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Water quality dynamics in a rapidly changing watershed: A case study of the Jeneberang River, South Sulawesi

Baharuddin Burhan[1], Riswal Karamma[2*], Roslinda Ibrahim[3], Agus Iftidah Turahmasnyah[4]

[1] Department of Environmental Engineering, Faculty of Engineering, University Hasanuddin, Makassar, 90245, Indonesia
[2] Department of Civil Engineering, Faculty of Engineering, University Hasanuddin, Makassar, 90245, Indonesia
[3] Department of Environmental Engineering, Faculty of Engineering, University Hasanuddin, Makassar, 90245, Indonesia
[4] Environmental Management Study Program, Graduate School, Hasanuddin University, Makassar 90245, Indonesia
* Corresponding author's e-mail: riswalk@unhas.ac.id

ABSTRACT

Water quality in river systems is strongly influenced by land use changes; however, spatial patterns of pollution in rapidly developing watersheds remain insufficiently understood. This study investigates the relationship between land use change and river water quality in the Jeneberang watershed, Indonesia, through an integrated approach combining field-based monitoring and GIS-based spatial analysis. A total of seventeen monitoring stations were established along a 29.51 km stretch of the river, representing upstream, midstream, and downstream sections, with observations conducted from November 2024 to May 2025. Key parameters analyzed included temperature, dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP). Water quality was evaluated using national standards and the Pollution Index (PI) method, while spatial distribution patterns were analyzed using the Inverse Distance Weighting (IDW) interpolation technique in ArcGIS. The results reveal pronounced seasonal variability in water quality. During the dry season, pollution levels remained low, with PI values ranging from 0.35 to 0.41, indicating good water quality conditions. In contrast, the rainy season showed a significant deterioration, with PI values increasing from 1.70 to 8.50, corresponding to lightly to moderately polluted conditions. The highest pollutant concentrations were observed in downstream areas, particularly at Station 16, where TSS reached 948 mg/L, BOD 43 mg/L, and COD 290 mg/L. Spatial analysis demonstrated a clear correlation between pollutant distribution and land use patterns, highlighting the impact of agricultural activities and urban expansion on water quality degradation. Although this study is limited by its short-term observation period and does not capture long-term climatic or hydrological variability, it provides a comprehensive framework for linking land use dynamics with river water quality. By integrating field measurements with geospatial modeling, this study offers a novel contribution to understanding spatial pollution dynamics in tropical watersheds and provides valuable insights for watershed management, including erosion control, pollution mitigation, and sustainable land use planning.

Keywords: water quality, land use, Jeneberang watershed, spatial modeling, pollution index.

INTRODUCTION

Water quality is a critical determinant of the sustainability of river ecosystems, particularly in watershed areas. Variations in land use, including agriculture, settlements, and industrial activities, can significantly alter the physical, chemical, and biological characteristics of water (Anh et al., 2023; Ahmad et al., 2021). In tropical regions, rapid and often unregulated land use change intensifies pressure on river systems, leading to increased surface runoff, erosion, and pollutant loading, which collectively contribute to water quality degradation.

The Jeneberang Watershed (DAS Jeneberang), located in South Sulawesi, Indonesia, represents a typical example of a rapidly developing tropical watershed under significant anthropogenic pressure. The conversion of natural vegetation into agricultural and urban land has accelerated in recent years, resulting in altered hydrological processes and increased transport of sediments, nutrients, and organic pollutants into the river system (Setiawan and Nugraha, 2022). Despite its strategic importance as a water resource for domestic use, agriculture, and ecosystem services, a comprehensive understanding of how land use dynamics influence spatial patterns of water quality in this watershed remains limited.

Previous studies in the Jeneberang basin have primarily focused on water quality monitoring or descriptive assessments of pollution levels. However, these studies have rarely incorporated long-term land use change analysis together with spatial modeling techniques to systematically identify pollution hotspots and their driving factors. This lack of integration limits the ability to develop effective, spatially targeted, and evidence-based watershed management strategies.

To address this gap, this study applies a comprehensive and integrated approach that combines field-based water quality monitoring with geospatial analysis of land use dynamics. By linking temporal land use changes with spatial variability in water quality, this approach enables a more robust understanding of pollution processes in a tropical watershed context. We hypothesize that areas experiencing rapid land use change exhibit higher pollutant concentrations, and that these spatial patterns correspond to specific land cover types.

