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Integrated Pollution Index and Quantitative Microbial Risk Assessment of 2021–2023 Surface Water Quality in The Kapuas River, Sanggau Regency, Indonesia

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ABSTRACT

The Kapuas River is the main source of water for the community in Sanggau Regency, West Kalimantan; however, increasing anthropogenic pressure has raised concerns about water quality and public health risks. This study integrated the Exceedance Ratio (ER), Pollution Index (PI), and Quantitative Microbiological Risk Assessment (QMRA) to evaluate surface water quality from 2021 to 2023 at four monitoring locations. Based on Class I standards, parameters that did not meet standards included iron (Fe) (ER = 4.00; 82% exceeded the limit), COD (ER = 2.37; 91%), BOD (ER = 2.10; 81%), and fecal coliforms (ER = 2.50; 82%). The PI values ranged from 2.16 to 5.07, classifying the rivers as lightly to moderately polluted, with a significant increase in 2023 (mean PI = 3.75 ± 0.82; $p = 0.015$). Although the Class II standards were nearly met, the QMRA indicated that the annual infection risk exceeded the WHO threshold (10^{-4} per person per year) at all locations. The exceedance factor (EF) in 2021–2022 ranged from 2.9–4.5 (adults) and 7.7–12 (children), increasing sharply in 2023 to 120 (adults) and 310 (children) at the water quality monitoring sites. These findings reveal a critical gap between regulation and health, highlighting the urgent need to strengthen sanitation management and health-based monitoring to support sustainable river governance and achieve Sustainable Development Goal (SDG) 6.

Introduction

The Kapuas River, with a total length of approximately 1,986 km, represents the most extensive fluvial system within the Indonesian territory and maintains a significant influence over the environmental, socioeconomic, and spatial frameworks in West Kalimantan. Residents in the vicinity of the Kapuas River in Sanggau Regency rely on it as their main source of water. Many economically disadvantaged households, especially those located in unregulated residential zones, utilize the river to fulfil routine domestic needs such as personal hygiene, laundering, and defecation in the open, primarily attributed to the deficiency of adequate sanitation infrastructure [1].

Despite its vital role in the region, the Kapuas River is increasingly strained by pollution resulting from human activities such as expanding settlements, agricultural runoff, and mining operations. These practices contribute to the accumulation of harmful substances, including heavy metals, which degrade water quality and pose significant health risks to nearby communities [2,3]. The 2024 Community-Based Total Sanitation

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Report highlights that more than 15,690 households in Sanggau still defecate in open areas and that there are slum areas and settlements on the banks of the Kapuas River covering an area of 53.68 hectares with a population of 4,611 [4,5]. This combination of unsafe water use and inadequate sanitation greatly raises the chances of disease spread and long-term health problems, especially among children and other vulnerable groups [6–11].

Water used for domestic activities, including bathing, washing, and routine hygiene practices, must meet established quality parameters to ensure safety for human health. These parameters include chemical and microbiological aspects, such as heavy metal concentrations, toxic chemicals, and the presence of pathogenic microorganisms [12]. Previous studies on river water quality in Indonesia have predominantly addressed physicochemical parameters or heavy metal contamination in isolation and have generally applied national water quality standards without explicitly linking pollution status to public health risks [13–15]. Furthermore, the interaction between river pollution, land-use patterns, and community water-use behaviour, particularly in informal settlements with limited access to safe water and sanitation, remains inadequately examined [16,17]. To fill this gap, this study employs an interdisciplinary framework integrating laboratory-based water quality analysis of the Kapuas River, Pollution Index (PI) assessment, land-use analysis, and sanitation risk evaluation based on environmental health standards for hygiene and sanitation water [3].

Many river water quality studies rely on composite indices such as the Water Quality Index (WQI) or PI to evaluate regulatory compliance and ecological condition [6,18–22]. However, these approaches rarely translate contamination levels into quantitative public health risk estimates. Conversely, applications of Quantitative Microbial Risk Assessment (QMRA) have primarily focused on recreational or drinking water systems without integrating pollution index–based regulatory assessment within a unified analytical framework [23–27]. In tropical river systems influenced by informal settlements and inadequate sanitation, multi-year integration of pollution indexing, exceedance analysis, and age-specific probabilistic infection modelling remains limited. To our knowledge, no previous study in the Kapuas River basin has combined longitudinal pollution evaluation with QMRA-based annual infection risk estimation, highlighting the need for a comprehensive and policy-relevant assessment linking surface water contamination to human health risk. The research conceptual framework is presented in Figure 1.

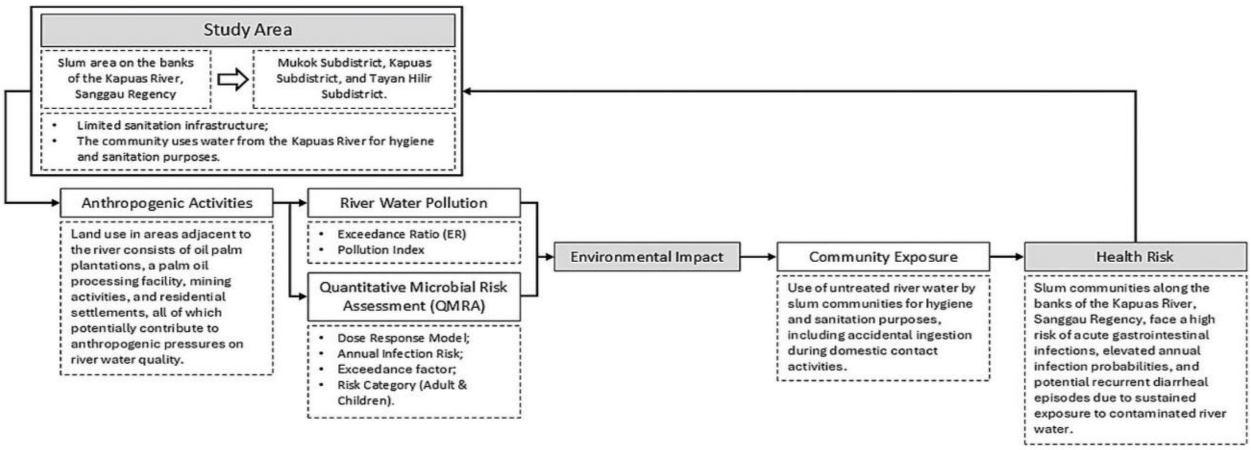

Figure 1. Research conceptual framework. This figure illustrates the research framework, beginning with the identification of anthropogenic pressures around the Kapuas River, including oil palm plantations, mining activities, and residential settlements that may contribute to water contamination. Pollution levels were assessed using the Pollution Index (PI), Exceedance Ratio (ER), and Quantitative Microbial Risk Assessment (QMRA) to evaluate potential microbial health risks. This framework highlights the linkage between human activities, river water degradation, community exposure, and potential public health risks along the Kapuas River.

