger B. Baird et al., 2017).

Total coliforms, fecal coliforms, and fecal streptococci were enumerated by membrane filtration. An appropriate volume of sample, or a decimal dilution when necessary, was filtered through a sterile 0.45 µm membrane. After filtration, the membrane was placed on the surface of the corresponding culture medium and incubated under the conditions specific to each bacterial group. Total coliforms were enumerated on Violet Red Bile Lactose agar after incubation at 37°C for 24 h. Characteristic colonies were counted, and results were expressed as colony-forming units per 100 mL (CFU/100 mL). Fecal

coliforms (thermotolerant) were enumerated on Violet Red Bile Lactose agar after incubation at 44°C for 24 h. Typical colonies were counted, and results were expressed as CFU/100 mL. (International Organization for Standardization., 2006). Fecal streptococci (enterococci) were enumerated on Slanetz and Bartley agar, with direct colony counting on the plate after incubation at 36 +/- 2 C for 44 +/- 4 h, and results were expressed as CFU/100 mL (International Organization for Standardization., 2018; Slanetz & Bartley, 1957). Total mesophilic aerobic flora was enumerated by the pour-plate technique on Plate Count Agar. 1 mL of sample, or an appropriate decimal dilution, was incorporated into the molten medium, incubated at 30 C for 72 h, and the resulting colonies were counted expressed as CFU/mL (International Organization for Standardization., 1999). Sulfite-reducing anaerobic bacteria were enumerated by deep inoculation on Tryptose Sulfite Cycloserine agar. After anaerobic incubation at 37 C for 24 to 48 h, characteristic black colonies were counted expressed as CFU/20 mL, consistent with the liquid-medium enrichment principle for sulfite-reducing clostridia (International Organization for Standardization., 1986).

For samples with high microbial loads, successive decimal dilutions were prepared to obtain plates with colony counts within the countable range, and final concentrations were calculated from the analysed volume and the applied dilution factor.

Physicochemical analyses

Physicochemical parameters were measured to characterize the aquatic environment and to serve as environmental covariates for microbiological indicators. pH, temperature, conductivity, total dissolved solids, and turbidity were measured in situ using a HACH HQ40d multimeter, with daily pH-meter calibration using traceable buffer solutions. Ammonium (NH₄), nitrites (NO₂), nickel (Ni), iron (Fe), copper (Cu), manganese (Mn), cadmium (Cd), mercury (Hg), lead (Pb), and aluminium (Al) were measured by UV-visible spectrophotometry using a 7600 spectrophotometer. The full physicochemical profile and toxicological risk assessment from this campaign have been published previously; in the present article, these parameters are used as explanatory covariates rather than as primary toxicological outcomes (Toure et al., 2026).

Quality control

Quality assurance and quality control procedures were applied during sample collection, transport, and analysis. For microbiological analyses, samples were collected in sterile bottles, handled aseptically, stored cold, and protected from light until arrival at the National Office for Quality Control laboratory. Analyses were conducted using standard laboratory procedures, culture media appropriate for each indicator, and decimal dilutions when the microbial load was high.

For physicochemical analyses, Sampling, cleaning and quality-control procedures for the physicochemical measurements followed those detailed in our earlier report on the same campaign (Toure et al., 2026); briefly, acid-washed glassware was used, instruments were calibrated daily, and analyses were run in triplicate against a certified reference material.

Statistical analysis

Statistical analyses were performed using RStudio version 4.1.2. Quantitative variables were described using medians and interquartile ranges because of asymmetric distributions and the presence of zero values. Borehole and river samples were compared using the Mann-Whitney test. Seasonal comparisons were explored separately by source type to limit confounding between season and source. Differences among localities were assessed using the Kruskal-Wallis test. All statistical tests were two-sided, and a p -value < 0.05 was considered statistically significant. For multiple correlation analyses, p -values were adjusted using the Benjamini-Hochberg false discovery rate procedure.

Three exploratory multivariable linear regression models were then fitted using $\log_{10}(x + 1)$ -transformed concentrations, a main model for total coliforms and two secondary models for fecal coliforms and total mesophilic aerobic flora. Explanatory variables were selected a priori based on environmental relevance and descriptive results. For each model, beta coefficients, 95% confidence intervals, and 10^{β} ratios were reported. The latter enables approximate multiplicative interpretation of changes in microbial concentration on the original scale. Model fit was assessed using R^2 , adjusted R^2 , and the Akaike Information Criterion (AIC) Variance inflation factors were used to assess collinearity. Given the limited sample size ($n = 36$), these models are interpreted as exploratory and hypothesis-generating, rather than confirmatory or causal.

Results

Physicochemical profile of water samples

The physicochemical parameters retained as environmental covariates showed substantial exceedances of WHO guideline values for drinking water (Table 1). Median turbidity reached 40.1 NTU, with a maximum of 627 NTU, and exceeded the 5 NTU guideline value in 63.9% of samples. Among metals, mercury exceeded the guideline value in all samples, as did lead, cadmium, nickel, and manganese. Copper exceeded the 2.0 mg/L guideline value in 55.6% of samples. Median metal concentrations and turbidity were consistently higher in river water than in boreholes.