Therefore, the objective of this study is to assess the spatial correlation between land use changes and river water quality in the Jeneberang watershed using a combination of statistical analysis and GIS-based spatial modeling. The novelty of this study lies in its integrative framework, which not only quantifies seasonal and spatial variations in water quality but also explicitly links these variations to land use dynamics.

MATERIAL AND METHODS

Research area

The study was conducted in the Jeneberang watershed (DAS Jeneberang), located in Gowa regency and Makassar City, south Sulawesi, Indonesia (approximately 5°15′–5°25′ S and 119°30′–119°50′ E), with a total area of approximately 760 km². The watershed is characterized by steep mountainous terrain in the upstream region and relatively flat lowland areas in the downstream zone, with elevation increasing toward the headwaters.

This study integrates field-based observations with geospatial analysis to investigate the relationship between land use and river water quality. Water quality monitoring was carried out over a six-month period from November 2024 to May 2025, encompassing both the rainy season (November–January) and the dry season (March–May) to capture seasonal variability. All analyses were based on direct field measurements and geospatial datasets; no modeled or forecast data were used. The geospatial datasets employed in this study include a digital elevation model (DEM) and Landsat satellite imagery, both with a spatial resolution of 30 m. These datasets were utilized to analyze land use patterns and the spatial characteristics of the watershed.

The spatial configuration of the study area, including watershed boundaries and elevation, is presented in Figure 1.

Sampling design and procedures

Seventeen monitoring stations were established along a 29.51 km stretch of the Jeneberang River, covering upstream (stations 1–8), midstream (stations 9–13), and downstream (stations 14–17) zones. The stations were selected to capture spatial variability in water quality influenced by land use, hydrology, and anthropogenic activities. Upstream areas were dominated by forest and agriculture, midstream by mixed land use and hydraulic structures (Bili-Bili reservoir and Bissua weir), and downstream by urban settlements, including Makassar City. Geographic coordinates of all stations were recorded using GPS (Table 1, Figures 2–3). The general configuration of the watershed and river system is illustrated in Figure 2, while the spatial distribution of sampling stations is presented in Figure 3.

Water samples were collected monthly at each station from November 2024 to May 2025 following the Indonesian National Standard SNI 6989-57-2008 for surface water sampling. The number of sampling points per station was determined by river discharge: one point for <5 m³/s (midstream, 0.5 depth), two points for 5–150 m³/s (1/3 and 2/3

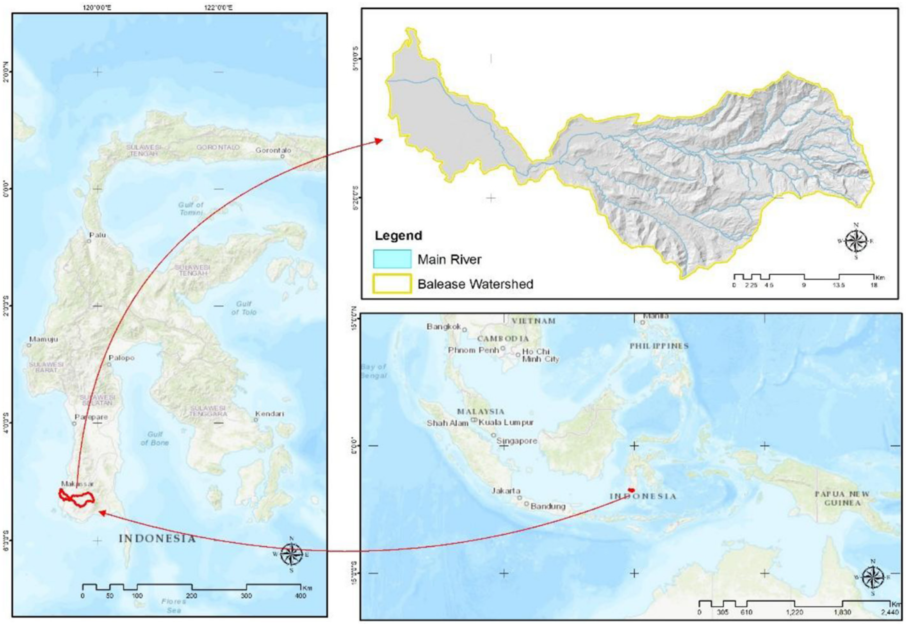

Figure 1. Location of the Jeneberang watershed showing watershed boundaries, elevation

