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Land use and seasonal effects on water quality and faecal contamination in Batang Layar river, Sarawak, Malaysia

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Abstract

Tropical river systems face increasing pollution from anthropogenic activities, yet integrated assessments of land use and seasonal effects on water quality remain limited. This study investigates the impact of land use and seasons on the physicochemical water quality and faecal coliform abundance in the Batang Layar River, Sarawak. Water samples were collected from five sites during the wet and dry seasons. We used a YSI ProDSS Multiparameter for in-situ measurements and performed *ex-situ* analyses for Faecal Coliform Count (FCC), Total Coliform Count (TCC), and Department of Environment-Water Quality Index (DOE-WQI) parameters. The WQI classified upstream sites (LS1, LS2, LS3) as Class I (Excellent) year-round, while downstream sites (LS4, LS5) shifted from Class II (Very good) in the wet season to Class I in the dry season. Despite the generally favourable WQI scores, wet season FCC concentrations (228.94 to 992.87 CFU/100 mL) exceeded DOE recreational water standards (< 400 CFU/100 mL), particularly near populated areas, due to surface runoff and sediment resuspension. Principal Component Analysis (PCA) identified organic pollution (48.39% variance) and sedimentation (25.75% variance) as dominant factors. Spearman correlation shows strong correlations between FCC, TCC, and organic parameters, confirming shared anthropogenic origins in both seasons. The notable discrepancy between favourable WQI scores and elevated microbial risks highlights the need to integrate bacteriological monitoring into water quality assessments. These findings emphasise the need for integrated water resource management (IWRM) strategies, including improved wastewater infrastructure and riparian buffers implementation, to mitigate seasonal contamination risks and safeguard public and ecosystem health in tropical basins.

Keywords Faecal coliforms, Land use impacts, Public health risks, River pollution, Seasonal variations, Water quality

1 Introduction

Degradation of water quality in riverine ecosystems, driven by the expansion of anthropogenic activities, presents a formidable global challenge that threatens both aquatic ecosystems and human health [1, 2]. The World Health Organisation (WHO) estimates that half of the global population will be living in water-stressed areas by 2025 due to climate change, population growth, and urbanisation [3]. In response to these challenges, the United Nations Sustainable Development Goal 6 (SDG 6) specifically targets ensuring the availability and sustainable management of clean water and sanitation for all by 2030 [4]. Despite these global efforts, freshwater ecosystems, particularly in tropical regions, face increasing pressures from rapid land-use changes and seasonal rainfall that synergistically exacerbate anthropogenic pollution and threaten freshwater resources [5–7].

The Batang Layar watershed, located in the Betong region of Sarawak, exemplifies these challenges with the complex interplay between land use, hydrology, and water quality in tropical river systems. The watershed features a diverse landscape comprising forest, agricultural land, and human settlements. The Dayak Iban communities residing within this watershed have strong ties to the land, relying on subsistence agriculture (including pepper farming and rubber cultivation), fishing, and traditional crafts for their livelihoods [8]. Unlike the Rajang and Sarawak Kiri basins, which have established baseline water quality data [9, 10], the Batang Layar watershed remains an understudied basin, lacking critical data on how land use and seasonal influences affect water quality. This gap prevents evidence-based management and impedes Malaysia's progress toward SDG 6 commitments [11].

Pathogenic contamination in surface waters arises from multiple sources, including urban stormwater, agricultural runoff, wildlife waste, effluent from wastewater treatment plants, and leakage from failing septic systems [12–16]. The impact of these sources is profoundly mediated by land use and seasonal hydrology. Specifically, the interplay of land use types and seasonal variations plays a crucial role in altering water quality, where urban stormwater and agricultural runoff during the wet season increase the flushing of contaminants from the land into rivers, significantly elevating microbial loads compared to the dry season [17–20]. This is consistent with the finding that urbanised and agricultural lands contribute significantly to contamination through stormwater runoff from impervious surfaces [1, 2, 18], underscoring the need for integrated monitoring of microbial indicators, such as *Escherichia coli*, faecal streptococci, and enterococci, which serve as indicators of faecal pollution and public health risks [21–23]. Among these, *E. coli* is considered a critical indicator of faecal coliforms due to its direct association with intestinal waste from humans and animals [24, 25]. Studies in similar Malaysian contexts, such as in Negeri Sembilan, further support that urbanisation and seasonal variability are key drivers of microbial contamination in local waters [12]. However, a comprehensive understanding of how land use types affect faecal coliform dynamics across distinct seasons within individual tropical catchments like Batang Layar remains unknown. This understanding is crucial for evaluating water safety and mitigating contamination, particularly in tropical watersheds like Batang Layar.

Complementing this, water quality assessment is critical for protecting ecosystem health, conducting accurate risk assessments, and remediating impaired water bodies. For the systematic evaluation of water quality, Malaysia employs the Water Quality

Index (WQI), a comprehensive tool that integrates physical, chemical, and biological parameters. The Malaysian WQI comprises six variables: Dissolved Oxygen (DO), Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Ammoniacal Nitrogen (NH_3-N), Suspended Solids (SS), and pH, to classify water quality [26]. The WQI serves as a benchmark for classifying water bodies. Maintaining acceptable water quality remains challenging in water resources management [27]. Extensive socioeconomic growth, combined with human, climate, and hydrological factors, drives pollutant accumulation in surface water, gradually altering water quality over time [28]. Few regional studies highlight the need for detailed monitoring by location and season to identify the pollution sources [29–33].

Thus, this study aims to address this knowledge gap by providing the first comprehensive water quality evaluation of the Batang Layar watershed through systematic seasonal sampling across key land uses (agricultural, residential, and forested). By combining a comprehensive analysis of physicochemical parameters via the Malaysian WQI with microbial indicators (*E. coli*), this study achieves the objectives in examining the effect of land-use on water quality and seasonal variation in faecal contamination levels in the Batang Layar river. These findings directly support SDG 6 by providing the necessary data for evidence-based management of water resources to improve water quality in the Batang Layar basin. Notably, this study approach forms a transferable framework for tropical mixed-land-use watersheds, addressing critical gaps in Sarawak water monitoring efforts.

2 Materials and methods

2.1 Study area and sampling sites

The study was conducted in the Batang Layar watershed, located in the Betong region of Sarawak, Malaysian Borneo. Five primary sites were selected along Batang Layar and its tributaries to capture the variation in land use: Paoh (LS1), Nanga Tiga (LS2), Linsum (LS3), Nanga Spak (LS4), and Jelau (LS5). These sites encompass a range of geographic and environmental contexts, from upstream regions with dense forest cover to downstream areas with significant agricultural and settlement influence. Site selection was based on accessibility, land use diversity (forest coverage, agricultural land use, and settlement areas), and proximity to anthropogenic activities.

Sites (LS1-LS5) denote broader zones, while sampling points (A, B, and C) reflect precise locations for replication (5 sites × 3 points) to capture micro-spatial variability (Figs. 1 and 2). The Area of Interest (AOI) for each sampling site was delineated using Geographic Information Systems (GIS). The centroid of each site was first identified and verified as a reference point. Based on the centroid, a square AOI measuring 500 × 500 m (approximately 25 hectares) was generated. The AOIs were then used to clip the existing land cover dataset, isolating land cover information within each boundary. The area of each landcover type was subsequently calculated and expressed in both hectares and as a percentage of the total AOI to allow comparison across sites. The source land use information was obtained through a combination of field observations and GIS mapping, ensuring accuracy. Table 1 provides detailed descriptions of each site's physical characteristics and land use, including site names, global positioning system (GPS) coordinates, total land area (Ha) and percentage of land cover (%).