Table 1

Physicochemical profile of water samples and proportion exceeding WHO guideline values (n = 36)

Parameter	WHO value	Median	Maximum	% > WHO Value
Mercury (Hg)	0.006 mg/L	0.425	2.91	100
Lead (Pb)	0.01 mg/L	0.41	1.77	100
Cadmium (Cd)	0.003 mg/L	0.15	1.18	100
Nickel (Ni)	0.07 mg/L	0.73	6	100
Manganese (Mn)	0.08 mg/L	0.65	13.2	100
Aluminium (Al)	0.2 mg/L	0.3	2.18	75
Turbidity	5 NTU	40.1	627	63.9
Copper (Cu)	2.0 mg/L	2.26	7.42	55.6
Iron (Fe)	0.3 mg/L	0.36	3.5	52.8
Ammonium (NH ₄)	1.5 mg/L	0.35	4.5	25
Nitrites (NO ₂)	3.0 mg/L	0.295	1.88	0
<i>Note. For Fe, Mn, Al, and NH₄, guideline values refer to acceptability or aesthetic values rather than strictly health-based thresholds. The full physicochemical profile and toxicological risk assessment were published previously (Toure et al., 2026).</i>				

Microbiological concentrations by source and season

Microbiological indicator concentrations were higher in river water than in borehole water (Fig. 2; Table 2). In boreholes, total mesophilic aerobic flora had a median of 50 CFU/mL, whereas the other indicators were low or most often undetectable. In river water, median values reached 1100 CFU/mL for total mesophilic aerobic flora, 280 CFU/100 mL for total coliforms, 120 CFU/100 mL for fecal coliforms, 11 CFU/100 mL for fecal streptococci, and 5.5 CFU/20 mL for sulfite-reducing anaerobic bacteria.

Table 2

Microbiological concentrations by source, according to the indicator-specific laboratory unit

Indicator	Borehole	River,	p-value*
	median [IQR]	median [IQR]	
TMF	50 [24–75]	1100 [650–2000]	< 0.001
TC	1 [0–3.5]	280 [111–418]	< 0.001
FC	0 [0–0]	120 [56–505]	< 0.001
FS	0 [0–0]	11 [5–49]	< 0.001
SRA	0 [0–0]	5.5 [0–16]	< 0.001
<i>Note. TMF = total mesophilic aerobic flora (CFU/mL); TC = total coliforms (CFU/100 mL); FC = fecal coliforms (CFU/100 mL); FS = fecal streptococci (CFU/100 mL); SRA = sulfite-reducing anaerobes (CFU/20 mL). * Mann-Whitney test.</i>			

Microbiological positivity and non-compliance

Microbiological non-compliance varied markedly by source type (Table 3). In river water, all samples were non-compliant for total coliforms in both seasons. For fecal coliforms, non-compliance reached 83.3% in the rainy season and 100% in the dry season. In borehole water, non-compliance was less frequent but not negligible: it ranged from 33.3% in the rainy season to 66.7% in the dry season for total coliforms, and from 0% to 33.3% for fecal coliforms.

Table 3

Proportion of non-compliant samples (TC, FC) or positive samples (TMF, FS, SRA) by source and season

Indicator	Type	Borehole	River	Interpretation Criterion
		Rain / Dry	Rain / Dry	
TC	WHO non-compliance	33.3% / 66.7%	100% / 100%	Absence in 100mL
FC	WHO non-compliance	0% / 33.3%	83.3% / 100%	Absence in 100mL
TMF	Positivity	100% / 100%	100% / 100%	Indicator of overall microbial load
FS	Positivity	0% / 0%	83.3% / 66.7%	Complementary indicator of fecal contamination
SRA	Positivity	0% / 0%	66.7% / 66.7%	Indicator of old or persistent contamination
<i>Note. TC and FC were interpreted according to WHO drinking-water criteria; TMF, FS, and SRA were interpreted as indicators of general microbiological deterioration or fecal/anaerobic contamination.</i>				

Comparisons by source, season, and locality

Microbiological concentrations differed significantly between borehole and river water for all five indicators (Mann-Whitney test, all $p < 0.001$). Seasonal effects, assessed separately by source type, were significant only in river water. In rivers, total coliform and fecal coliform concentrations were higher in the dry season than in the rainy season, with p values of 0.005 and < 0.001 , respectively. No significant seasonal difference was observed in borehole water.

The exploratory comparison of the three localities, each represented by 12 samples, did not show significant differences for any of the five microbiological indicators (Kruskal-Wallis test, all $p > 0.12$). These findings suggest that the observed variation was more strongly structured by source type than by sampling locality.

Microbiology physicochemistry correlations

Among 45 Spearman correlations tested, 16 remained significant after Benjamini-Hochberg adjustment (Fig. 3). Turbidity showed the strongest positive associations: total coliforms ($\rho = 0.81$), total mesophilic aerobic flora ($\rho = 0.75$), fecal coliforms ($\rho = 0.66$), fecal streptococci ($\rho = 0.60$), and sulfite-reducing anaerobes ($\rho = 0.52$). Copper was correlated with total coliforms ($\rho = 0.43$) and fecal coliforms ($\rho = 0.40$), and manganese with several indicators. Conductivity and total dissolved solids were negatively correlated with fecal streptococci ($\rho = -0.57$ and -0.58 , respectively). pH was not significantly correlated with any indicator after adjustment.

Exploratory multivariable models

The three $\log_{10}(x + 1)$ models, all with variance inflation factors below 1.9, are presented as exploratory. In the main total coliform model (Fig. 4; $R^2 = 0.908$), source type was the dominant factor ($\beta = 1.75$; $10^\beta = 55.9$; 95% CI 1.46–2.04). Dry season ($10^\beta = 3.14$), turbidity ($p = 0.020$), and copper ($10^\beta = 1.40$; $p = 0.004$) were positively associated with total coliforms, whereas mercury was negatively associated ($10^\beta = 0.57$; $p = 0.034$), without causal inference.

Comparison of the three models (Fig. 4) showed the consistency of the source effect, with 95% confidence intervals excluding zero in all three models (TC $10^\beta = 55.9$; FC 41.3; TMF 14.3), as well as the role of turbidity. Dry season was significant only for total and fecal coliforms, whereas pH was significant only for fecal coliforms ($\beta = -0.36$; $p = 0.008$).