Materials and Methods

Study Area and Monitoring Sites

This study was conducted in three subdistricts in Sanggau Regency, West Kalimantan, which are crossed by the Kapuas River. The locations for monitoring river water quality were selected based on their proximity to residential areas without access to adequate sanitation facilities. In these locations, the community directly relies on untreated river water for hygiene activities such as bathing, washing, and open defecation. The coordinates of the monitoring locations are described in detail in Table 1.

Table 1. Coordinates of river water quality monitoring location in Sanggau Regency, West Kalimantan, Indonesia. This presents the river water quality monitoring locations in Sanggau Regency, West Kalimantan. Four sampling sites were selected to represent the upstream, middle, and downstream sections of the Kapuas River: Semuntai Bridge (MK1), Sanggau Water Supply Intake (KP1), Tayan Palace Mosque (TY1), and Al Ikhlas Mosque (TY2).

Sub district	Monitoring locations	Monitoring code	Coordinates		River width (m)	Information
			Latitude	Longitude		
Mukok	Semuntai Bridge	MK1	0.06918289	110.7360667	880	Upstream
Kapuas	Sanggau Water Supply Intake	KP1	0.036267062	110.1113919	870	Middle Stream
Tayan Hilir	Tayan Palace Mosque	TY1	0.1271979	110.6094508	1,440	Downstream
	Al Ikhlas Mosque	TY2	0.040426417	110.1286301	1,030	Downstream

Data Collection Methods

Time-series data were obtained from the Environmental and Forestry Agency of West Kalimantan Province and subsequently validated by the Environmental Agency of Sanggau Regency to ensure data reliability and institutional accuracy of the data. The dataset covered a three-year period from 2021 to 2023. Each year, data were collected biannually to capture seasonal variability, comprising measurements during the dry season (April–August) and the wet season (September–December). This consistent semi-annual sampling design enabled the assessment of temporal and seasonal fluctuations in water quality parameters. The analysed parameters included physical, chemical, and biological indicators of water quality. Water quality assessment was performed in accordance with prevailing environmental protection and management regulations, ensuring compliance with established water quality standards. The parameters and quality standards are presented in Table 2.

Table 2. Parameters analyzed in this stud*y.* This table presents the maximum allowable limits for selected physical, chemical, and microbiological parameters for Class I and Class II surface water according to water quality standards. The parameters include indicators of organic pollution, nutrients, heavy metals, and microbial contamination that are commonly used to assess river water quality and compliance with environmental regulations [28].

Parameters	Unit	Max level Class I	Max level Class II
Physical Parameters			
Total Suspended Solids	mg/L	40	50
Chemical Parameters			
Biochemical Oxygen Demand (BOD)	mg/L	2	3
Chemical Oxygen Demand (COD)	mg/L	10	25
Dissolve Oxygen Demand (Do)	mg/L	6	4
Phosphate (P)	mg/L	0.2	0.2
Chromium Hexavalent (Cr^{6+}) (dissolved)	mg/L	0.05	0.05
Manganese (Mn)	mg/L	0.1	-
Nitrate (as NO3) (dissolved)	mg/L	10	10
Power of Hydrogen (pH)	mg/L	6–9	6-9
Plumbum (Pb)	mg/L	0.03	0.03
Cuprum (Cu)	mg/L	0.02	0.02
Zinc (Zn)	mg/L	0.05	0.05
Cadmium (Cd)	mg/L	0.01	0.01
Hydrargyrum (Hg)	mg/L	0.001	0.002
Selenium (Se)	mg/L	0.01	0.05
Arsenik (As)	mg/L	0.05	0.05
Microbiology Parameters			
Fecal Coliform (FC)	MPN/100 mL	100	1,000
Total Coliform (TC)	MPN/100 mL	1,000	5,000

Exceedance Ratio (ER)

ER was employed to quantify the degree of regulatory non-compliance for each water quality parameter. The ER is calculated as the ratio of the measured concentration to the applicable standard threshold, with a value greater than 1 indicating an excess, calculated using Equation 1 [29]. For parameters governed by minimum criteria, an inverse ratio was applied to ensure consistent interpretation [30,31]. The exceedance rate (%) is also calculated using Equation 2, which describes the proportion of observations exceeding regulatory limits at various locations and during different season [32,33].

$$ER = \frac{C\ measured}{C\ standard} \tag{1}$$

Description:

$C\ measured$ = Measured concentration of the parameter

$C_{standard}$ = Applicable regulatory or guideline standard

Interpretation**:** ER ≤ 1 → Concentration complies with the standard, ER > 1 → Concentration exceeds the standard.

$$Exceendance\ Frequaency\ (\%) = (\frac{N\ exceed}{n\ total})\ x\ 100 \tag{2}$$

Pollutant Index (PI) Assessment

The PI method, in accordance with Minister of Environment Regulation Number 115 of 2003 [34], is used to evaluate water quality status. PI combines various water quality parameters, including physical parameters such as odour, turbidity, temperature, and total dissolved solids (TDS), chemical parameters such as iron (Fe), chromium hexavalent (Cr^{6+}) (dissolved), manganese (Mn), nitrate (as NO_3) (dissolved), nitrite (as NO_2), hydrogen power (pH), and microbiological parameters such as *Escherichia coli* and total coliform into a single index value, categorising pollution levels as good, slightly polluted, moderately polluted, or severely polluted [2,6]. The PI is calculated using Equation 3 [34].