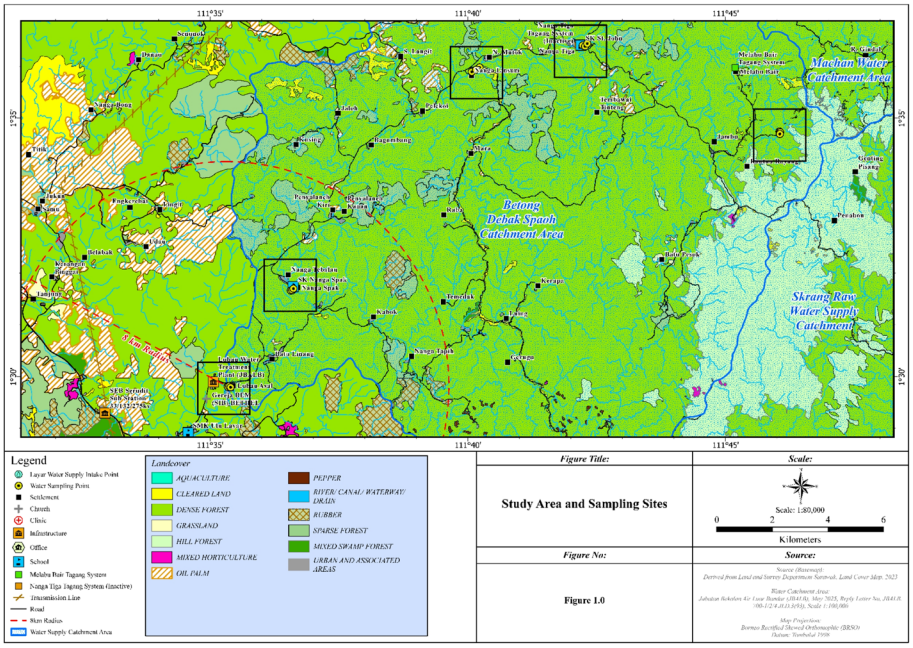

Fig. 1 Map of the sampling sites (as shown in the smaller boxes) and land uses in the study area

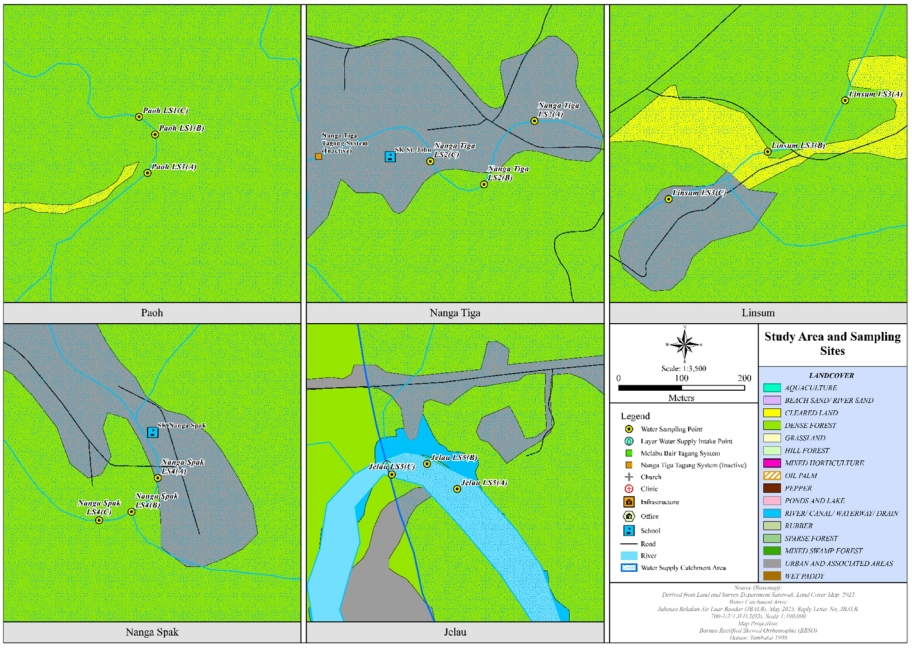

Fig. 2 Detailed view of the sampling sites and the surrounding land covers

2.2 Sampling strategy and laboratory analysis

2.2.1 Sample collection

Surface water samples were collected from five selected sites within the Batang Layar watershed to compare the impacts on water quality across different land use types: forested (LS1) and mixed agricultural settlements (LS2, LS3, LS4, and LS5). All samples were collected as grab samples [34–36]. To capture seasonal variability, a total of thirty (30) grab samples for fifteen (15) grab samples per season (5 sites × 3 points) were

Table 1 Study area coordinates and description

Site Name	Description	Point	GPS coordinates
Paoh (LS1)	Upstream, far from built-up areas, as a reference site, flat terrain, and a shallow river • 98.74% dense forest; 24.68 Ha • 1.23% cleared land; 0.31 Ha	A	N 01.57791° E 111.76753°
		B	N 01.57859° E 111.76764°
		C	N 01.57906° E 111.76776°
Nanga Tiga (LS2)	Midstream, inactive *tagang* system, school area and village settlements; small-scale oil palm plantation and mixed agricultural farm • 64.30% dense forest; 16.07 Ha • 35.67% urban and associated areas; 8.92 Ha	A	N 01.60737° E 111.70507°
		B	N 01.60663° E 111.70447°
		C	N 01.60721° E 111.70407°
Linsum (LS3)	Midstream, village settlements, and mixed agricultural farms • 77.68% dense forest; 19.42 Ha • 12.54% cleared land; 3.14 Ha • 9.74% urban and associated areas; 2.44 Ha	A	N 01.59943° E 111.67016°
		B	N 01.59916° E 111.66927°
		C	N 01.59833° E 111.66789°
Nanga Spak (LS4)	Midstream, school area, and small-scale poultry farm • 74.56% dense forest; 18.64 Ha • 25.41% urban and associated areas; 6.35 Ha	A	N 01.52844° E 111.61006°
		B	N 01.52801° E 111.60981°
		C	N 01.52801° E 111.60950°
Jelau (LS5)	Downstream, village settlements, and mixed agricultural farms • 73.13% dense forest; 18.28 Ha • 18.30% urban and associated areas; 4.57 Ha • 8.54% river/canal/waterway/drain; 2.13 Ha	A	N 01.49652° E 111.58996°
		B	N 01.49688° E 111.58953°
		C	N 01.49667° E 111.58882°

**tagang system*- a method used to conserve aquatic life

Table 2 Calibration protocols for the YSI ProDSS multiparameter probe

Sensor	Calibration Protocol
pH sensor	Using three-point calibration with pH 4, 7, and 10 standard buffers.
Conductivity sensor	Using a standard solution of known conductivity (e.g., 1000 µS/cm)
Optical DO sensor	Using one-point calibration in water-saturated air, place the sensor in a 100% humid environment.
Turbidity sensor	Using an acceptable standard, including AMCO-AEPA standards, Formazin standard, and Hach StablCal® standard

collected during two distinct seasons: the wet season (December 2023) and the dry season (June 2024) to ensure statistical robustness. Samples were collected from upstream, midstream, and downstream of the river channel at depths of 20 to 40 cm below the water surface, avoiding disturbed sediment and bankside vegetation. The samples were collected using pre-cleaned 1 L sterile polyethylene bottles to avoid contamination. Samples were immediately stored on ice in a coolbox (maintained at approximately 4 °C) and transported to the IBEC laboratory at UNIMAS within six hours for further analysis.

2.2.2 In-Situ measurements

In-situ parameters, including temperature, DO, specific conductance (SPC), conductivity, total dissolved solids (TDS), pH, and turbidity, were measured using a YSI ProDSS Multiparameter Water Quality Meter. The instrument was calibrated before each sampling session in accordance with manufacturer protocols to ensure data accuracy [37, 38], as detailed in Table 2.

At each sampling point (A, B, and C) within the sites, the probe was placed below the water surface in flowing water, specifically at an upstream position against the researcher to avoid disturbance. The probe was allowed to stabilise until readings for all parameters (particularly pH, DO, and turbidity) remained constant for approximately 30 s [39].

Three readings were taken at each point, and the average value was recorded for data analysis.

2.2.3 Ex-Situ laboratory

Ex-situ parameters, including BOD, COD, TSS, and NH_3-N, were analysed following standard procedures provided by the American Public Health Association (APHA) and the Hach water analysis handbook [40–42]. All analyses were performed in triplicate, and mean values are reported. Quality assurance and quality control (QA/QC) were implemented, including the analysis of blank samples (deionised water) run with each batch to confirm the absence of contamination. All glassware was acid-washed and rinsed with deionised water. Method detection limits (MDL) and key procedure details are summarised in Table 3.

2.2.4 Biological parameters

The standard methods used for measuring biological parameters are in accordance with APHA Method 9222 [40], where faecal coliform counts (FCC) and total coliform counts (TCC) were determined using the membrane filtration method. Briefly, 2 mL of water samples were selected to yield a countable range of 30–300 colonies and were filtered in triplicate through sterile, 0.45 µm pore size cellulose nitrate membranes (Whatman, UK), followed by aseptically transferred onto HiChromeTM ECC Selective Agar (Himedia) at 37 °C for 24 h [43]. Following incubation, the colonies formed on the filter paper were counted using a stereomicroscope. All colonies that exhibited dark blue colour were enumerated as faecal coliform (presumptive *E. coli*), and other colour colonies that exhibited different colours (e.g. pink, purple, white, etc.) were counted as total coliforms. Quality control measures were followed as per standard guidelines [40]. This includes the analysis of sterile water as blank samples to confirm the absence of contamination and using a positive control culture (*E. coli* ATCC 25922) to produce typical blue colonies.