Discussion

This study assessed the microbiological quality of borehole and river water in three artisanal gold mining localities of Siguiri and examined its relationship with physicochemical parameters measured in the same samples. The main finding was a clear contrast between water sources, with river water showing consistently higher microbiological contamination than borehole water. The exploratory multivariable

models mainly confirmed the importance of source type, whereas associations with season, pH, copper, and mercury should be interpreted cautiously because of the limited sample size.

The higher contamination of river water is consistent with the vulnerability of surface waters in artisanal mining areas. Rivers are directly exposed to runoff, domestic discharges, ore washing, sediment resuspension, bank erosion, and multiple community uses. Boreholes are relatively protected by soil filtration and partial separation from surface inputs, but they were not fully exempt from contamination. The detection of total coliforms and, less frequently, fecal coliforms in some borehole samples may indicate poor construction, inadequate sealing, insufficient drainage around water points, or infiltration during runoff events (Guy Howard & Jamie Bartram, 2003; Sikder et al., 2021).

This pattern is consistent with evidence from neighbouring West African settings. In Mali, water bodies affected by artisanal gold mining in the Sikasso region showed heavy metal concentrations exceeding WHO guideline values (Keita et al., 2018). In Burkina Faso, borehole water in Ouagadougou showed substantial microbiological non-compliance, including total coliforms and *Escherichia coli* (Traoré et al., 2023), while mining-affected areas in northern Burkina Faso showed mercury and arsenic contamination around gold mining sites (Dabiré & Sako, 2024). Evidence from Ghana and Nigeria also indicates that mining activities can impair both physicochemical and biological water quality in surface and groundwater resources (Akindele et al., 2023; Amidu et al., 2026; Armah, 2014; Bello et al., 2023). These comparisons suggest that the situation observed in Siguiri reflects a broader vulnerability of water resources in West African artisanal gold mining areas, while remaining strongly shaped by local hydrology, sanitation, and mining practices.

The detection of fecal or thermotolerant coliforms is the most relevant public health signal. WHO guidance is based on the principle that fecal indicators should be absent in 100 mL of drinking water (World Health Organization, 2022, 2023). In this study, all river samples were non-compliant for total coliforms in both seasons, and fecal coliform non-compliance reached 83.3% in the rainy season and 100% in the dry season. These results do not identify specific pathogens, but they indicate intestinal contamination compatible with infectious risk if water is consumed without treatment. Total coliforms should be interpreted mainly as indicators of source vulnerability or sanitary integrity failure, whereas fecal coliforms and *E. coli* remain more directly informative for drinking-water microbiological safety (Odonkor & Ampofo, 2013; Sikder et al., 2021).

The other microbiological indicators provided complementary information. Total mesophilic aerobic flora, detected in all samples, reflected the overall culturable bacterial load rather than specific fecal contamination. Fecal streptococci and sulfite-reducing anaerobes, mainly detected in river water, suggested persistent or sediment-associated contamination. These indicators should not be interpreted as strict drinking-water compliance criteria, but they support the evidence of general microbiological deterioration in river water.

The seasonal pattern requires cautious interpretation. Although rainfall often increases microbial contamination through runoff, total and fecal coliform concentrations were higher in river water during

the dry season. This may reflect reduced river flow, lower dilution, and concentration of microorganisms in smaller water volumes. Conversely, rainfall may increase microbial inputs while diluting measured concentrations at the time of sampling. Similar complexities have been reported where rainfall, runoff, flow, and temperature interact to shape microbial loads (Engloner & Németh, 2025; Kistemann et al., 2002). This microbiological pattern differs from the metal dynamics previously reported in Siguiri, where some risk indices were more marked during the rainy season (Toure et al., 2026).

Turbidity was the physicochemical parameter most strongly associated with microbiological indicators, with Spearman coefficients ranging from 0.52 to 0.81. This association is biologically plausible because suspended particles can provide attachment surfaces for bacteria, enhance persistence, and reduce disinfection efficiency (LeChevallier et al., 1981). In artisanal mining areas, turbidity is driven by soil disturbance, ore washing, sediment resuspension, bank erosion, and runoff. It may therefore serve as a simple and inexpensive warning indicator for water-quality surveillance in resource-limited settings, although it cannot replace microbiological testing.

Associations with pH, copper, and mercury should be interpreted as exploratory. The negative association between pH and fecal coliforms may reflect local physicochemical conditions affecting bacterial survival, but it cannot be generalized from 36 samples. The positive association between copper and coliforms probably reflects spatial co-occurrence of mining inputs, domestic discharges, sediments, metals, and bacteria. Conversely, the negative association with mercury should not be interpreted as a protective effect. Heavy metals can exert selective pressure on microbial communities, and co-selection between metal resistance and antimicrobial resistance has been described (Gillieatt & Coleman, 2024; Seiler & Berendonk, 2012). However, this study did not assess bacterial species, resistance genes, or metal tolerance profiles.

These findings complement earlier work in Siguiri. The physicochemical study conducted in the same area documented major exceedances of guideline values for several metals and elevated health risk indices, particularly for children through ingestion (Toure et al., 2026). The knowledge, attitudes, and practices survey also found gaps in risk perception and prevention practices among populations living in artisanal mining areas (Toure et al., 2025). Together, these findings indicate that water safety in this setting requires responses combining environmental monitoring, source protection, water treatment, sanitation, and community risk communication.

The operational implications are therefore direct. Surveillance in artisanal mining areas should combine simple microbiological indicators, especially fecal coliforms or *E. coli*, with easily measurable physicochemical parameters such as turbidity. Technical responses should also account for co-contamination: chlorination may be less effective when turbidity is high, while basic filtration may not remove dissolved metals. More realistic strategies should combine clarification, filtration, point-of-use disinfection, physical protection of water sources, improved sanitation around water points, and community-oriented risk communication (Mwabi et al., 2012).