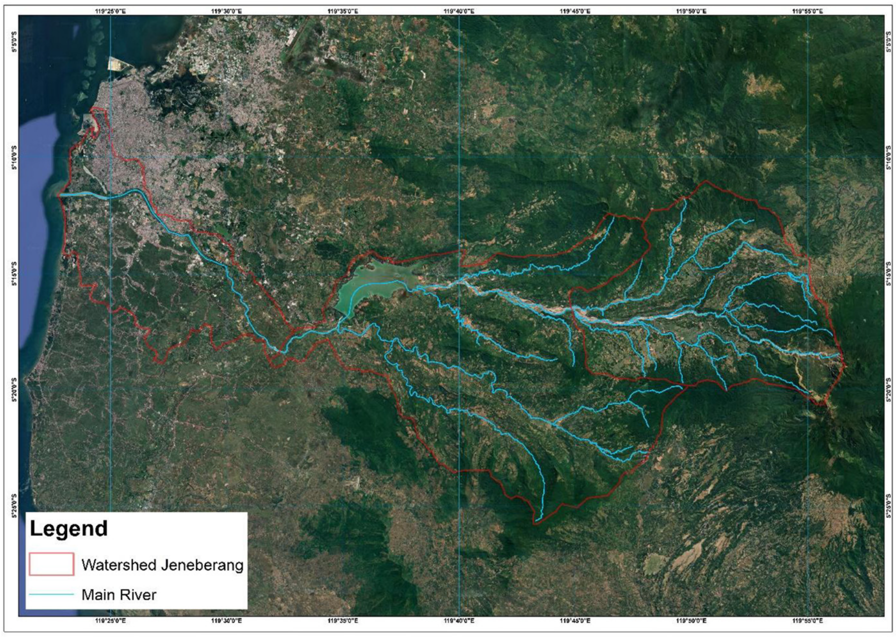

Figure 2. Location of the Jeneberang watershed and river system

of width), and up to six points for >150 m³/s with multi-depth sampling (surface 0.2, mid 0.5, near-bottom 0.8). Sampling was conducted between 08:00 and 12:00 local time under stable weather conditions, avoiding extreme rainfall events. Samples were collected in pre-cleaned 1-liter polyethylene bottles, stored at 4 °C in a cool box, and transported to the laboratory within 24 hours. Field parameters such as temperature and dissolved oxygen (DO) were measured in situ using portable instruments, while laboratory analyses were conducted for BOD, COD, TSS, total nitrogen (TN), total phosphorus (TP), and pesticides following standard methods (APHA). The spatial distribution and classification of all sampling stations are summarized in Table 1.

Water quality standards

Water quality assessment in this study followed the Government Regulation of the Republic of Indonesia No. 22 of 2021, Annex VI, which