Table 3 Description of *ex-situ* analytical methods

Parameter	Method Reference	Key Procedure Details
Biochemical Oxygen Demand (BOD)	APHA Method 5210B	Samples were collected in 300 mL BOD bottles, filled to exclude air, and sealed. The samples were incubated in the dark at 20 °C ± 1.0 °C for 5 days. The BOD was calculated by subtracting the initial DO concentration from the final DO concentration. The detection limit for the DO was 0.1 mg/L. [40]
Chemical Oxygen Demand (COD)	APHA Method 5520	A 2 mL sample was digested with a pre-prepared low-range (LR) COD reagent vial at 150 °C for 2 h in a Hach DBR200 reactor. The absorbance of the cooled solution was measured at 420 nm using a HACH DR/890 portable colourimeter (Hach Company, USA). The method has a stated detection range of 3 to 150 mg/L. A 100 mg/L standard solution was prepared for daily calibration verification. [40]
Total Suspended Solids (TSS)	APHA Method 2540	A 1 L water sample was filtered through a pre-weighed glass fibre filter (1.5 µm pore size, Whatman GF/C). The filter was dried at 105 °C for 1 h, cooled in a desiccator, and reweighed. The TSS concentration was calculated from the weight difference divided by the sample volume. The detection limit for this method was 0.5 mg/L for a 1 L sample. [42]
Ammonia Nitrogen (NH_3-N)	Hach Method 8155	Analysis using the salicylate method (Hach Method 8155), which uses two types of powder pillows (Ammonia Salicylate and Ammonia Cyanurate). A 10 mL water sample was added with Ammonia Salicylate powder pillows (reaction time: 3 min) and Ammonia cyanurate powder pillow (reaction time: 15 min). The solutions were analysed at 610 nm using a HACH DR/890 portable colorimeter. The method has a stated detection range of 0.01 to 0.50 mg/L. [41]

The coliform density of each specimen (colony-forming unit, CFU/100 mL) was calculated using the formula [44], as stated in Eq. (1):

$$\text{Coliforms}/100\ \text{mL} = \text{Number of colonies} \times 100/\text{Sample volume (mL)} \quad (1)$$

The geometric mean of coliform density (CFU/100 mL) was calculated to determine the average coliform count across samples. The geometric mean was calculated using the Nth root method [44], as shown in Eq. (2):

$$\text{Geometric Mean} = \sqrt[n]{x_1 x_2 x_3 \ldots \ldots x_n} \quad (2)$$

Where $x_1 x_2 x_3 \ldots \ldots x_n$ represent the coliform densities observed from the "n" number of specimens, respectively.

2.3 Water quality index (WQI) and data processing

The WQI was calculated using the Malaysian WQI, a standard by the Department of Environment (DOE), Malaysia. This index was chosen due to its direct relevance to the local regulatory standards for assessing river water monitoring and classification in Malaysia. Six parameters were included in DOE's WQI equation, which integrates Dissolved Oxygen (DO), Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Ammoniacal Nitrogen (NH_3-N), Suspended Solids (SS), and pH. Before WQI calculation, raw water quality data underwent a pre-processing stage. Any missing data for the six key parameters were handled by excluding that specific sampling event from the WQI calculation to ensure the integrity of the index. No further data normalisation was required as the DOE's sub-index equations inherently convert all parameter concentrations (e.g., mg/L for BOD, COD, NH_3-N, and SS; percentage saturation for DO) into a standardised scale. The overall WQI of water was calculated using the formula as stated in Eq. (3):

$$\begin{aligned}[\text{WQI} &= (0.22 \times \text{SIDO}) + (0.19 \times \text{SIBOD}) + (0.16 \times \text{SICOD}) \\ &+ (0.15 \times \text{SIAN}) + (0.16 \times \text{SISS}) + (0.12 \times \text{SIpH})]\end{aligned} \quad (3)$$

where SIDO is the sub-index for DO (% saturation); SIBOD is the sub-index for BOD (mg/L); SICOD is the sub-index for COD (mg/L); SIAN is the sub-index for NH_3-N (mg/L); SISS is the sub-index for SS (mg/L); and SIpH is the sub-index for pH [26]. The sub-indices were calculated based on the raw data for each parameter as per the standard DOE sub-index equations [26], as detailed in Table 4.

Water quality for each site was then classified (Class I to V) based on the computed WQI scores [26] as provided in Table 5. This classification system determines the water suitability for various uses, from protecting sensitive aquatic species and conserving the natural environment (Class I), to sources for supplying drinking water after conventional treatment, and safe body contact recreation (Class II).

2.4 Statistical and data analysis techniques

All statistical analyses were performed using R version 4.4.1 software, with a significance level of $p < 0.05$. Prior to analysis, the dataset was screened for missing values, which were found to be absent, and continuous variables were normalised to ensure comparability across different scales.

Table 4 DOE Sub-Index (SI) calculation equations and ranges

Parameter	Unit	Range of x	Sub-index (SI) Equation
Dissolved Oxygen (DO)	% saturation	for $x \leq 8$	0
		for $x \geq 8$	100
		for $x << 92$	$-0.395 + 0.030 \times^2 - 0.00020 x^3$
Biochemical Oxygen Demand (BOD)	mg/L	for $x \leq 8$	$100.4 - 4.23x$
		for $x > 5$	$108*\exp(-0.055x) - 0.1x$
Chemical Oxygen Demand (COD)	mg/L	for $x \leq 20$	$-1.33x + 99.1$
		for $x > 20$	$103*\exp(-0.0157x) - 0.04x$
Ammoenical Nitrogen (NH_3-N)	mg/L	for $x \leq 0.3$	$100.5 - 105x$
		for $0.3 < x < 4$	$94*\exp(-0.573x) - 5* \lvert x - 2 \rvert$
		for $x \geq 4$	0
Suspended solids (SS)	mg/L	for $x \leq 100$	$97.5*\exp(-0.00676x) + 0.05x$
		for $100 < x < 1000$	$71*\exp(-0.0061x) - 0.015x$
		for $x \geq 1000$	0
pH	-	for $x < 5.5$	$17.2 - 17.2x + 5.02 \times^2$
		for $5.5 \leq x < 7$	$-242 + 95.5x - 6.67 \times^2$
		for $7 \leq x < 8.75$	$-181 + 82.4x - 6.05 \times^2$
		for $x \geq 8.75$	$536 - 77.0x + 2.76 \times^2$

*Note: * means multiplication, exp represents the exponential function, and represents the concentration of each parameter in its respective unit

Table 5 Malaysian WQI classification

WQI Range	Class	Water Quality Status
> 92.7	I	Excellent
76.5–92.7	II	Good
51.9–76.5	III	Average
31.0-51.9	IV	Polluted
< 31.0	V	Highly Polluted

2.4.1 Principal component analysis (PCA)

Principal Component Analysis (PCA) was used to explore the dominant factors that influence water quality across land uses and seasons. Variables were standardised to a mean of zero and unit variance (Z-scores) to account for differences in measurement units. The suitability of the data for Principal Component Analysis (PCA) was evaluated by Bartlett's Test of Sphericity, which was significant ($p < 0.05$), indicating sufficient correlation among variables [45–47]. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was 0.50, which is below the conventional threshold of 0.6. Despite this, PCA was deemed appropriate for an exploratory analysis and visualisation via biplots. The robustness of PCA in environmental studies for pattern exploration and the strong result from Barlett's test provided further justification. Components were extracted following the Kaiser criterion (eigenvalue >1) [48]. To examine the reliability of the component solution, a bootstrapping approach was used on the loading matrix, and the stability of the outcomes across repeated samples was considered as evidence of robustness. The PCA biplots were generated to visualise the clustering of the sites that were grouped by land use and season, allowing for an assessment of spatial and temporal variations in water quality. The proximity of variables in the biplot indicates their correlation with closely clustered parameters, suggesting similar influencing factors.

2.4.2 Spearman correlation coefficient

For the correlation analysis, the Spearman correlation coefficient was selected due to its robustness against non-normal data distributions. This was justified using Shapiro-Wilk

tests, which confirmed widespread non-normality ($p < 0.05$ for most parameters). The Spearman correlation coefficients were calculated to assess the strength and direction of associations between the water quality parameters in different seasons. A correlation coefficient (ρ) value near − 1 or 1 means a strong negative or positive correlation, a ρ value between 0.3 and 0.7 indicates a moderate correlation, while one close to 0 demonstrates a weak or no correlation [49].

2.5 Quality assurance and control

To ensure data reliability and accuracy, a comprehensive Quality Assurance and Control (QA/QC) was implemented throughout the study [40, 50, 51]. All field and laboratory instruments (e.g. YSI ProDSS Multiparameter Water Quality Meter, and HACH DR/890 portable colorimeter) were calibrated in accordance with manufacturer specifications using certified standards. To monitor potential contamination, field blanks and reagent blanks were processed with each sample batch at a frequency of one per every twenty samples. Field duplicates were collected at 10% of the sampling sites to assess sampling precision and spatial variability. Additionally, sterile techniques were employed during sample collection and processing to prevent contamination. The accuracy of the analytical methods was validated by analysing certified reference materials (CRMs) with each batch of samples, with results consistently within the established and accepted recovery range [40, 51, 52]. Data validation included cross-checking field measurements with laboratory results and performing consistency checks across replicates and standards. Any data points outside of expected ranges were flagged for re-analysis or rejection.