$$PI_j = \sqrt{\frac{(C_i/L_{ij})^2_{Max} + (C_i/L_{ij})^2_{Avg}}{2}} \tag{3}$$

Description:

PI = Pollution Index

C_i = Concentration of water quality parameter

L_{ij} = Quality standard for water quality parameter concentration

$(C_i/L_{ij})^2_{Max}$ = Value C_i/L_{ij} Maximum

$(C_i/L_{ij})^2_{Avg}$ = Value C_i/L_{ij} Average

The evaluation of the Pollution Index value refers to the decision of the Minister of Environment [34]: $0 \leq PI_j \leq 1.0$ = Quality standards (good); $1.0 < PI_j \leq 5.0$ = Lightly polluted; $5.0 < PI_j \leq 10$ = Moderately polluted; $PI_j > 10$= Heavily polluted.

Quantitative Microbial Risk Assessment (QMRA)

The QMRA was conducted to estimate the annual probability of infection associated with unintentional ingestion of surface water [27]. In the absence of direct *Escherichia coli* data, fecal coliform (FC) concentrations were converted using an 80% ratio (*E. coli* = 0.8 × FC), consistent with reported dominance of *E. coli* within FC groups in tropical surface waters.

Exposure Assessment

The exposure assessment aims to estimate the potential intake of microorganisms during contact with contaminated water. The dose ingested during each exposure event is determined based on the concentration of pathogens in the water and the estimated volume of water accidentally ingested during the contact activity. The QMRA uses Equation 4 [26,27].

$$Dose = C_{ec} \times V \tag{4}$$

where:

C_{ec} = Concentration of *E. coli* (MPN/mL)

V = Accidental ingestion volume per exposure (mL)

Accidental ingestion volumes were assumed to be 20 mL per event for adults and 50 mL per event for children, consistent with recreational exposure studies [26,29]. Annual exposure frequency was set at 100 events per year to represent regular domestic or recreational contact [27].

Dose–Response Assessment

The dose–response assessment was conducted to determine the relationship between the ingested microbial dose and the probability of infection. The likelihood of infection for each exposure event was estimated using the Beta–Poisson model the dose-response assessment was calculated using Equation 5 [27].

$$P_{inf} = 1 - \left[1 + \frac{Dose}{N_{50}}\left(2^{\frac{1}{\alpha}} - 1\right)\right]^{-\alpha} \quad (5)$$

where:

P_{inf} = Probability of infection per exposure

N_{50} = Median infectious dose

α = Pathogen-specific infectivity parameter

Annual Risk Estimation

Annual risk estimation was performed to evaluate the cumulative probability of infection over a one-year period. The annual infection probability was calculated by considering repeated exposure events occurring throughout the year. The annual probability of infection is calculated by considering repeated exposures that occur throughout the year. The annual risk estimate is calculated using Equation 6 [26,27].

$$P_{annual} = 1 - (1 - P_{inf})^n \quad (6)$$

where:

n = number of exposure events per year (n = 100); risk levels were evaluated against the WHO health-based target of [26,29] ($P_{annual} \leq 10^{-4}$).

Results and Discussion

Result

Evaluation against Government Regulation No. 22/2021 standards presented in Table 3 shows substantial non-compliance under Class I criteria, primarily driven by Fe (ER = 4.00; 82%), COD (ER = 2.37; 91%), BOD (ER = 2.10; 81%), fecal coliform (ER = 2.50; 82%), and total coliform (ER = 2.10; 73%). Total phosphate (TP) also exceeded the threshold (ER = 1.10; 55%), while dissolved oxygen indicated marginal conditions (ER = 1.36; 73%). In contrast, parameters such as pH, TSS, NO_3-N, and trace metals (Hg, As, Se, Cd, Mn, Zn, Cu, Cr^{6+}) largely complied with regulatory limits. Under Class II standards, exceedance intensity decreased considerably, with COD (ER = 0.95; 27%) and microbial indicators (ER = 0.25–0.42; 9–18%) generally meeting the criteria. However, Fe (ER = 1.20; 45%), BOD (ER = 1.40; 64%), and total phosphate (ER = 1.10; 55%) remained above unity, while Pb persisted at the regulatory boundary (ER = 1.00; 27%). These findings indicate that the water body fails to satisfy Class I requirements but approaches Class II compliance, albeit with persistent organic and nutrient pressures.

Table 3. Summary of water quality parameters, mean concentrations (±SD) parameters, regulatory standards (Class I and Class II), ER, and exceedance frequency (%) for the Kapuas River monitoring sites. The table compares observed values with Indonesian water quality standards (Government Regulation No. 22/2021) [28] and provides a compliance assessment indicating whether each parameter meets or exceeds the applicable limits.

Parameters	Mean ± SD	Class I Std	ER (C-I)	Freq. exceed (%) C-I	Class II Std	ER (C-II)	Freq. exceed (%) C-II	Compliance summary
pH	6.4 ± 0.9	6–9	-	0	6–9	-	0	Complied
BOD	4.21 ± 1.20	2	2.10	81	3	1.40	64	**Exceeded**
COD	23.7 ± 4.3	10	2.37	91	25	0.95	27	Mostly Class II
TSS	18 ± 5	25	0.72	18	50	0.36	0	Complied
DO	4.4 ± 0.8	≥6	1.36	73	≥4	0.91	18	Marginal
NO_3-N	3.45 ± 0.9	10	0.35	0	10	0.35	0	Complied
TP	0.22 ± 0.07	0.2	1.10	55	0.2	1.10	55	**Exceeded**