This study has several strengths, including the analysis of microbiological and physicochemical parameters in the same samples, the comparison of water sources used by local populations, and the inclusion of two seasons in a poorly documented Guinean mining area. However, limitations must be acknowledged. The small sample size reduced statistical power and limited the number of covariates included in the models. The cross-sectional design over a single year did not capture interannual variability. The absence of bacterial species identification, enteric pathogen testing, and resistance profiling limited interpretation of infectious risk. Finally, the multivariable models should be considered exploratory rather than confirmatory or causal. Future longitudinal studies including more sites, hydrological data, pathogen identification, and resistance-gene analysis would help clarify contamination mechanisms and interactions between microbiological and metallic pollution

Conclusion

This study shows substantial microbiological contamination of water resources in the artisanal gold mining area of Siguiri, particularly in river water, where non-compliance with drinking-water microbiological criteria was widespread. Boreholes appeared comparatively less contaminated but were not systematically free from microbial indicators, highlighting the need for source protection and routine surveillance. Source type and turbidity were the main factors associated with microbial contamination, whereas associations with pH and metals should be interpreted as exploratory.

These findings indicate that water safety in artisanal mining communities cannot rely only on the apparent clarity of water or on the type of source used. Integrated water-quality monitoring should combine fecal indicators with simple physicochemical parameters, especially turbidity, to better identify sources at risk. Practical interventions should prioritize protection of water points, reduction of direct contamination around rivers and boreholes, point-of-use water treatment, improved sanitation around water sources, and community risk communication. In mining-affected areas where microbiological and chemical hazards may coexist, prevention strategies should account for co-contamination, since chlorination may be less effective when turbidity is high and simple filtration may not remove dissolved metals.

Further longitudinal studies integrating hydrological monitoring, pathogen identification, and antimicrobial-resistance profiling would help clarify contamination pathways and better characterize health risks in mining-affected communities.

Declarations

Competing interests

The authors declare that they have no financial or non-financial competing interests related to this work.

Ethics approval

No human participants were directly involved in this study; only environmental water samples were collected. Therefore, ethics approval was not required. All sampling procedures complied with national environmental regulations.

Consent to participate

Not applicable. This study did not involve human participants.

Consent for publication

Not applicable. This study did not use individual personal data.

Clinical trial number

Not applicable.

Ethical responsibilities statement

All authors have read, understood, and have complied as applicable with the statement on “Ethical responsibilities of Authors” as found in the Instructions for Authors

AI Declaration

AI was used to support language editing, formatting, and improvement of manuscript readability. All scientific content, data interpretation, methodological descriptions, references, and conclusions were critically reviewed, verified, and validated by the authors, who take full responsibility for the final manuscript.

Funding

The French National Research Institute for Sustainable Development (IRD), through the West African Network of Infectious Diseases Centers of Excellence (WANIDA), funded sample collection and analysis.

Author Contribution

ABT, MSD, SS, and AD conceived the study and developed the protocol. ABT, SS, AC, AT and AD designed the analysis plan. ABT, MSD, DK, ST, AS, and AK performed the laboratory analyses. ABT, MD, SC, and KJJOK analyzed the data and interpreted the results. ABT drafted the manuscript, FTB, SCC, MD and KJJOK critically revised and approved the final manuscript. All authors read and approved the final version.

Acknowledgement

The authors thank the French National Research Institute for Sustainable Development (IRD), through the West African Network of Infectious Diseases Centers of Excellence (WANIDA), for financial support for data collection as part of this doctoral research. They also thank Gamal Abdel Nasser University of Conakry (UGANC), Guinea, and the African Center of Excellence for the Prevention and Control of Communicable Diseases (CEA-PCMT) for academic supervision and institutional support.

Data Availability

The raw data supporting the findings of this study will be made available by the corresponding author upon reasonable request.

References

1. Akindele, E. O., Oladeji, T. A., Kowobari, E. D., Adedapo, A. M., Fagbohun, I. R., Akinpelu, O. T., & Oyeku, O. G. (2023). Gold mining impairs the biological water quality of a culturally important river and UNESCO World Heritage Site in Nigeria. *Environmental Pollution (Barking, Essex: 1987)*, 326, 121470. <https://doi.org/10.1016/j.envpol.2023.121470>
2. Amidu, H. nnan, E., Kiti, J., & Tahiru, A. S. (2026). Water pollution and treatment challenges from artisanal gold mining in Ghana: A decade review (2014–2024). *Scientific African*, 32, e03413. <https://doi.org/10.1016/j.sciaf.2026.e03413>
3. Armah, F. A. (2014). Relationship Between Coliform Bacteria and Water Chemistry in Groundwater Within Gold Mining Environments in Ghana. *Water Quality, Exposure and Health*, 5(4), 183–195. <https://doi.org/10.1007/s12403-014-0110-1>
4. Bain, R., Cronk, R., Hossain, R., Bonjour, S., Onda, K., Wright, J., Yang, H., Slaymaker, T., Hunter, P., Prüss-Ustün, A., & Bartram, J. (2014). Global assessment of exposure to faecal contamination through drinking water based on a systematic review. *Tropical Medicine & International Health: TM & IH*, 19(8), 917–927. <https://doi.org/10.1111/tmi.12334>
5. Baudart, J., & Paniel, N. (2014). Sources et devenir des micro-organismes pathogènes dans les environnements aquatiques. *Revue Francophone Des Laboratoires*, 2014(459), 29–39. [https://doi.org/10.1016/S1773-035X\(14\)72362-7](https://doi.org/10.1016/S1773-035X(14)72362-7)
6. Bello, O. O., Akinpeloye, B. O., Bello, T. K., Oluwafemi, Y. D., & Osungbemiro, B. W. (2023). Evaluation of the physicochemical properties and bacterial loads of selected rivers in Ondo State, Nigeria. *Iranian Journal of Microbiology*, 15(6), 788–795. <https://doi.org/10.18502/ijm.v15i6.14159>
7. Cissé, F. B. (2019). *Étude des impacts de l'exploitation artisanale de l'or en république de Guinée (cas de la préfecture de Siguiro)*. <http://archipel.uqam.ca/id/eprint/12475>. Accessed November 10, 2023
8. Dabiré, B. A. M., & Sako, A. (2024). Comprehensive assessment of heavy metal pollution of agricultural soils impacted by the Kalsaka abandoned gold mine and artisanal gold mining in