3 Results

3.1 Water quality index (WQI) across sites and seasons

Data distribution was confirmed to be normal using the Shapiro-Wilk test ($p = 0.604$, $p > 0.05$). Consequently, a two-way ANOVA was performed to compare water quality between seasons and sites. The analysis revealed that the Water Quality Index (WQI) was significantly influenced by both sampling sites ($F(4, 4) = 9.58$, $p = 0.025$) and season ($F(1, 4) = 8.50$, $p = 0.043$) as shown in Table 6.

Post-hoc Tukey's HSD tests revealed that the Water Quality Index (WQI) at the downstream site LS5 was significantly lower than at the upstream site LS1 ($p = 0.027$). The difference between LS5 and LS2 also approached significance ($p = 0.053$). No other pairwise comparisons between sites were statistically significant. There is a significant difference in the WQI between the dry and wet seasons ($p < 0.05$, $p = 0.043$). Table 7 presents the detailed Water Quality Index (WQI) classification [26] for each site across seasons.

As visually summarised in Fig. 3, upstream forested sites (LS1, LS2, LS3) consistently maintained excellent Class I water quality, while LS4 and LS5 showed seasonal shifts from Class II in the wet season to Class I in the dry season. This decline was statistically significant ($p = 0.027$), a fluctuation that may be attributed to land use patterns, with

Table 6 Two-Way ANOVA of WQI across sites and seasons

	Df	Sum Sq	Mean Sq	F value	Pr(> F)
Site	4	40.35	10.086	9.581	0.0251
Season	1	8.95	8.949	8.501	0.0434
Residuals	4	4.21	1.053	-	-

Table 7 Water quality index (WQI) classification of each site

Parameter	Paoh (LS1)		Nanga Tiga (LS2)		Linsum (LS3)		Nanga Spak (LS4)		Jelau (LS5)	
	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
Dissolved oxygen (%)	93.67	90.87	94.80	95.13	96.73	95.92	94.80	93.84	94.13	93.10
Biochemical oxygen demand (mg/L)	1.34	0.88	1.43	1.18	1.48	1.13	1.29	1.02	1.55	0.89
Chemical oxygen demand (mg/L)	1.33	1.33	4.67	3.33	10.33	6.33	10.33	7.67	12.67	9.33
Ammoniacal nitrogen (NH_3-N)	0.02	0.01	0.04	0.03	0.16	0.14	0.08	0.06	0.18	0.13
Total suspended solids (mg/L)	6.67	2.00	9.56	3.33	8.56	6.33	33.09	8.33	33.34	10.00
pH	7.21	7.22	6.95	7.40	7.02	7.61	7.07	7.53	7.07	7.07
Water Quality Index	**97.12**	**97.49**	**95.80**	**96.85**	**92.81**	**94.08**	**92.14**	**95.00**	**89.90**	**93.81**
Class	**I**	**I**	**I**	**I**	**I**	**I**	**II**	**I**	**II**	**I**

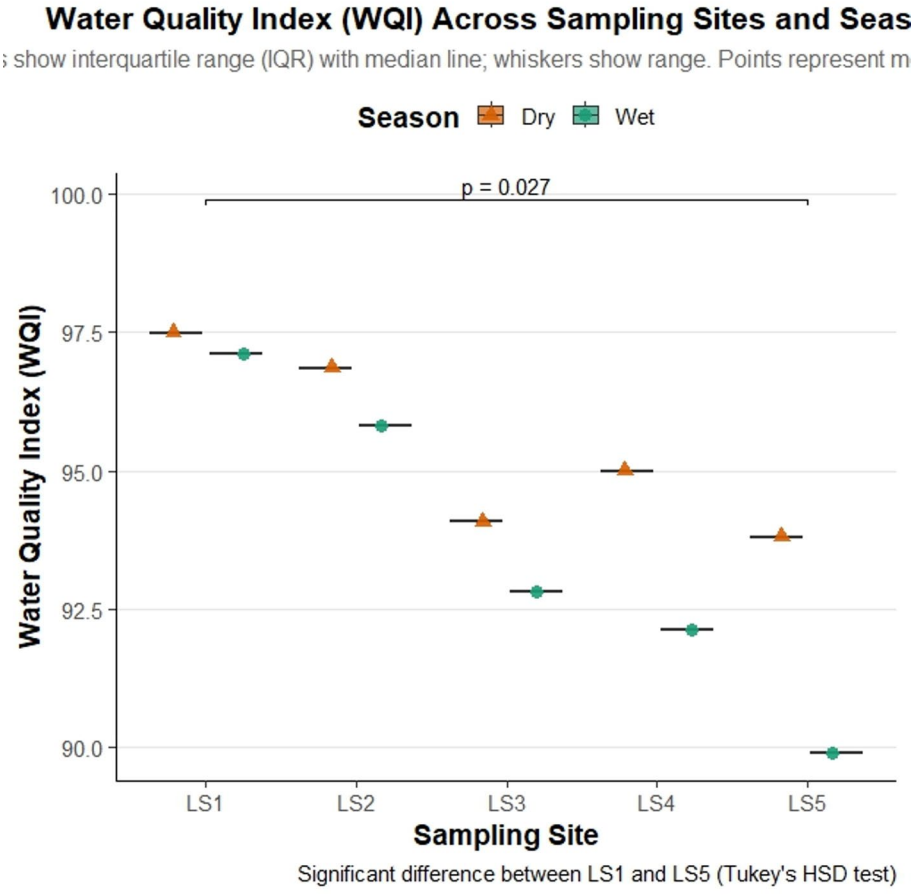

Fig. 3 WQI across sites and seasons. Boxes show interquartile range (IQR) with median line; whiskers show range. The point represents the means

upstream sites surrounded by dense forest and downstream sites influenced by built-up areas and anthropogenic activities.

Dissolved Oxygen (DO) remained consistently high (> 90%) across all sites, while BOD and COD were both lower in the dry season. The elevated COD levels at LS5 during wet seasons (12.67 mg/L) compared to dry seasons (9.33 mg/L) suggested increased organic pollution from urban runoff. Ammoniacal nitrogen (NH_3-N) concentrations were higher

at LS3, LS4 and LS5, indicating possible organic waste contamination from agricultural land or sewage. Total suspended solids (TSS) showed noticeable spatial variation with downstream sites (33.09–33.34 mg/L) exceeding upstream levels (6.67–9.56 mg/L) during wet seasons, likely due to erosion and urban runoff. All sites showed pH levels within the optimal range (7-7.6) for most aquatic organisms.

The study revealed distinct seasonal influences and spatial patterns in water quality, where downstream sites (LS4 and LS5) exhibited wet season deterioration to Class II due to increased runoff of sediments, nutrients, and organic pollutants. In the dry season, improved clarity and lower pollutant load were observed, as all sites were classified as Class I. Spatially, upstream sites such as LS1, which are surrounded by forests with minimal anthropogenic impact, maintained Class I throughout both seasons, underscoring their critical role as water quality buffers. The seasonal fluctuations downstream (LS4 and LS5) demonstrate the vulnerability of these areas to anthropogenic impacts from urban and agricultural activities. Despite these variations, water quality remains good to excellent at all sites (Class I-II), indicating the ecosystem's resilience to moderate anthropogenic stress. Hence, protecting upstream forested areas and managing urban runoffs are critical in maintaining overall water quality.

3.2 Faecal coliform levels and health thresholds

Faecal coliform (FC) concentrations showed a clear temporal trend with significantly higher concentrations during the wet season. Geometric means ranged from 228.94 to 992.87 CFU/100 mL, where four of five sites exceeded the DOE recreational standard of 400 CFU/100 mL (Fig. 4). These exceedances were most prominent at Nanga Tiga (LS2) and Jelau (LS5) during the wet season (992.87 CFU/100 mL; 2.5× the limit and 683.10 CFU/100 mL; 1.7× the limit, respectively), suggesting rainfall and surface runoff as major drivers of contamination. However, Linsum (LS3) exceeded the threshold standard in both wet (526.86 CFU/100 mL) and dry (660.00 CFU/100 mL) seasons, indicating a persistent point source pollution that was unrelated to rainfall.

Spatial analysis revealed a clear contamination gradient. The most upstream forested site, Paoh (LS1), maintained low counts and was compliant with the DOE standard in both seasons. In contrast, sites progressively further downstream (LS2 to LS5) near settlements and school areas showed frequent exceedances. Hence, the distinct difference in FC levels between upstream and downstream sites reveals a clear spatial variation in contamination. Worth mentioning, total coliform counts (TCC) were elevated throughout the watershed, but are presented for context only, as no direct regulatory thresholds for TCC under the current DOE standards.