Parameters	Mean ± SD	Class I Std	ER (C-I)	Freq. exceed (%) C-I	Class II Std	ER (C-II)	Freq. exceed (%) C-II	Compliance summary
FC	250 ± 300	100	2.50	82	1,000	0.25	9	**Exceeded (C-I)**
TC	2,100 ± 4,000	1,000	2.10	73	5,000	0.42	18	**Exceeded (C-I)**
Hg	0.00082 ± 0.00003	0.001	0.82	0	0.002	0.41	0	Complied
As	0.0010 ± 0.0001	0.05	0.02	0	0.05	0.02	0	Complied
Se	0.0015 ± 0.001	0.01	0.15	0	0.01	0.15	0	Complied
Fe	1.20 ± 0.6	0.3	4.00	82	1.0	1.20	45	**Exceeded**
Cd	0.001 ± 0.0001	0.01	0.10	0	0.01	0.10	0	Complied
Mn	0.04 ± 0.03	0.1	0.40	0	0.1	0.40	0	Complied
Zn	0.03 ± 0.02	0.05	0.60	9	0.05	0.60	9	Complied
Cu	0.015 ± 0.01	0.02	0.75	18	0.02	0.75	18	Complied
Pb	0.03 ± 0.02	0.03	1.00	27	0.03	1.00	27	Borderline
Cr^{6+}	0.01 ± 0.005	0.05	0.20	0	0.05	0.20	0	Complied

The comparative heatmap (Figure 2) under identical color scaling demonstrates a clear reduction in exceedance intensity from Class I to Class II standards. Under Class I criteria, iron (Fe) exhibited the highest deviation (ER ≈ 4.00; 82% exceedance), followed by COD (ER ≈ 2.37; 91%), BOD (ER ≈ 2.10; 81%), fecal coliform (ER ≈ 2.50; 82%), and total coliform (ER ≈ 2.10; 73%). Dissolved oxygen showed moderate non-compliance (ER ≈ 1.36; 73%), while total phosphate slightly exceeded the threshold (ER ≈ 1.10; 55%). These results indicate persistent organic, microbiological, and iron-related pressures under the more stringent Class I standard.

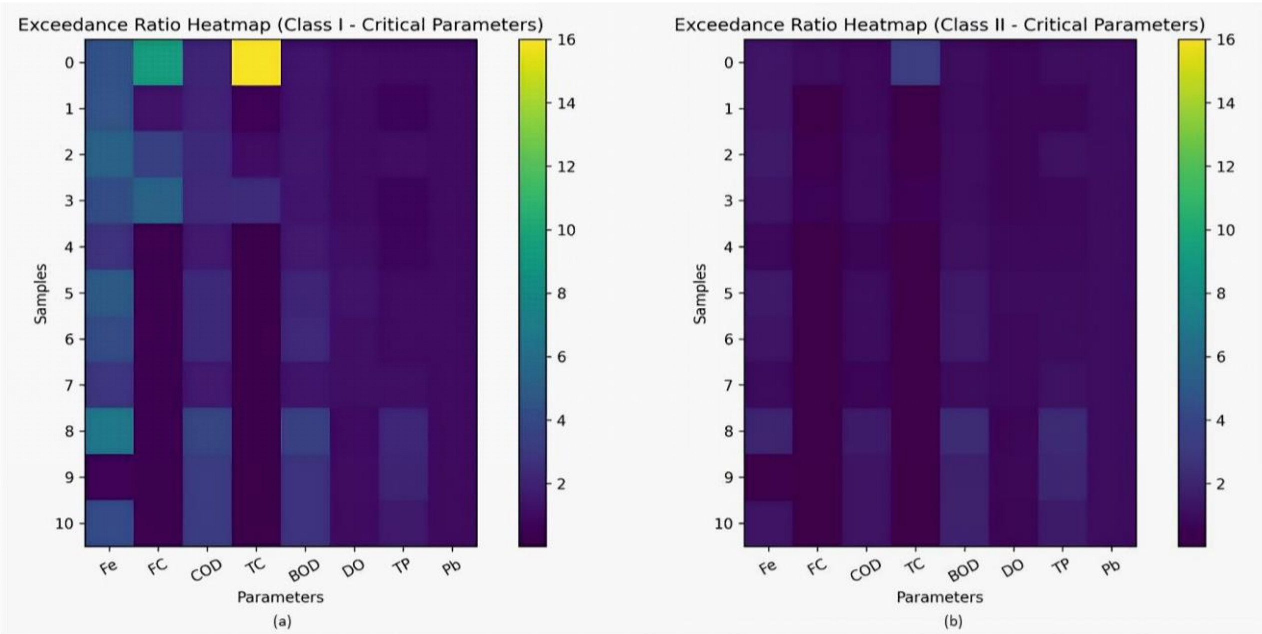

Figure 2. Heatmap of ER values comparing observed water quality with regulatory standards. (a) Under Class I standards, Fe, FC, COD, and TC emerge as critical parameters, indicating dominant organic and microbiological pollution. (b) Under Class II standards, exceedance levels decrease, although Fe, BOD, and TP remain the main parameters exceeding the thresholds).

River Water Quality Analysis using the Pollution Index (PI) Approach

The analysis of the PI is utilized to evaluate the extent of river water contamination in relation to established water quality benchmarks [7,8,12,35]. This methodology requires integrating data on water quality indicators, current conditions, and classification of quality levels by comparing observed metrics with predefined standards. It generates a numerical representation of pollution intensity, with comprehensive findings illustrated in Table 4, summarizing river water quality conditions derived from the PI approach.

Table 4. Seasonal PI values and water quality status at monitoring locations along the Kapuas River in Sanggau District from 2021–2023. The table presents the average and maximum C_i/L_{ij} ratios, calculated PI values, and corresponding water quality classifications for dry and rainy seasons based on the Pollution Index method.