- northern Burkina Faso. *Environmental Monitoring and Assessment*, 196(8), 755.
<https://doi.org/10.1007/s10661-024-12894-7>
9. Engloner, A. I., & Németh, K. (2025). Exploring the combined effects of water temperature and flow on river water quality: Problems with highly variable data sets and possible solutions. *Heliyon*, 11(17), e44193. <https://doi.org/10.1016/j.heliyon.2025.e44193>
 10. GBD 2021 Diarrhoeal Diseases Collaborators. (2025). Global, regional, and national age-sex-specific burden of diarrhoeal diseases, their risk factors, and aetiologies, 1990–2021, for 204 countries and territories: A systematic analysis for the Global Burden of Disease Study 2021. *The Lancet. Infectious Diseases*, 25(5), 519–536. [https://doi.org/10.1016/S1473-3099\(24\)00691-1](https://doi.org/10.1016/S1473-3099(24)00691-1)
 11. Gillieatt, B. F., & Coleman, N. V. (2024). Unravelling the mechanisms of antibiotic and heavy metal resistance co-selection in environmental bacteria. *FEMS Microbiology Reviews*, 48(4), fuae017. <https://doi.org/10.1093/femsre/fuae017>
 12. Guinea-ASGM-NAP. (2021). *Plan d'Action National Pour l'Extraction Minière Artisanale et A Petite Echelle de l'Or (EMAPE) FR.pdf*.
https://www.mercuryconvention.org/sites/default/files/documents/national_action_plan/Guinea-ASGM-NAP-2021-FR.pdf. Accessed September 15, 2024
 13. Guy Howard, & Jamie Bartram. (2003). *Domestic water quantity, service level and health*.
<https://iris.who.int/items/c04d458a-6574-4a12-9196-7b76257b04b2>. Accessed January 15, 2026.
 14. Institut National de la Statistique (INS). (2025). *Recensement Général de la population et de l'habitation (RGPH 4)*. https://www.stat-guinee.org/images/Documents/Publications/INS/rapports_enquetes/RGPH-4/Resultats_preliminaires_rgph_4.pdf. Accessed May 10, 2026
 15. International Organization for Standardization. (1986). *ISO 6461-2:1986. Water quality. Detection and enumeration of the spores of sulfite-reducing anaerobes (clostridia). Part 2: Method by membrane filtration*. Geneva : ISO; ISO. <https://www.iso.org/standard/12818.html>
 16. International Organization for Standardization. (1999). *ISO 6222:1999. Water quality. Enumeration of culturable micro-organisms. Colony count by inoculation in a nutrient agar culture medium*. Geneva: ISO; ISO. <https://www.iso.org/standard/28960.html> Accessed May 10, 2026
 17. International Organization for Standardization. (2006). *ISO 4832:2006, Microbiology of food and animal feeding stuffs. Horizontal method for the enumeration of coliforms—Colony-count technique*. https://www.iso.org/obp/ui/fr/?__cf_chl_f_tk=XMYzdxcgE_N1elb_kyD27IC9KM4rpcylZPTDkpVQts-1783427075-1.0.1.1-vxPLY3geREGSykKq2Lv4vmeqE917K3BS7Ywzi9fWCis#iso:std:iso:4832:ed-3:v1:en. Accessed May 10, 2026
 18. International Organization for Standardization. (2018). *ISO 8199:2018. Water quality. General requirements and guidance for microbiological examinations by culture*. ISO. <https://www.iso.org/standard/64151.html>. Accessed May 10, 2026
 19. Keita, M. M., Ogendi, G. M., Owuor, O., & Nyamao, W. N. (2018). Impacts of Artisanal Gold Mining on Water Quality: A Case Study of Tangandougou Commune in Sikasso Region, Mali. *Journal of*