The observed faecal coliform exceedances are strongly tied to the land use composition at each site (Table 1). Upstream Paoh (LS1), which is 98.7% forested, consistently remained below the DOE standard, highlighting the importance of intact riparian vegetation. In contrast, Nanga Tiga (LS2), with 35.7% urban/settlement land and small-scale plantations, recorded the highest exceedance (993 CFU/100 mL) during the wet season, implicating human settlements and agricultural runoff as major contributors. Similarly, Linsum (LS3), characterised by 22% combined cleared and urban land, showed persistent exceedances in both seasons, suggesting chronic point-source inputs that could stem from sewage leakage. Nanga Spak (LS4), with 25.4% urban cover and proximity to a poultry farm, exhibited wet-season exceedances consistent with livestock waste

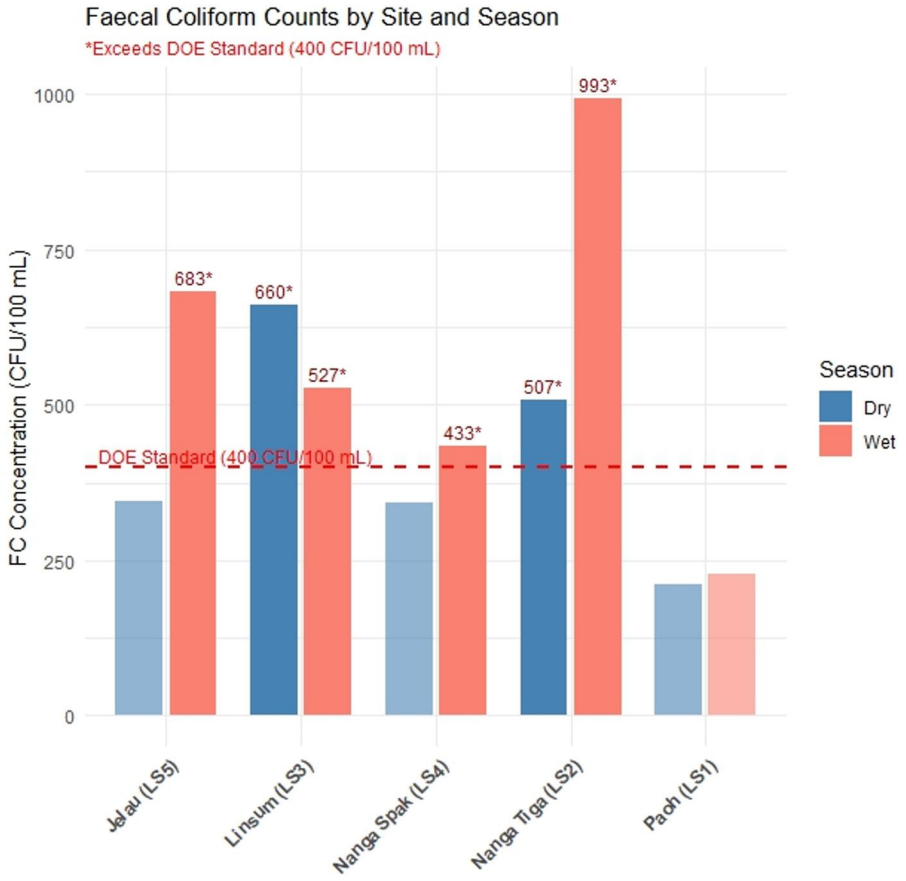

Fig. 4 Faecal coliform counts (CFU/100 mL) by site and season. The dashed red line indicates the DOE recreational water quality standards for faecal coliform counts (400 CFU/100 mL). An asterisk (*) denotes exceedances

contributions. Downstream Jelau (LS5), influenced by 18.3% urban land and river/ditch networks, also exceeded standards in the wet season, reflecting cumulative anthropogenic impacts.

3.3 Multivariate statistical analysis

3.3.1 Principal component analysis (PCA)

The PCA was performed to identify the main factors that influence the water quality across land uses and seasons. The PCA revealed that the first two principal components are the most essential factors, which signify > 74.14% (PC1: 48.39%, PC2: 25.75%) of the total variance in water quality data (Fig. 5). The first four principal components were retained, aligning with the Kaiser criterion (eigenvalue > 1). The PCA loadings table (Table 8) indicates the correlation between the water quality parameters and the first four principal components.

PC1 (48.39%) was interpreted as the organic pollution and the domestic factor. This component showed strong positive loadings from BOD (0.358), TSS (0.338), and turbidity (0.368). These parameters are key indicators of organic matter and suspended solids, often associated with domestic sewage and agricultural runoff. The positive loading of TCC (0.319) further supports this interpretation as it indicates the presence of microbial contamination.

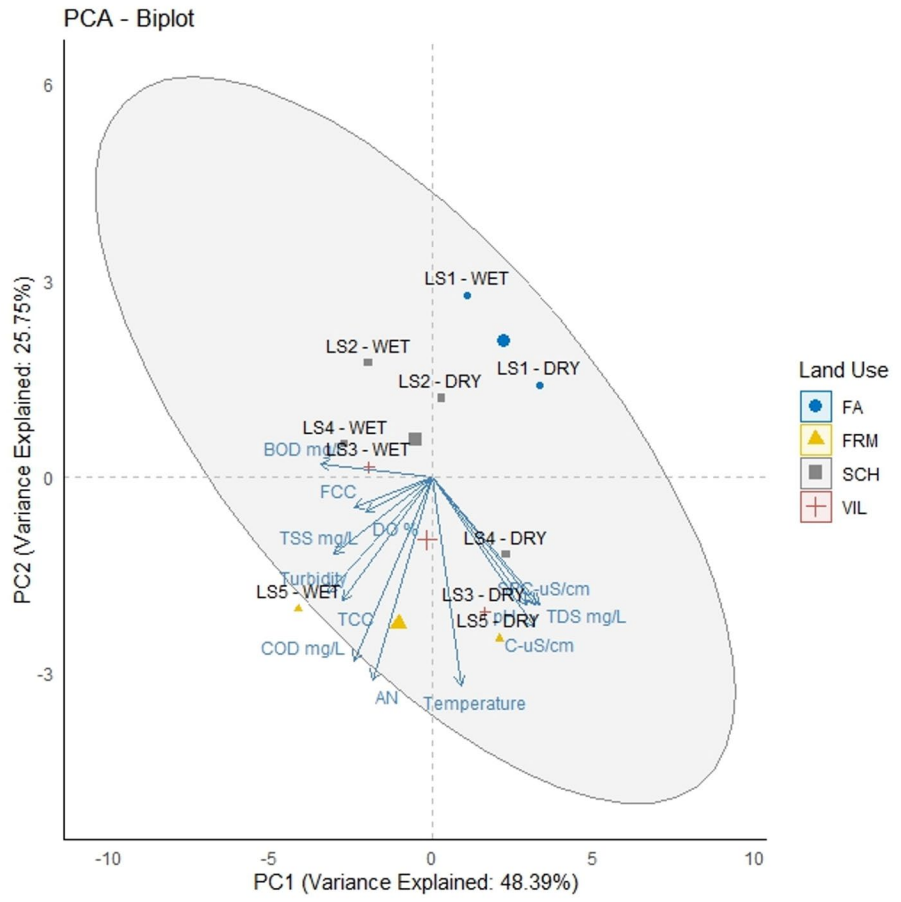

Fig. 5 PCA biplot of water quality across sites for both wet and dry seasons across different land use. (FA: Forested Area, FRM: Farm/Agricultural Land, SCH: School area, VIL: Village/Settlement Area)

Table 8 PCA loadings for water quality parameters

	PC1	PC2	PC3	PC4
FCC	0.258	0.011	0.453	-0.589
TCC	0.319	0.203	-0.133	-0.507
Temperature	-0.040	0.495	0.298	-0.166
DO%	0.219	0.046	0.623	0.429
BOD mg/L	0.358	-0.120	-0.029	0.120
COD mg/L	0.301	0.347	-0.101	0.275
SPC-µS/cm	-0.308	0.353	-0.164	-0.036
TDS mg/L	-0.296	0.350	-0.170	-0.085
TSS mg/L	0.338	0.085	-0.358	0.139
Turbidity	0.368	0.172	-0.279	-0.057
pH	-0.270	0.360	0.164	0.112
AN	0.243	0.404	0.036	0.227

Meanwhile, PC2 (25.75%) interpreted as the temperature and nutrient factor, with high positive loadings from temperature (0.495), AN (0.404), and SPC (0.353), TDS (0.350). This combination suggests that PC2 represents a factor influenced by thermal conditions and the concentration of dissolved ions and nutrients. The positive loadings of SPC and TDS indicate higher concentrations of dissolved ions, often associated with lower

water levels during drier periods. The positive loading of ammoniacal nitrogen (AN) also points to a relationship with nutrient pollution from sources like agricultural runoff.