Monitoring location	Year of monitoring	Season	$C_i/L_{ij\ Average}$	$C_i/L_{ij\ Max}$	PI_j	Water quality*
Sanggau Water Supply Intake	2023	Dry season	1.44	7.02	5.07	Moderately polluted
	2023	Rainy season	1.25	5.54	4.02	Lightly polluted
	2022	Dry season	0.58	3.16	2.28	Lightly polluted
	2022	Rainy season	0.49	2.41	2.6	Lightly polluted
	2021	Dry season	0.81	2.90	2.16	Lightly polluted
	2021	Rainy season	0.80	2.84	2.87	Lightly polluted
Semuntai Bridge	2023	Dry season	0.83	4.25	3.06	Lightly polluted
	2023	Rainy season	0.85	4.62	3.32	Lightly polluted
	2022	Dry season	0.66	4.44	3.19	Lightly polluted
	2022	Rainy season	0.40	0.97	1.54	Lightly polluted
	2021	Dry season	1.03	5.13	3.72	Lightly polluted
Tayan Palace Mosque	2023	Dry season	1.10	4.61	3.35	Lightly polluted
	2023	Rainy season	0.76	5.76	4.1	Lightly polluted
	2022	Dry season	0.74	4.06	2.94	Lightly polluted
	2022	Rainy season	0.57	2.44	2.61	Lightly polluted
	2021	Dry season	0.81	2.61	2.54	Lightly polluted
Al Ikhlas Mosque	2023	Dry season	1.18	4.66	3.4	Lightly polluted
	2023	Rainy season	0.95	5.09	3.66	Lightly polluted
	2022	Dry season	0.63	3.31	2.4	Lightly polluted
	2022	Rainy season	0.51	1.93	2.17	Lightly polluted
	2021	Dry season	0.89	4.13	3.01	Lightly polluted
	2021	Rainy season	0.70	2.30	2.53	Lightly polluted

Seasonal boxplot analysis (Figure 3) shows persistent exceedance of several key parameters, with Fe exhibiting the highest deviation (ER ≈ 4.00; 82% exceedance under Class I; ER ≈ 1.20; 45% under Class II), indicating sustained geogenic and anthropogenic influence. Microbiological indicators were strongly elevated under Class I, with FC (ER ≈ 2.50; 82%) and TC (ER ≈ 2.10; 73%) displaying greater dispersion during the rainy season, consistent with runoff-driven contamination. Organic pollution remained significant, as reflected by BOD (ER ≈ 2.10; 81%) and COD (ER ≈ 2.37; 91%), with BOD still exceeding Class II standards (ER ≈ 1.40; 64%). Total phosphate slightly surpassed regulatory limits (ER ≈ 1.10; 55%), while dissolved oxygen showed moderate non-compliance (ER ≈ 1.36; 73%), indicating oxygen stress associated with organic loading. Overall, seasonal variability amplifies contamination intensity, but elevated iron and organic pressure persist irrespective of season.

The Pollution Index (PI_j) values summarized in Table 4 illustrate the water quality status at four monitoring locations along the Kapuas River over the 2021–2023 monitoring period during both dry and rainy seasons. Overall, most monitoring points indicate light pollution, with PI_j values varying between 1.54 and 4.10. A notable exception occurred at the Sanggau water intake in the 2023 dry season, where the PI_j reached 5.07, reflecting a moderately polluted condition. The results also indicate a seasonal pattern in which pollution levels tend to increase during the dry season, which may be associated with lower river discharge and a reduced capacity of the river to dilute contaminants.

The inferential statistical analysis (Table 5) revealed no significant spatial variation in the PI among monitoring locations ($p = 0.796$; $\eta^2 = 0.03$), indicating a relatively homogeneous distribution of pollution levels across sites with a small effect size. Similarly, seasonal comparison showed no statistically significant difference between dry and rainy seasons ($p = 0.632$; $r = 0.10$), suggesting that seasonal hydrological fluctuations exerted only a negligible influence on PI variability during the study period. In contrast, temporal analysis demonstrated a statistically significant difference among years ($p = 0.015$; $\eta^2 = 0.28$), with a moderate effect size. Post-hoc analysis confirmed that PI values in 2023 were significantly higher than those recorded in 2021 and 2022. These findings indicate a recent escalation in pollution pressure, underscoring the need for strengthened water quality management and mitigation strategies.