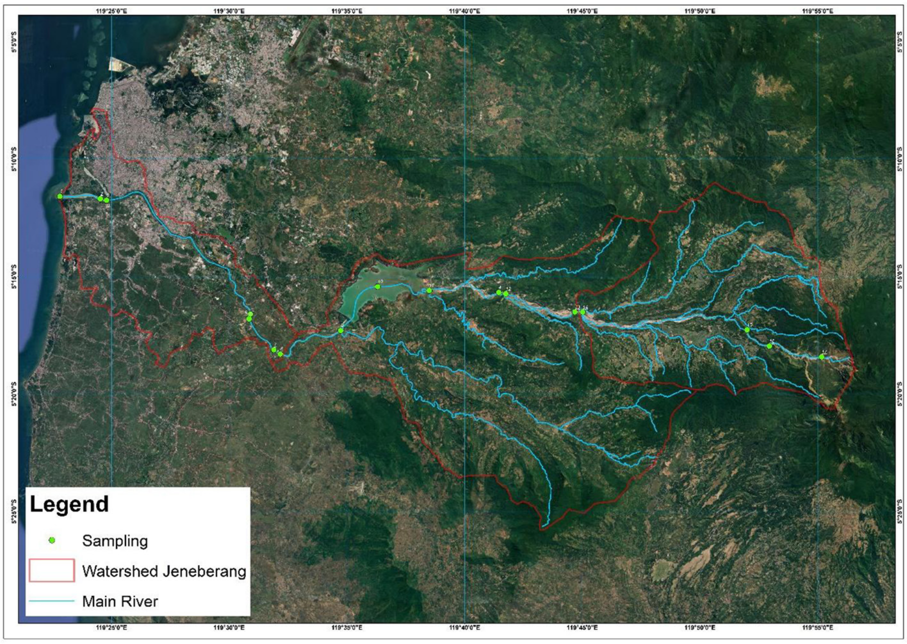

Figure 3. Distribution of sampling stations along the Jeneberang River

Table 1. Sampling locations in the Jeneberang watershed

No	Station	Longitude (E)	Latitude (S)	Zone
1	1	119°22’48.198”	5°11’34.750”	Upstream
2	2	119°24’31.441”	5°11’40.832”	Upstream
3	3	119°24’47.016”	5°11’44.880”	Upstream
4	4	119°41’26.694”	5°15’40.307”	Upstream
5	5	119°30’54.238”	5°16’35.398”	Upstream
6	6	119°30’50.427”	5°16’48.139”	Upstream
7	7	119°31’53.612”	5°18’06.921”	Upstream
8	8	119°32’09.804”	5°18’17.382”	Upstream
9	9	119°34’43.946”	5°17’17.830”	Midstream
10	10	119°36’18.117”	5°15’25.511”	Midstream
11	11	119°38’29.554”	5°15’35.381”	Midstream
12	12	119°41’44.751”	5°15’43.671”	Midstream
13	13	119°44’40.708”	5°16’30.070”	Midstream
14	14	119°45’01.031”	5°16’30.259”	Downstream
15	15	119°51’59.889”	5°17’16.012”	Downstream
16	16	119°52’56.498”	5°17’57.468”	Downstream
17	17	119°55’09.966”	5°18’24.731”	Downstream

defines Class II water quality standards. This standard applies to water intended for recreational purposes, freshwater aquaculture, livestock, irrigation, and as raw water sources for drinking water after appropriate treatment.

The parameters evaluated included pH, temperature, TSS, TDS, DO, BOD, COD, TN, TP, and pesticide residues. Laboratory analyses were conducted according to APHA standard methods, while field measurements of temperature and DO were carried out using calibrated portable instruments. To provide an integrated evaluation of water quality status, pollution index (PI) values were calculated by comparing measured concentrations with the regulatory standards (Effendi, 2003). The PI approach enables assessment of overall water quality by combining multiple parameters into a single, interpretable index.

Sampling methodology and field procedures

Water sampling procedures strictly followed the Indonesian National Standard SNI 6989-57-2008 for surface water sampling to ensure reproducibility and consistency.

At each of the 17 monitoring stations, samples were collected monthly, resulting in a total of six sampling events per station during the study period. At each station, the number of sampling points was determined based on river discharge conditions: one sampling point for low discharge (<5 m^3/s), two points for medium discharge (5–150 m^3/s), and up to six points for high discharge (>150 m^3/s).

Sampling depth was standardized at approximately 0.5 of the total water depth for single-point sampling, while for multi-point sampling, water was collected at surface (0.2 depth), mid (0.5 depth), and near-bottom (0.8 depth) positions to represent vertical variation. Horizontally, sampling points were distributed proportionally across the river width (e.g., 1/3 and 2/3 of the width for two-point sampling).

All samples were collected during daytime (08:00–12:00 local time) under stable weather conditions. Extreme weather events such as heavy rainfall were avoided to minimize short-term variability and ensure representative measurements. Weather conditions at the time of sampling were recorded for each station.

Water samples were collected using pre-cleaned 1-liter polyethylene bottles. Samples for laboratory analysis were immediately stored in a cool box at approximately 4 °C and transported to the laboratory within a maximum holding time of 24 hours. Parameters such as temperature and DO were measured in situ using calibrated portable instruments.

Quality assurance and quality control (QA/QC)

QA/QC procedures were implemented throughout both sampling and laboratory analysis to ensure data reliability. Field duplicates were collected at selected stations to assess sampling consistency, while blank samples were used to detect potential contamination during sampling and transport. Spiked samples were analyzed to evaluate analytical accuracy.

Instrument calibration and strict adherence to APHA standard methods minimized measurement uncertainty. Consistent sampling protocols and controlled laboratory procedures ensured reproducibility and comparability of the results across all sampling stations.