The PCA biplot (Fig. 5) displays clear seasonal and spatial clustering patterns. Spatially, samples from agricultural land (FRM) and settlement areas (VIL) aligned with high PC1 scores, linking these land uses to organic and particulate pollution. In contrast, forested areas (FA) correlated with negative PC1 values, demonstrating their role in preserving water quality. These relationships demonstrate the significant impact of land use on water quality variability. Seasonally, the biplot shows that certain sites, particularly during the dry season, cluster along this component, suggesting seasonal shifts in these factors. The co-loading of temperature and AN on this axis suggests that seasonal warming may enhance the dissolved substances and influence nutrient levels. Downstream wet-season samples (LS4-WET, LS5-WET) clustered positively in both PC1 and PC2, indicating combined organic pollution and nutrient effects during high rainfall periods. Both wet and dry season samples from upstream forested sites (LS1) clustered negatively along PC1, reflecting lower contamination levels. This suggests a synergistic impact of both organic pollution and nutrient enrichment, likely exacerbated by rainfall-induced runoff from the surrounding land.

The distribution of the samples along the principal components directly demonstrates the significant impact of both land use and seasonal changes on water quality. These PCA results quantitatively support the spatial and seasonal patterns observed in the WQI and coliform data, ensuring the component significance of identified patterns.

3.3.2 Correlation analysis

The relationship among the water quality parameters was determined using the Spearman correlation coefficient method. The Spearman correlation coefficient (ρ) ranges from − 1 to 1, where 1 indicates a strong positive correlation, -1 indicates a strong negative correlation, and 0 means no correlation. The statistical significance of these correlations was evaluated using a p-value ($p < 0.05$). The results are presented visually in Spearman correlation matrices for the wet season (Fig. 6) and the dry season (Fig. 7). A more detailed summary of the key correlations and their statistical significance (p-values) for both wet and dry seasons is provided in Table 9. Only strong correlations ($\rho > 0.7$) that were statistically significant ($p < 0.05$) are included to focus on ecologically meaningful relationships and to reduce clutter in the large matrices.

In the wet season, temperature showed a strong positive correlation between temperature with total suspended solids (TSS) and turbidity ($\rho = 0.97$, $p < 0.05$ for both). This suggests that higher temperatures during the wet season may be associated with increased suspended matter. Similarly, chemical oxygen demand (COD) demonstrates a strong positive correlation with ammoniacal nitrogen (AN) and turbidity ($\rho = 0.97$, $p < 0.05$ for both) and with temperature ($\rho = 0.92$, $p < 0.05$). This indicates an association between organic matter, nutrients, and reduced water clarity during rainfall periods. TSS and turbidity also show a strong positive correlation ($\rho = 0.90$, $p < 0.05$), which was expected as both parameters measure particulate matter in the water. A strong positive correlation was also observed between specific conductance (SPC) and conductivity (C) with total dissolved solids (TDS), ($\rho = 0.90$, $p < 0.05$ for both), confirming that they share sources or are linked by the same ecological processes in measuring similar water quality characteristics. Other significant relationships included faecal coliform count (FCC) and total

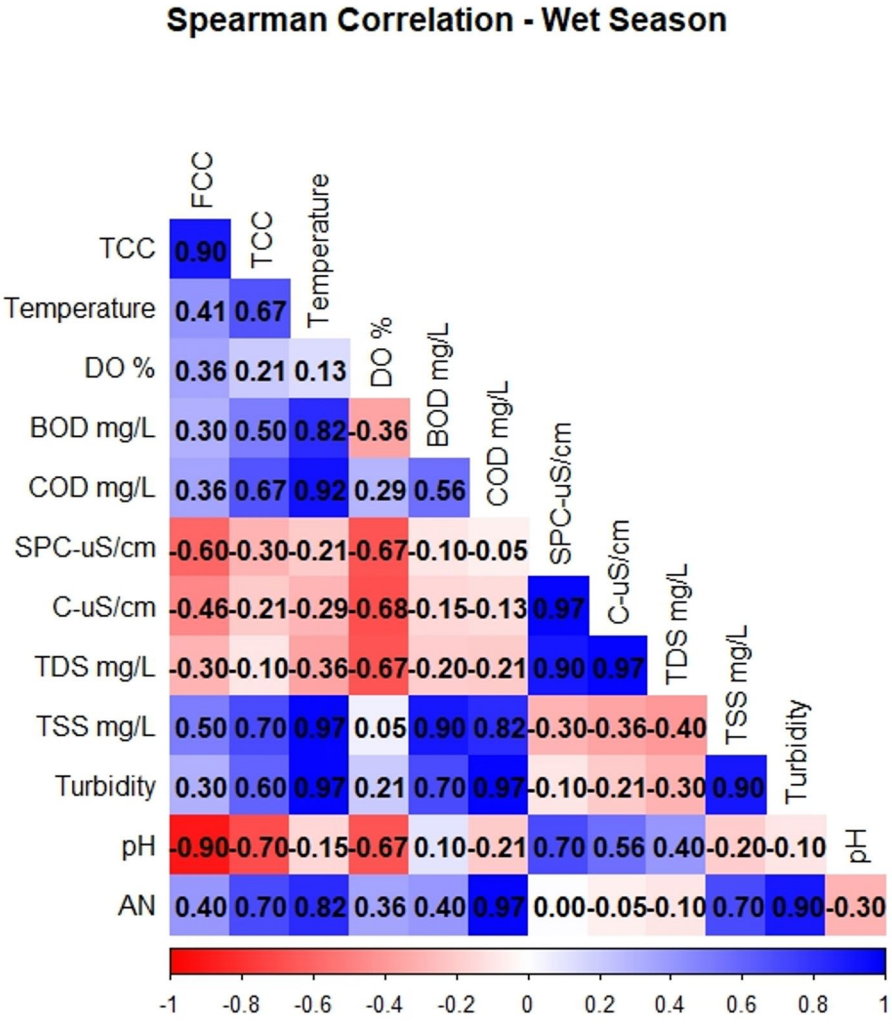

Fig. 6 Spearman correlation matrix between all parameters studied in the wet season

coliform count (TCC) ($\rho = 0.90$, $p < 0.05$), pointing to similar contamination sources, likely from stormwater runoff. Interestingly, a strong correlation between COD and TSS ($\rho = 0.82$) was not statistically significant ($p > 0.05$) during this season.

In the dry season, a different set of strong and significant correlations was observed. Some relationships that were non-significant in the wet season became perfectly correlated and significant in the dry season. For instance, the correlations between COD and turbidity, TSS and turbidity, COD and TSS, and temperature and AN all reached a perfect positive correlation ($\rho = 1.00$, $p < 0.05$). Furthermore, parameters that showed a weak or inverse relationship in the wet season shifted dramatically. The correlation between pH and AN changed from a weak, non-significant negative correlation (ρ = -0.30, $p > 0.05$) in the wet season to a strong, significant positive correlation ($\rho = 0.90$, $p < 0.05$) in the dry season. A similar reversal was observed for temperature and pH ($\rho = 0.90$, $p < 0.05$). The relationship between FCC and Dissolved Oxygen (DO) also strengthened considerably from weak and non-significant ($\rho = 0.36$, $p > 0.05$) to strong and significant ($\rho = 0.90$, $p < 0.05$).