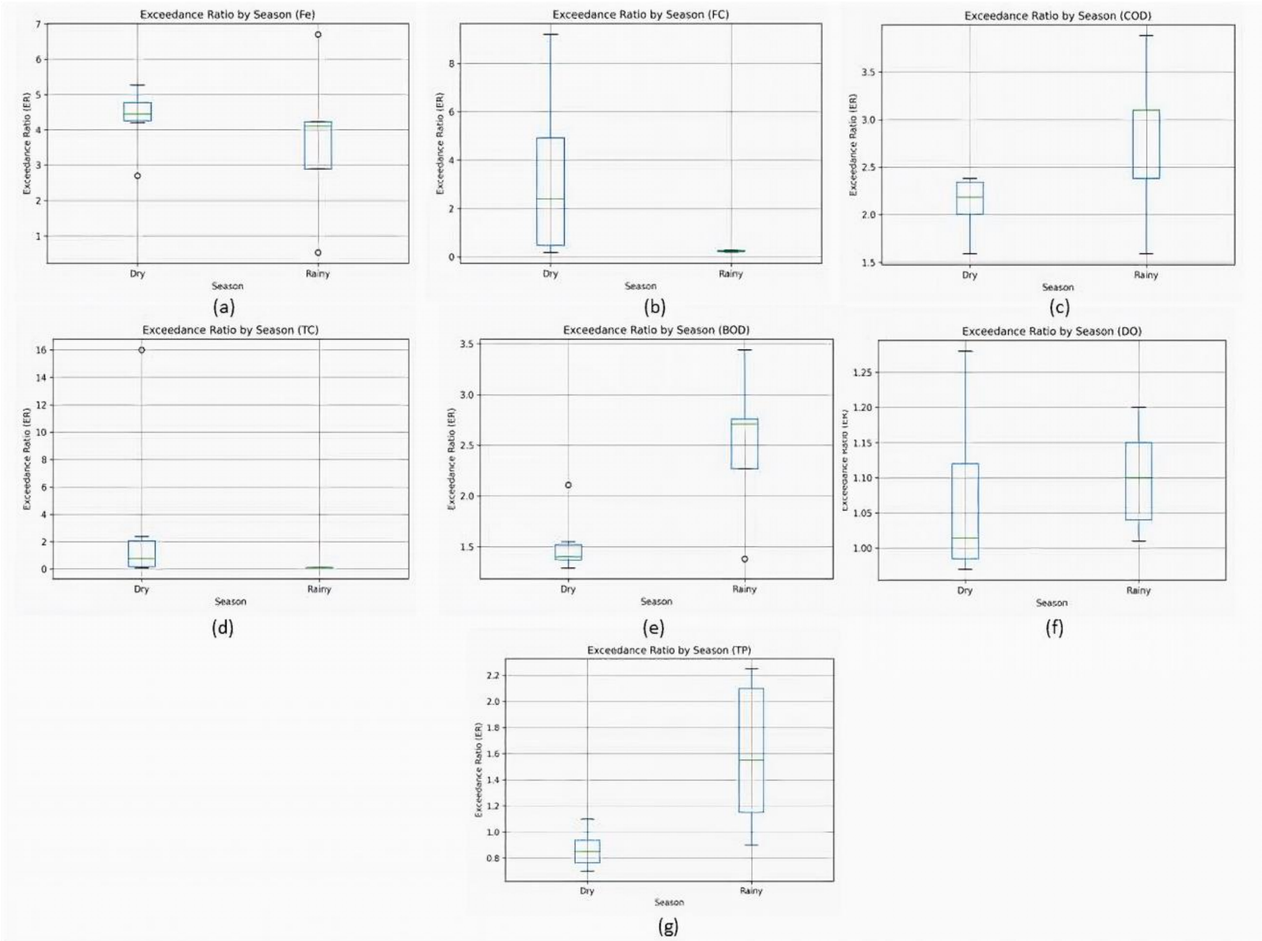

Figure 3. Seasonal variation of ER for critical water quality parameters in the Kapuas River, Sanggau District, during 2021–2023. The parameters shown include (a) Fe, (b) FC, (c) COD, (d) TC, (e) BOD, (f) DO, and (g) TP.

Table 5. Statistical comparison of PI values across monitoring locations, seasons, and years in the Kapuas River, Sanggau District. The table presents descriptive statistics (mean ± SD, median with IQR, and range) and results of non-parametric tests (Kruskal–Wallis and Mann–Whitney) used to evaluate spatial, seasonal, and temporal differences in water quality (2021–2023).

Variable		n	Mean ± SD	Median (IQR)	Min–Max	Statistic	p-value	Effect size
Location	Sanggau Intake	6	3.17 ± 1.15	2.74 (2.16–5.07)	2.16–5.07	-	-	-
	Semuntai Bridge	5	2.97 ± 0.84	3.19 (1.54–3.72)	1.54–3.72	-	-	-
	Tayan Palace Mosque	5	3.11 ± 0.64	2.94 (2.54–4.10)	2.54–4.10	-	-	-
	Al Ikhlas Mosque***	6	2.86 ± 0.59	2.77 (2.17–3.66)	2.17–3.66	H=1.02	0.796	η^2=0.03
Season	Dry	12	3.09 ± 0.84	3.07 (2.40–3.72)	2.16–5.07			
	Rainy**	10	2.94 ± 0.82	2.74 (2.30–3.66)	2.17–4.10	U=52	0.632	r=0.10
Year	2021[a]	6	2.81 ± 0.49	2.70 (2.16–3.01)	2.16–3.72			
	2022[a]	8	2.47 ± 0.37	2.51 (2.17–2.94)	2.17–3.19			
	2023[b]***	8	3.75 ± 0.82	3.38 (3.06–5.07)	3.06–5.07	H=8.41	0.015*	η^2=0.28

*Significant at α = 0.05
** Mann–Whitney test; *** Kruskal–Wallis test
Different superscript letters (a,b) indicate significant differences based on Dunn post-hoc test with Bonferroni correction.

Quantitative Microbial Risk Assessment (QMRA)

Table 6 presents the estimated annual infection risk (P_a) and Exceedance Factor (EF) for adults and children under the unintentional ingestion scenario, expressed relative to the WHO benchmark (10^{-4} infections per person per year) to enable temporal and spatial comparison [26]. Fecal coliform was used as a surrogate for *Escherichia coli* with an 80% conversion ratio due to the absence of direct pathogen measurements, an approach supported in microbial risk assessment frameworks when pathogen-specific data are unavailable [26,27]. Although standardized exposure assumptions may introduce uncertainty, they are consistent with established QMRA methodologies, and the consistently elevated EF values particularly the marked increase observed in 2023 indicate that the conclusion of significant microbial risk remains robust despite these limitations [25,36–38].

Table 6. Estimated annual infection risk expressed as EF for adult and child populations at different monitoring locations along the Kapuas River from 2021–2023. EF values are presented for exposure frequencies of 70%, 80%, and 90%, illustrating the relative magnitude of infection risk compared with the WHO health-based target (10^{-4} per person per year) [26].

Year	Location	Adult EF 70%	Adult EF 80%	Adult EF 90%	Child EF 70%	Child EF 80%	Child EF 90%
2021	Sanggau Water Supply Intake	3.68	4.20	4.73	9.63	11	12.38
2021	Semuntai Bridge	3.94	4.50	5.06	10.50	12	13.50
2021	Tayan Palace Mosque	3.68	4.20	4.73	9.63	11	12.38
2021	Surau Al-Ikhlas	2.98	3.40	3.83	7.88	9.0	10.13
2022	Sanggau Water Supply Intake	2.54	2.90	3.26	6.74	7.7	8.66
2022	Semuntai Bridge	2.80	3.20	3.60	7.44	8.5	9.56
2022	Tayan Palace Mosque	3.15	3.60	4.05	8.31	9.5	10.69
2022	Al Ikhlas Mosque	3.33	3.80	4.28	8.58	9.8	11.03
2023	Sanggau Water Supply Intake	105	120	135	271	310	349
2023	Semuntai Bridge	14.88	17	19.13	38.50	44	49.50
2023	Tayan Palace Mosque	40.25	46	51.75	105	120	135
2023	Al Ikhlas Mosque	62.13	71	79.88	166.25	190	213.75

Table 6 presents the EF values for adults and children under three fecal coliform–to–*E. coli* conversion scenarios (70%, 80%, and 90%) across the monitoring sites from 2021 to 2023. During 2021–2022, EF values for adults ranged from 2.54 to 4.50, while children showed higher values between 6.74 and 12, indicating moderate microbial risk relative to the WHO benchmark. In contrast, EF values increased sharply in 2023**,** particularly at the Sanggau Water Supply Intake (EF = 120 for adults and 310 for children under the 80% scenario), demonstrating a substantial escalation of microbial contamination, with children consistently exhibiting higher risk levels than adults.