20. Kistemann, T., Classen, T., Koch, C., Dangendorf, F., Fischeder, R., Gebel, J., Vacata, V., & Exner, M. (2002). Microbial load of drinking water reservoir tributaries during extreme rainfall and runoff. *Applied and Environmental Microbiology*, 68(5), 2188–2197. <https://doi.org/10.1128/AEM.68.5.2188-2197.2002>
21. LeChevallier, M. W., Evans, T. M., & Seidler, R. J. (1981). Effect of turbidity on chlorination efficiency and bacterial persistence in drinking water. *Applied and Environmental Microbiology*, 42(1), 159–167. <https://doi.org/10.1128/aem.42.1.159-167.1981>
22. Mwabi, J. K., Mamba, B. B., & Momba, M. N. B. (2012). Removal of *Escherichia coli* and faecal coliforms from surface water and groundwater by household water treatment devices/systems: A sustainable solution for improving water quality in rural communities of the Southern African development community region. *International Journal of Environmental Research and Public Health*, 9(1), 139–170. <https://doi.org/10.3390/ijerph9010139>
23. Nacanabo, S. A., Koussoube, Y., Hama, N. A., Ammami, M. T., & Ouahbi, T. (2025). A Novel Water Quality Index (Novel WQI) for the Assessment of Water Body Pollution in a Semi-Arid Gold Mining Area (Bam Province, Burkina Faso). *Hydrology*, 12(11), 290. <https://doi.org/10.3390/hydrology12110290>
24. Nunoo, S., Manu, J., Owusu-Akyaw, F. K. B., & Nyame, F. K. (2022). Impact of artisanal small-scale (gold and diamond) mining activities on the Offin, Oda and Pra rivers in Southern Ghana, West Africa: A scientific response to public concern. *Heliyon*, 8(12), e12323. <https://doi.org/10.1016/j.heliyon.2022.e12323>
25. Odonkor, S. T., & Ampofo, J. K. (2013). *Escherichia coli* as An Indicator of Bacteriological Quality of Water: An Overview. *Microbiology Research*, 4(1), e2. <https://doi.org/10.4081/mr.2013.e2>
26. Rodger B. Baird, Eugene W. Rice, & Steven Posavec. (2017). *Standard Methods For The Examination Of Water And Wastewater 23th-Amer Public Healt.pdf*. Slideshare. <https://www.slideshare.net/slideshow/standard-methods-for-the-examination-of-water-and-wastewater-rodger-b-baird-eugene-w-rice-and-steven-posavec-standard-methods-for-the-examination-of-water-and-wastewater-23thamer-public-healtpdf/258384659>. Accessed July 1, 2026
27. Seiler, C., & Berendonk, T. U. (2012). Heavy metal driven co-selection of antibiotic resistance in soil and water bodies impacted by agriculture and aquaculture. *Frontiers in Microbiology*, 3, 399. <https://doi.org/10.3389/fmicb.2012.00399>
28. Shawon, H. H., Bhuiya, M. S. K., Kee, T., Hossan, M. S., Hasan, M. J., Nafi, W. H., Hossain, A.-N., & Uddin, M. N. (2026). Predicting Seasonal Variations in River Water Quality: An Artificial Intelligence (AI) Approach Integrating Physicochemical Parameters. *Sustainability*, 18(4), 1746. <https://doi.org/10.3390/su18041746>
29. Sikder, M., Naumova, E. N., Ogudipe, A. O., Gomez, M., & Lantagne, D. (2021). Fecal Indicator Bacteria Data to Characterize Drinking Water Quality in Low-Resource Settings: Summary of Current

- Practices and Recommendations for Improving Validity. *International Journal of Environmental Research and Public Health*, 18(5), 2353. <https://doi.org/10.3390/ijerph18052353>
30. Slanetz, L. W., & Bartley, C. H. (1957). Numbers of enterococci in water, sewage, and feces determined by the membrane filter technique with an improved medium. *Journal of Bacteriology*, 74(5), 591–595. <https://doi.org/10.1128/jb.74.5.591-595.1957>
31. Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy metal toxicity and the environment. *Experientia Supplementum* (2012), 101, 133–164. https://doi.org/10.1007/978-3-7643-8340-4_6
32. Toure, A. B., Diallo, M. S., Sidibe, S., Bangoura, S. T., Grovogui, F. M., Diaby, M., Bangoura, M. A., Youla, Y., Kourouma, M., & Delamou, A. (2025). Knowledge, attitudes, and practices of people living in artisanal mining areas on water pollution in Siguiri, Guinea, 2023. *Frontiers in Public Health*, 13. <https://doi.org/10.3389/fpubh.2025.1482032>
33. Toure, A. B., Hounmenou, C. G., Nabe, A. B., Sylla, Y., Bongono, E. F., Sylla, A., Kaba, A., Dabre, D., Traore, S., Diallo, M. S., Sidibe, S., & Delamou, A. (2026). Assessment of physico-chemical water parameters and health risk characterization in the mining areas of Siguiri, Guinea. *Discover Public Health*, 23(1), 136. <https://doi.org/10.1186/s12982-026-01400-8>
34. Traoré, O., Kpoda, D. S., Dembélé, R., Saba, C. K. S., Cairns, J., Barro, N., & Haukka, K. (2023). Microbiological and Physicochemical Quality of Groundwater and Risk Factors for Its Pollution in Ouagadougou, Burkina Faso. *Water*, 15(21), 3734. <https://doi.org/10.3390/w15213734>
35. Volf, G., Sušanĳ Čule, I., Atanasova, N., Zorko, S., & Ožanić, N. (2025). Explaining and Predicting Microbiological Water Quality for Sustainable Management of Drinking Water Treatment Facilities. *Sustainability*, 17(15), 6659. <https://doi.org/10.3390/su17156659>
36. World Health Organization. (2022). *Guidelines for drinking-water quality: Fourth edition incorporating the first and second addenda*. <https://www.who.int/publications/i/item/9789240045064>. Accessed September 15, 2024
37. World Health Organization. (2023). *Drinking-water*. <https://www.who.int/news-room/fact-sheets/detail/drinking-water>. Accessed September 15, 2024
38. World Health Organization. (2025). *Progress on household drinking-water, sanitation and hygiene 2000–2024: Special focus on inequalities*. <https://www.who.int/publications/m/item/progress-on-household-drinking-water-sanitation-and-hygiene-2000-2024-special-focus-on-inequalities>. Accessed September 15, 2024