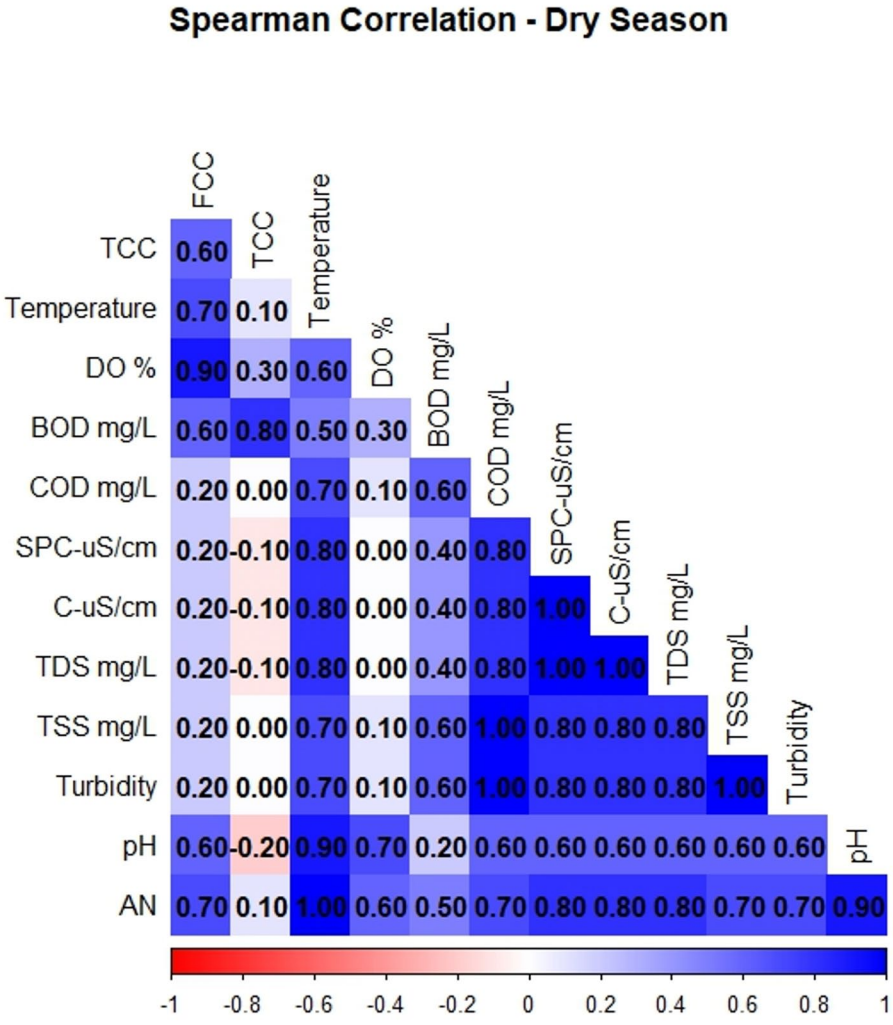

Fig. 7 Spearman correlation matrix between all parameters studied in the dry season

Notably, a clear contrast can be observed in the correlation patterns between seasons. Some parameters showed consistent strong positive corelations with significance throughout both seasons, including TSS and turbidity ($\rho = 0.90$ in wet, $\rho = 1.00$ in dry), COD and turbidity ($\rho = 0.97$ in wet, $\rho = 1.00$ in dry), SPC and TDS ($\rho = 0.90$ in wet, $\rho = 1.00$ in dry), and C and TDS ($\rho = 0.90$ in wet, and $\rho = 1.00$ in dry). Meanwhile, several coefficients achieved statistical significance predominantly in the dry season compared to the wet season. This suggests that the shifting of these parameters might be influenced by the seasonal impact.

4 Discussion

4.1 Land use and seasonal influence

This study provides qualitative and quantitative evidence that land use and seasonal rainfall influence water quality and faecal contamination patterns in the Batang Layar watershed. Through the combined application of DOE-WQI, FCC, and multivariate statistical approaches, this study has revealed a significant spatial-temporal gradient that is directly associated with anthropogenic influence.

Table 9 Correlation coefficients across water quality parameters (Wet and dry season)

Water Quality Parameter	Wet season		Dry season	
	ρ	*p*-value	ρ	*p*-value
Temperature vs. TSS	0.97	0.0048*	0.70	0.1881
Temperature vs. turbidity	0.97	0.0048*	0.70	0.1881
COD vs. AN	0.97	0.0048*	0.70	0.1881
COD vs. turbidity	0.97	0.0048*	1.00	0.0000*
Temperature vs. COD	0.92	0.0263*	0.70	0.1881
FCC vs. TCC	0.90	0.0374*	0.60	0.2848
TSS vs. turbidity	0.90	0.0374*	1.00	0.0000*
Turbidity vs. AN	0.90	0.0374*	0.70	0.1881
COD vs. TSS	0.82	0.0886	1.00	0.000*
FCC vs. DO	0.36	0.5528	0.90	0.0374*
SPC vs. TDS	0.90	0.0374*	1.00	0.0000*
C vs. TDS	0.90	0.0374*	1.00	0.0000*
pH vs. AN	-0.30	0.6238	0.90	0.0374*
Temperature vs. pH	-0.15	0.8048	0.90	0.0374*
Temperature vs. AN	0.82	0.0886	1.00	0.000*

*denote significance difference ($p < 0.05$)

As highlighted in Sect. 3.2, faecal coliform exceedances were concentrated at downstream sites (LS2-LS5), while the upstream forested site (LS1) consistently remained compliant with DOE standards. These patterns are closely linked to the land use profiles of the watershed (Table 1), where higher proportions of urban and agricultural land correspond to elevated FC levels, particularly during the wet season. Although the WQI classified all sites as Class I or II, suggesting good water quality, elevated coliform counts reveal a critical discrepancy. This exposes the limitation in the Malaysian WQI framework, which excludes microbiological parameters despite their significance as indicators of waterborne pathogens and public health risks. Persistent dry-season FC exceedances at LS2/LS3 suggest chronic contamination from poor sanitation [53-55], emphasising the need for integrated monitoring that includes microbial indicators. Seasonal rainfall patterns significantly influence pollution dynamics, with wet season FCC exceedances reaching 992.87 CFU/100 mL due to surface runoff and sediment resuspension, similar to findings in Nigeria and Ghana [56-57].

Downstream sites (LS4 and LS5) with mixed urban-agricultural land use experience greater seasonal fluctuation, exhibiting water quality declines to Class II during wet seasons due to runoff-driven mobilisation of sediments, nutrients, and faecal matter. This pattern aligns with studies linking anthropogenic activities to the elevation of microbial and organic pollution during high rainfall periods [32–35]. The multivariate statistical analysis provides further quantitative evidence. The PCA identified organic pollution and domestic factors (PC1: 48.39% variance) as the dominant influence on water quality. This component had strong positive loadings from parameters like BOD (0.358), TSS (0.338), turbidity (0.368) and TCC (0.319). The PCA biplot showed a clear spatial clustering, with samples from agricultural and settlement areas aligning with high PC1 scores, directly linking these land uses to organic and particulate pollution. Furthermore, the Spearman correlation analysis confirms this link, showing strong positive correlations between FCC and TCC (ρ = 0.90) and between COD and AN (ρ = 0.97) during the wet season. This supports the conclusion that agricultural and domestic runoff are major contributors to organic pollution, a finding consistent with studies in other tropical river

systems. For example, a study in a similar Malaysian context highlighted that urbanisation and seasonal variability are key drivers of microbial contamination. Our findings also align with [7, 62] in terms of anthropogenic influences leading to seasonal shifts in tropical river water quality. Agricultural land use significantly contributes to amplifying nutrient and microbial inputs into aquatic systems through runoff containing fertilisers, organic waste, and sediments [58-60], while urban areas contribute point-source pollution. These comparisons align with site-specific observations in the Batang Layar watershed reflect a broader trend in tropical catchments where downstream areas with dense human settlements and agricultural activities are more vulnerable to pollution during the wet season, while in the dry season, reduced runoff leads to improved water quality, as reflected in the WQI classifications shifting from Class II to Class I.

In contrast, upstream forested areas (LS1) maintain stable water quality with Class I status throughout both seasons, reflecting the buffering capacity of intact riparian vegetation in reducing erosion and filtering pollutants [39–41]. While Nanga Tiga (LS2), are associated with the inactive tagang system, a community-based aquatic conservation practice that promotes pristine water conditions, it still exhibits FC exceedances, suggesting that the systems require consistent management to remain effective [69].

The location of LS5 near the raw water intake point for the gazetted Betong/Debak/Spaoh Water Catchment Area (WCA) highlights the critical role of regulatory frameworks in protecting water sources. Land use restrictions implemented within the 8-km radius of the intake points (established in 2000 under Swk. L.N. 46/2000) help mitigate contamination risks, though seasonal runoff remains a challenge for maintaining water quality standards.

Notably, this study's baseline insights into seasonal and land use influences on water quality in the Batang Layar watershed are constrained by its single-year sampling design and two seasonal snapshots. As such, the findings capture seasonal contrasts rather than long-term temporal trends, and spatial patterns are restricted to site-specific observations rather than fine-scale modelling. Thus, the study demonstrates that relying solely on WQI may mask underlying microbial contamination in watersheds, particularly in regions with intensive land use and seasonal rainfall. This study underscores the necessity of maintaining and enforcing protective measures in critical zones, implementing integrated monitoring approaches that include microbiological parameters and land use assessments, and preserving forested headwaters that provide natural water quality protection [65-68]. These measures are essential to mitigate seasonal contamination and safeguard water resources in tropical catchments.

4.2 Implications for water safety

Despite favourable WQI classifications, elevated faecal coliform levels pose health risks, especially during the wet season. This discrepancy underscores the need to integrate microbiological assessments with physicochemical indices for comprehensive water quality evaluation. Our findings move beyond simple data presentation by linking observed contamination levels to actionable public health frameworks. Sites located near schools and densely populated settlements exhibit persistent FC exceedances, such as LS3's dry-season breach, indicating chronic contamination likely stemming from inadequate sanitation infrastructure. These findings are not merely observational; they can directly implicate a higher probability of gastrointestinal diseases and other

waterborne illnesses in vulnerable populations, especially children at nearby schools. This aligns with [14], who emphasised the public health risks associated with faecal pollution and the limitations of traditional indicators in capturing episodic contamination events. Moreover, the pronounced wet-season spikes correspond with global health advisories for recreational waters, as outlined in the [70], which recommends stricter microbial thresholds during high-risk periods.