The results indicate (Table 7) that all monitoring sites consistently exceeded the WHO annual risk benchmark (10^{-4} infections per person per year) throughout the 2021–2023 observation period, with no Exceedance Factor (EF) values falling at or below unity. During 2021–2022, EF values for adults ranged between 2.9 and 4.5, corresponding to moderate exceedance levels, while children exhibited higher values (7.7–12), reflecting moderate to high risk. Spatial differences among sites during these two years were relatively limited, suggesting a uniform distribution of microbial contamination.

In contrast, a pronounced escalation was observed in 2023, with EF values increasing by more than one order of magnitude compared to the preceding years. The most critical condition occurred at the Sanggau Water Supply Intake, where EF reached 120 for adults and 310 for children, representing extreme exceedance. Similar upward trends were identified at Tayan Palace Mosque and Al Ikhlas Mosque, which fell within the high to extreme categories, whereas Semuntai Bridge exhibited high but comparatively lower values. These findings highlight a substantial deterioration in microbial water quality in 2023 and confirm the consistently greater susceptibility of children to infection risk. Log-scale analysis of the EF (Figure 4) revealed that all monitoring sites (SA1–SA4) consistently exceeded the WHO benchmark (10^{-4} infections per person per year) from 2021 to 2023. During 2021–2022, EF values ranged from 2.9–4.5 in adults and 7.7–12 in children, indicating moderate to high exceedance with limited spatial variability.

Table 7. Results of the QMRA showing annual infection probability (P_a), EF, and risk category for adult and child populations at four monitoring locations along the Kapuas River during 2021–2023. The table illustrates the temporal variation in microbial health risks, indicating higher infection probabilities and risk levels for children compared with adults across most sites.

Year	Analysis code	Location	Adult P_a	Adult EF	Adult category	Child P_a	Child EF	Child category
2021	SA1	Sanggau Water Supply Intake	4.2×10^{-4}	4.2	Moderate	1.1×10^{-3}	11	High
2021	SA2	Semuntai Bridge	4.5×10^{-4}	4.5	Moderate	1.2×10^{-3}	12	High
2021	SA3	Tayan Palace Mosque	4.2×10^{-4}	4.2	Moderate	1.1×10^{-3}	11	High
2021	SA4	Surau Al-Ikhlas	3.4×10^{-4}	3.4	Moderate	9.0×10^{-4}	9.0	Moderate
2022	SA1	Sanggau Water Supply Intake	2.9×10^{-4}	2.9	Moderate	7.7×10^{-4}	7.7	Moderate
2022	SA2	Semuntai Bridge	3.2×10^{-4}	3.2	Moderate	8.5×10^{-4}	8.5	Moderate
2022	SA3	Tayan Palace Mosque	3.6×10^{-4}	3.6	Moderate	9.5×10^{-4}	9.5	Moderate
2022	SA4	Al Ikhlas Mosque	3.8×10^{-4}	3.8	Moderate	9.8×10^{-4}	9.8	Moderate
2023	SA1	Sanggau Water Supply Intake	1.2×10^{-2}	120	Extreme	3.1×10^{-2}	310	Extreme
2023	SA2	Semuntai Bridge	1.7×10^{-3}	17	High	4.4×10^{-3}	44	High
2023	SA3	Tayan Palace Mosque	4.6×10^{-3}	46	High	1.2×10^{-2}	120	Extreme
2023	SA4	Al Ikhlas Mosque	7.1×10^{-3}	71	High	1.9×10^{-2}	190	Extreme

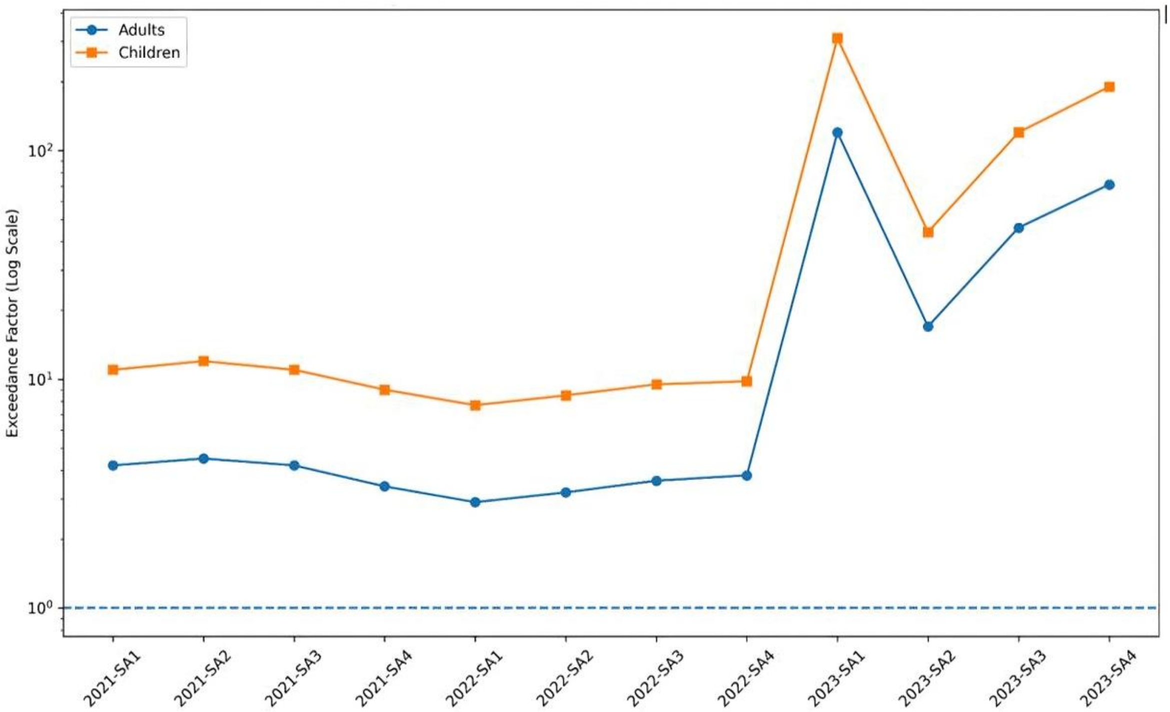

Figure 4. Log-scale analysis of the EF for microbial infection risk at monitoring sites SA1–SA4 in the Kapuas River during 2021–2023. EF values consistently exceeded the WHO benchmark (10^{-4} infections per person per year), with a pronounced increase in 2023 and higher risk levels observed for children compared with adults.