Figures

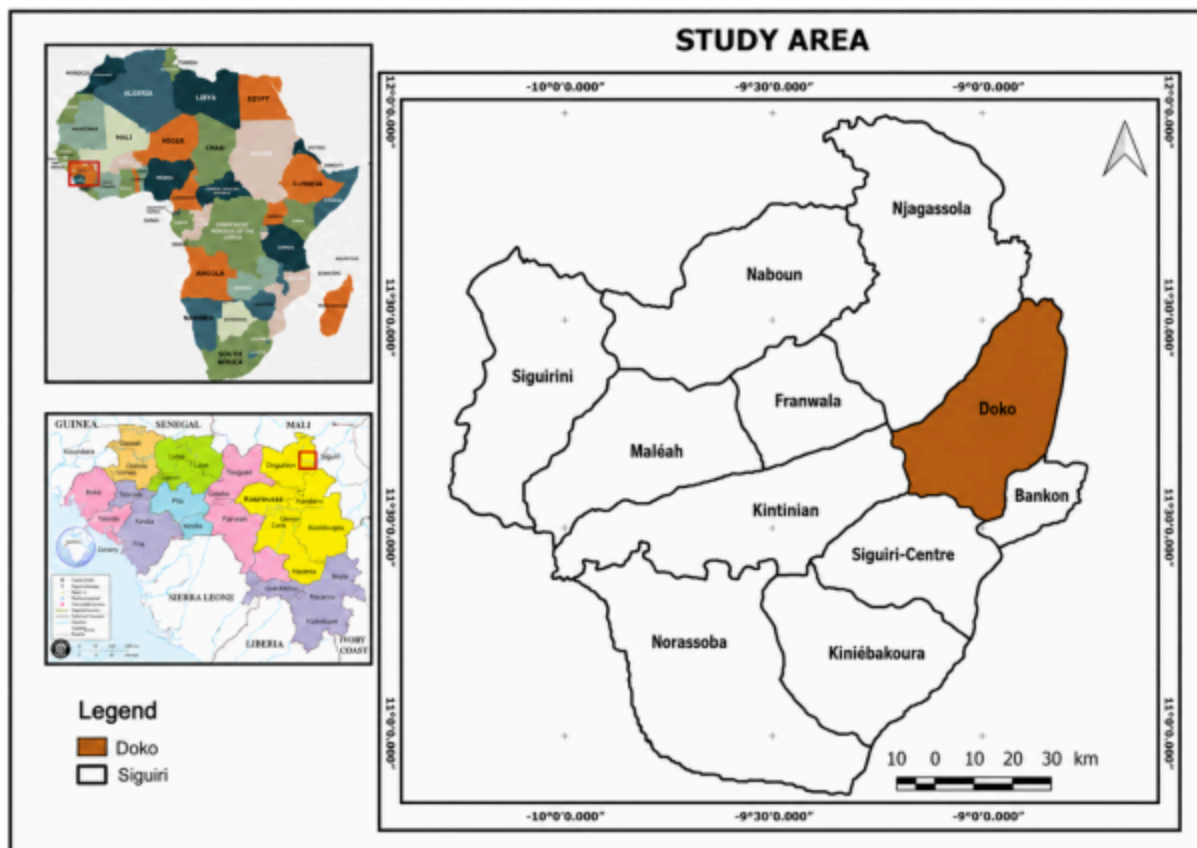


Figure 1

Map of the Siguiri study area in Guinea

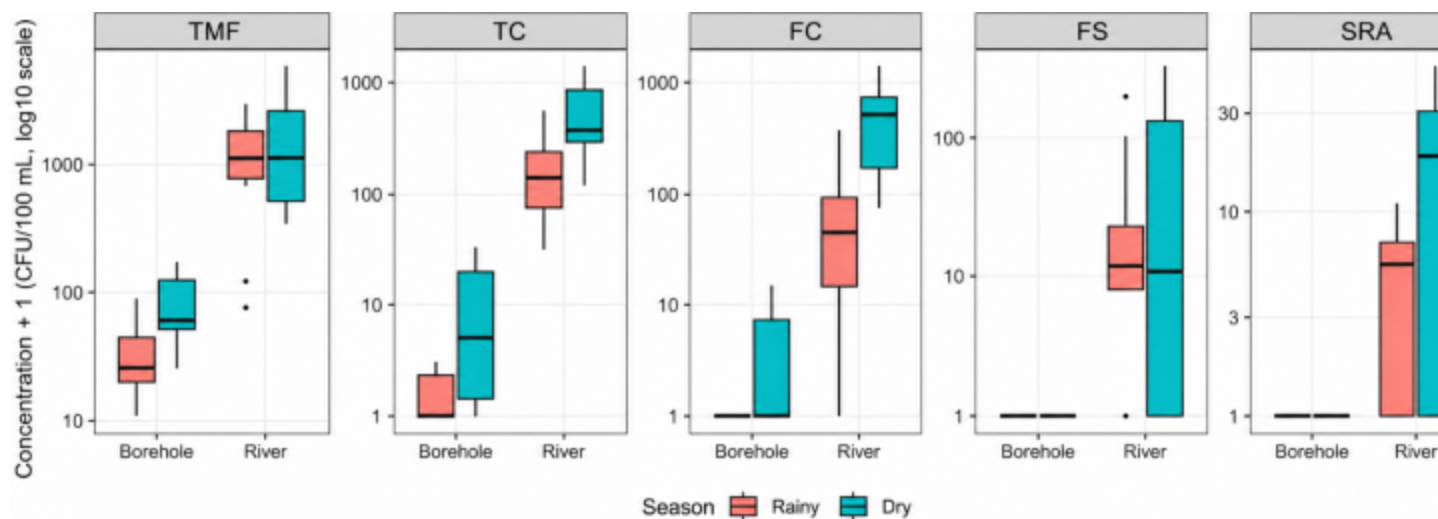


Figure 2

Distribution of microbiological indicators by source and season on a log10-transformed scale.