To mitigate these risks and provide a clear policy roadmap, this study supports a multifaceted approach grounded in land use planning, sanitation infrastructure, and seasonal monitoring. Based on the persistent exceedances of FCC at LS3 and other settlement-agricultural sites, policymakers should prioritise investments in sanitation infrastructure upgrades in agro-urban areas. First, the preservation of forested headwaters and the enforcement of riparian buffer zones are essential strategies for reducing microbial runoff [71]. demonstrated the effectiveness of such buffers in tropical agricultural catchments, highlighting their role in nutrient and pathogen filtration. Additionally, addressing sewage leakage and improving waste management systems in peri-urban settlements is critical [72]. identified sanitation access barriers in West African peri-urban zones, while [73] emphasised microbial and AMR risks linked to agro-ecosystem runoff and poor waste containment.

A One Health (OH) surveillance model that incorporates climate-sensitive antimicrobial resistance (AMR) monitoring across environmental, human, and animal health domains has been proposed [74]. This is vital for addressing the broader antimicrobial resistance threat amplified by faecal pollution. Expanding microbial testing during monsoon periods is vital for capturing episodic contamination events. This will allow for the capture of contamination spikes and the implementation of a more accurate, risk-based water safety plan. The integration of this microbial data into a public health response system, such as the CDC's Waterborne Disease and Outbreak Surveillance System (WBDOSS) [75], enable early detection and targeted interventions, directly reducing the disease burden.

Beyond infrastructure and monitoring, these findings carry important implications for waterborne disease surveillance and community health education. Strengthening local capacity to detect and respond to contamination events through early warning systems and public outreach can significantly reduce disease burden. Community engagement initiatives that promote safe water practices and hygiene awareness are especially vital in high-risk zones near settlements and schools. To reinforce the generalizability of these findings, this study aligns with [73], whose regional synthesis identified sanitation, land use, and climate variability as consistent predictors of microbial contamination across diverse geographic contexts. Together, these insights support the development of SDG 6-aligned policies that integrate both microbiological and physicochemical metrics, ensuring safer water access and more resilient public health systems.

4.3 Policy and management recommendations

To mitigate contamination risks in the Batang Layar watershed, the implementation of Integrated Water Resource Management (IWRM) is essential [76]. This approach should prioritise land use regulation, particularly in upstream catchment zones, and incorporate seasonal water quality monitoring to capture temporal variations in pollutant loads. The findings from Batang Layar watershed seasonal contamination patterns are shown,

particularly in wet season FCC exceedances near settlements and agricultural lands. These land use-driven water quality fluctuations necessitate integrated interventions that align with studies in Malaysia and South Asia that highlighted fragmented governance and unregulated land use are major barriers to effective IWRM [61, 62].

Strengthening surveillance through microbial source tracking (MST), increased sampling frequency, and sanitary surveys will enable more precise identification of pollution sources and inform targeted interventions. For instance, LS3 persistent dry season FC breaches (>400 CFU/100 mL DOE standard) could pinpoint contamination origins by integration of MST. Integration of MST, including host-specific qPCR assays, has been validated in both temperate and tropical watersheds as an effective tool for tracing faecal contamination and guiding remediation efforts [63, 64]. These recommendations align with global best practices, including the CDC's Waterborne Disease and Outbreak Surveillance System (WBDOSS), which advocates for tiered monitoring frameworks and inter-agency data integration to enhance early warning capabilities [75]. Moreover, aligning local strategies with the WHO/UNICEF Joint Monitoring Programme (JMP) reinforces Malaysia's commitment to Sustainable Development Goal 6, which emphasises universal access to safe water and sanitation, and the sustainable management of water resources [80].

Studies by [81] propose a tiered riparian buffer framework for small Indian rivers, calibrated to slope, soil, vegetation, and land use intensity. Their findings show that fixed-width buffer policies often fail in diverse landscapes, and that adaptive widths (10–30 m for erosion control, 30–100 m for nutrient retention) are more effective. This approach resonates with the Batang Layar context, where land-use pressures and ecological variability demand flexible, evidence-based interventions. This enforcement can be prioritised on agricultural and urban areas (LS2 to LS5), where PCA identified organic pollution (PC1:48.39% variance). Incorporating community-based water safety planning can empower local Iban communities within the watershed through capacity-building initiatives and sanitation management, eventually enhancing adaptive governance and fostering public trust. These studies align with [81] and underscore that participatory approaches and inclusive stakeholder engagement significantly improve the effectiveness of riparian buffer strategies. These locally grounded interventions not only address immediate contamination risks but also contribute to long-term ecological resilience and institutional accountability.

To operationalise these recommendations, local authorities such as the Department of Environment (DOE), Sarawak Rivers Board, and district health offices must collaborate with community leaders, NGOs, and academic institutions to coordinate monitoring, enforcement, and education efforts. The concrete steps should include: (i) establishing a multi-agency watershed task force led by the Sarawak Natural Resources and Environment Board (NREB), (ii) piloting MST and buffer zone enforcement in high-risk subcatchments such as LS3, and (iii) integrating water quality data into district-level land use planning [82]. Feasibility depends on securing adequate funding through federal environmental allocations or international grants (e.g., GEF and ASEAN Transboundary Water Initiatives), technical capacity through partnerships with local universities and research institutes, and political will, particularly for MST implementation and buffer zone enforcement [77-79, 83, 84]. Future implementation should be phased, beginning

with pilot projects in high-risk zones to evaluate cost-effectiveness and community uptake before scaling region-wide [85].

Taken together, the recommendations outlined above advocate for a multi-tiered, evidence-based policy framework tailored to the unique hydrological and socio-environmental dynamics of the Batang Layar watershed. By integrating scientific monitoring, adaptive land use regulation, and community participation, Sarawak can move toward a more robust and equitable water governance model. Such efforts are critical not only for safeguarding public health but also for ensuring the sustainability of water resources in the face of climate variability and development pressures.

5 Conclusion

Overall, this study demonstrates that land use patterns and seasonal rainfall significantly impact faecal contamination and water quality dynamics in the Batang Layar River. Findings reveal that wet season FC levels frequently exceeded the DOE standards (reaching up to 992.87 CFU/100 mL), particularly in downstream areas impacted by settlements and agricultural lands. While WQI classifications remained generally favourable (Class I-II), the persistent microbial contamination underscores the importance of integrating standard physicochemical assessments with bacteriological monitoring for a more comprehensive assessment. Spatial analysis showed downstream sites exhibited seasonal fluctuation linked to anthropogenic activities, whereas upstream forested areas maintained stable water quality throughout both seasons, emphasising the protective role of intact riparian vegetation.

Despite the clear seasonal and spatial patterns, detailed trend analyses and spatial distribution modelling were beyond the scope of this baseline assessment. Future research using multi-year data and GIS-based modelling is needed to capture long-term trends and finer-scale contamination hotspots. Additionally, microbial source tracking (MST) using molecular techniques should be employed to identify contamination origins and investigate potential antimicrobial resistance (AMR) patterns associated with faecal pollution using a One Health framework. To address these challenges, the study recommends several practical interventions. These include the development of scientifically designed riparian buffers (30–100 m width) in erosion-prone areas and the improvement of sanitation infrastructure to mitigate contamination. These evidence-based management strategies would significantly contribute to achieving SDG 6 targets while ensuring the long-term sustainability of the tropical mixed-use watersheds, such as Batang Layar River, as a vital water resource.

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Author contributions

SL conceptualised the study, supervised the research, and contributed to drafting the manuscript. SJ conducted the experiments and co-drafted the manuscript. TMA conducted the experiments and performed data analysis. MBUT and FSA were involved in water sampling and critically reviewed and edited the manuscript for intellectual content. KKWH contributed to drafting and reviewing the manuscript. JM, JG, and LL critically reviewed and edited the manuscript for intellectual content.

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Data availability
Data supporting the findings of this study include information on water catchment areas obtained from the Jabatan Bekalan Air Luar Bandar (JBALB) and land cover maps from the Land and Survey Department (LSD). These data are subject to access restrictions as they are classified under a non-disclosure agreement (NDA) for research purposes and are not publicly available. Access to this data may be requested directly from the said agencies, subject to approval by the agency in accordance with government data regulations.All data generated or analysed during this study are included in this published article as supplementary data.

Declarations

Ethics approval and consent to participate
All authors are consent in participate in this research.not applicable.

Consent for publication
All authors are consent in this research publication.

Competing interests
The authors declare no competing interests.

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