A substantial escalation occurred in 2023, with EF increasing by more than one order of magnitude compared to previous years. The most critical condition was observed at SA1 (water intake), where EF reached 120 in adults and 310 in children. Similar upward trends were identified at SA3 and SA4, reflecting intensified microbial contamination. Across all sites and years, children consistently exhibited higher EF values than adults, underscoring their greater susceptibility to microbial exposure. These findings indicate persistent exceedance of acceptable microbial risk levels under recreational exposure assumptions, with a pronounced and statistically meaningful surge in 2023.

Discussion

An integrated assessment using the ER, PI, and QMRA shows significant water quality degradation in the Kapuas River, mainly caused by organic, nutrient, and microbiological pollution. Key parameters such as BOD, COD, TP, Fe, and fecal indicators consistently exceed regulatory thresholds, resulting in non-compliance with Class I standards. During the 2021–2023 monitoring period, the average BOD and COD values at several locations often approached or exceeded Class II thresholds, indicating moderate organic loads, while PI values often fell into the mild to moderate pollution category [6,39,40]. The relatively narrow spatial variation range indicates that pollution sources are widely dispersed along the river corridor, consistent with diffuse inputs from untreated domestic wastewater and limited sanitation coverage in riverside settlements. In contrast to many industrial river basins where heavy metals are a major factor in pollution severity, the Kapuas River shows relatively low heavy metal exceedances, with Fe as the main chemical concern; other heavy metals remain below critical thresholds at most locations. This contrasts with findings in highly industrialized river basins such as the Citarum River and Brantas River, where textile and other industrial waste have historically elevated COD to values well above standards (e.g., COD >100 mg/L in some segments), and water quality indices are consistently rated from Fair to Poor based on various assessment methods [22,41,42].

Temporal trends in the Kapuas River, which crosses Sanggau district, show a significant increase in pollution in 2023, as indicated by an increase in the EF calculated from QMRA, which indicates an increase in microbial load. Although seasonal differences were not statistically significant, microbial indicator variability increased during the rainy season, indicating increased stormwater runoff and non-point source contamination. This is consistent with observations in other large tropical rivers where hydrological fluctuations facilitate pulsed microbiological inputs during high flows [25,27]. Annual QMRA estimates indicate that the risk of infection consistently exceeds the WHO threshold of 10^{-4} infections per person per year in all locations during the 2021–2023 period. These findings are consistent with several other studies showing that children have a much higher probability of infection due to behavioural and physiological vulnerabilities [43–45]. Sensitivity analysis confirms the robustness of these estimates under different fecal indicator conversion assumptions. The contrast between near compliance with Class II regulatory standards and the continued exceedance of health risk thresholds highlights a disconnect between regulatory criteria and actual public health protection. Concentration-based water quality standards may underestimate true health risks, particularly in situations where frequent human contact with contaminated water occurs and microbial pathogenicity is not fully captured [27,44]. Therefore, combining pollution indices with probabilistic risk assessment approaches such as QMRA can provide a more comprehensive and health-oriented framework for water resource management [38,45,46].

Comparative studies on major rivers in Indonesia support these findings. In the Citarum River, water quality index values have been reported to range from fair to poor, with WQI scores as low as approximately 11–18, indicating severe pollution dominated by organic contaminants and fecal-related substances [22,47]. Similarly, assessments of rivers in Java show that BOD, COD, and coliform counts often exceed regulatory limits, mainly due to domestic sewage and urban runoff, although industrial impacts can exacerbate conditions in certain segments [42,48]. More broadly, studies across rivers in Indonesia have shown that BOD, COD, and coliform concentrations frequently exceed regulatory standards due to untreated domestic sewage and urban runoff, although industrial discharges may intensify water quality degradation in certain river segments [6,22,41,42,48]. Compared to these main rivers, the Kapuas River has a dominant influence from organic and microbiological pressures while showing relatively lower heavy metal contamination, reinforcing the interpretation that sanitation-related inputs underlie its pollution status [6,22,42]. Overall, this evidence highlights that widespread domestic wastewater remains a pervasive challenge for main rivers in Indonesia, suggesting that improvements in sanitation infrastructure, wastewater treatment, and drinking water source protection are critical to reducing health risks and advancing progress toward SDG 6.

Conclusions

This study demonstrates persistent non-compliance of Kapuas River surface water with health-based safety standards, driven by elevated iron, organic pollution, nutrients, and microbial contamination, with a significant escalation observed in 2023. Quantitative Microbial Risk Assessment (QMRA) confirmed that annual infection risks exceeded the WHO benchmark at all sites, reaching extreme levels at the water intake location, with children consistently facing higher vulnerability. These findings underscore the urgent need for strengthened watershed governance, improved sanitation infrastructure, and evidence-based regulatory interventions to mitigate escalating health risks and support progress toward SDG6 in tropical river systems.

Author Contributions

RW: Conceptualization, Methodology, Software, Investigation, Writing - Review & Editing; **AMF:** Conceptualization, Review & Editing, Supervision; **SB:** Review & Editing, Supervision; **SP:** Review & Editing Supervision; and **NSW:** Review & Editing, Supervision.

AI Writing Statement

The authors did not use artificial intelligent assisted technologies in writing process.

Conflicts of interest

There are no conflicts to declare.

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