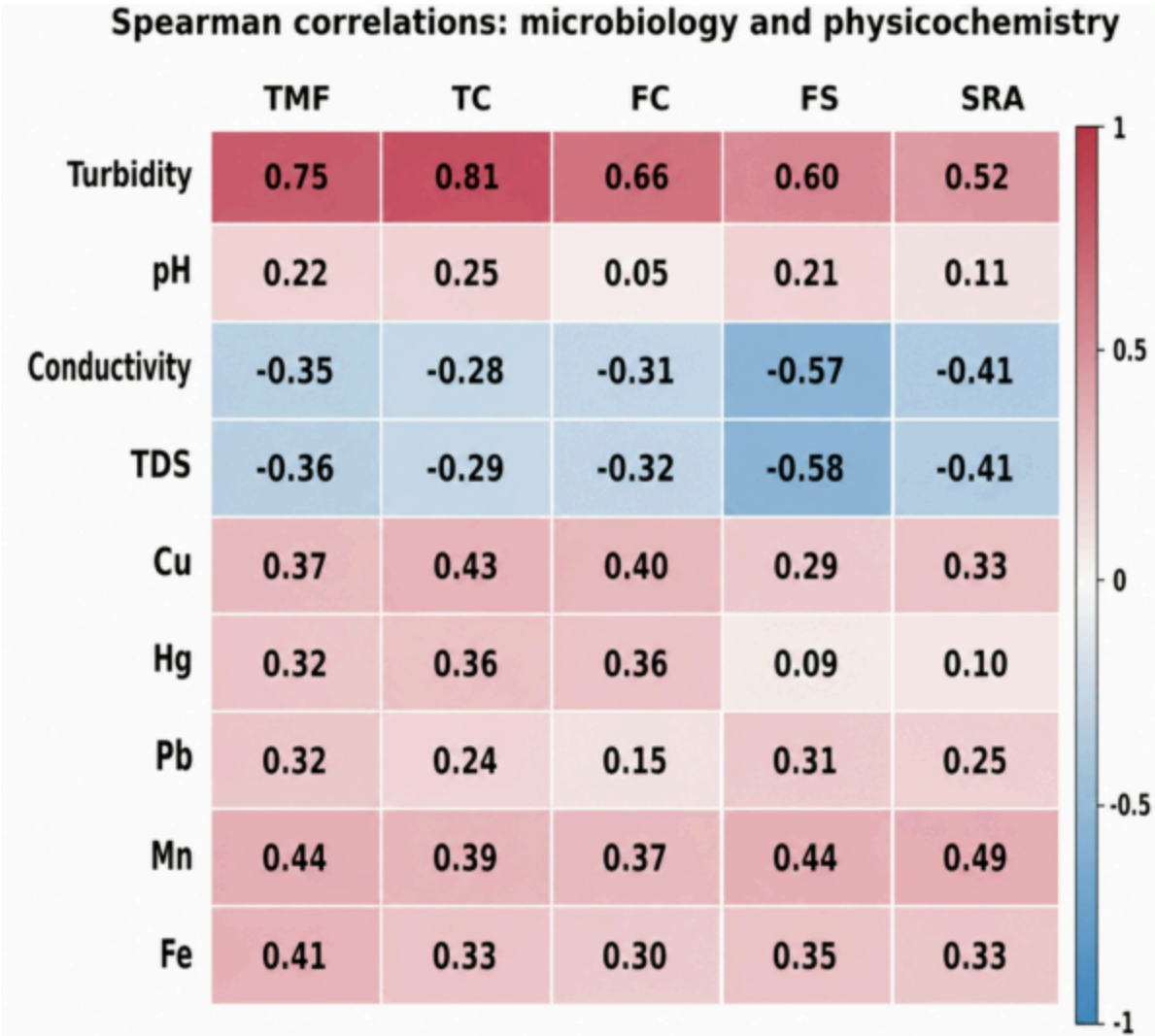


Figure 3

Spearman correlation heatmap between microbiological indicators and physicochemical parameters

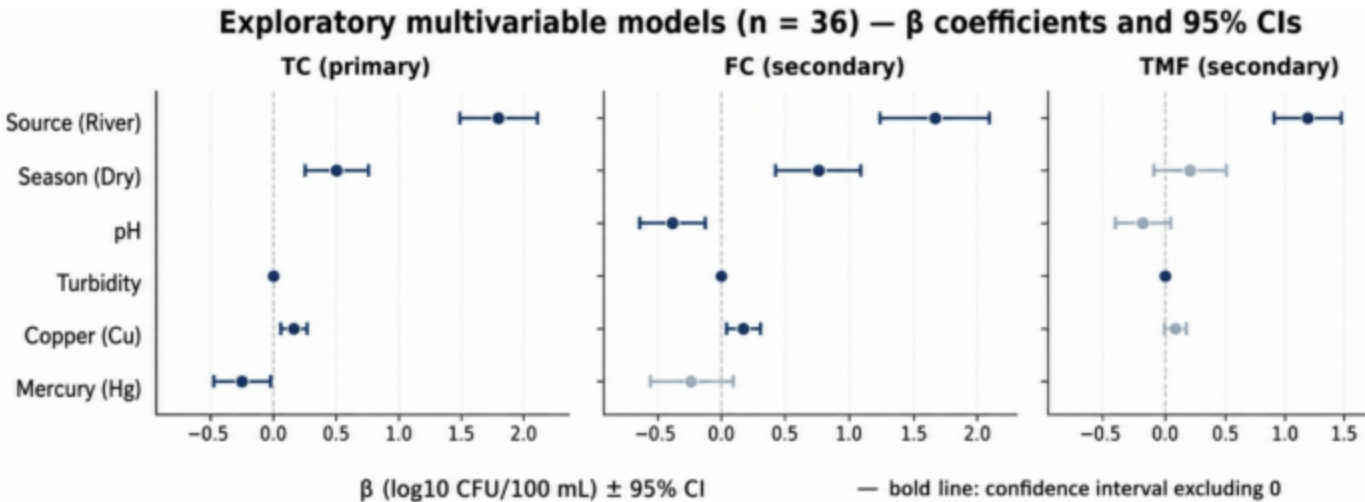


Figure 4

Combined forest plot of the three exploratory multivariable models (TC, FC, TMF): beta coefficients and 95% confidence intervals for $\log_{10}(\text{concentration} + 1)$