Land use analysis and classification

Land use patterns in the Jeneberang watershed were analyzed to assess spatial distribution and temporal changes across upstream, midstream, and downstream zones. Landsat 8 OLI/TIRS imagery (30 m resolution) for 2015 and 2025 was obtained from the United States Geological Survey (USGS), complemented with high-resolution Google Earth Pro imagery (2025) for visual interpretation and validation. Land use classification combined visual interpretation and on-screen digitization in ArcGIS 10.8, a method widely applied in heterogeneous landscapes due to its accuracy and flexibility (Rofikha et al., 2024; Bari et al., 2022). Classification criteria integrated spectral and visual characteristics:

- vegetation (forest and shrubland): identified using NDVI thresholds, with higher values indicating dense vegetation cover;
- agricultural land: recognized by regular patterns and seasonal variability;
- settlements: identified based on building density, geometric features, and low vegetation index values;
- open land: characterized by bare soil or sparse vegetation;
- water bodies: distinguished by spectral signatures and low reflectance.

Reference data from the Indonesian Ministry of Environment and Forestry (KLHK, 2023) were used to improve classification accuracy. Temporal changes were assessed using post-classification comparison between 2015 and 2025 maps, allowing quantification of land cover transformations. For reproducibility, the GIS layers and land use maps generated in this study are available from the corresponding author upon reasonable request.

Water quality analysis

Water quality in the Jeneberang River Basin was assessed across upstream, midstream, and downstream zones for parameters including temperature, pH, TSS, TDS, DO, BOD_5, COD, TN, TP, and pesticide residues. Analyses followed APHA Standard Methods:

- BOD_5: 5-day incubation (APHA 5210B),

- COD: dichromate reflux (APHA 5220C),
- TSS: gravimetric method (APHA 2540D),
- TDS: filtration and drying (APHA 2540C),
- DO: electrometric method (APHA 4500-O),
- pH: calibrated pH meter (APHA 4500-H^+),
- TN: persulfate digestion (APHA 4500-N),
- TP: ascorbic acid method (APHA 4500-P),
- Pesticides: gas chromatography (GC).

Instrument accuracy and detection limits were suitable for environmental monitoring (e.g., DO ±0.2 mg/L, pH ±0.01, BOD_5 ±5%, COD ±5–10%, TN/TP 0.01–0.05 mg/L). Instruments were calibrated with certified standards, and spectrophotometric analyses showed correlation coefficients (R^2) exceeding 0.99.

QA/QC procedures included blanks, duplicate samples, and spiked/internal standard samples, with recovery maintained between 85–115%. All chemical reagents were analytical grade from certified suppliers (Merck, Sigma-Aldrich).

Water quality was evaluated against Class II standards (Government Regulation No. 22 of 2021). The PI method was applied following Effendi (2003) using average and maximum concentrations. Spatial distribution of water quality parameters was visualized using inverse distance weighting (IDW) interpolation in ArcGIS 10.8.

Data analysis

The relationship between land use and water quality in the Jeneberang Watershed was evaluated using both statistical and spatial approaches. Pollution index (PI) values were calculated for each sampling station using measured concentrations (Ci) relative to Class II standard thresholds (Lij) according to Effendi (2003):

$$PIj = \sqrt{\frac{(C_i/L_{ij})_M^2 + (C_i/L_{ij})_R^2}{2}} \quad (1)$$

where: PI_j – pollution index at station j; C_i – Measured concentration of parameter i; L_{ij} – standard value of parameter i(PP No. 22 of 2021); $(C_i/L_{ij})_M$ – maximum value of the rati; $(C_i/L_{ij})_R$ – average value of the ratio.

Spatial patterns of water quality were visualized using IDW interpolation in ArcGIS 10.8 (power = 2, variable search radius including 12 nearest stations). Geographic coordinates of all sampling stations (Table 1) were used as input. Cross-validation via a leave-one-out approach and root mean square error (RMSE) assessment confirmed that interpolation accuracy was acceptable for representing spatial variability. The PI values were categorized into four classes according to Government Regulation No. 22 of 2021 (Table 2).

Statistical analyses were conducted using Microsoft Excel 2019 and IBM SPSS Statistics 25. Descriptive statistics (mean ± SD) were calculated for all parameters. One-way ANOVA tested for seasonal differences (dry vs. rainy) at $p < 0.05$. Prior to analysis, data were screened for outliers, tested for normality, and log-transformed where necessary.

All raw data, PI calculations, and GIS outputs (including shapefiles in Excel, CSV, and SHP formats) are provided as supplementary materials, ensuring transparency and reproducibility of the analysis.

Table 2. Relationship between pollution index and water quality status

Pollution index	Water quality status
0 ≤ IPj ≤ 1.0	Meets quality standards (Good condition)
1.0 < IPj ≤ 5.0	Lightly polluted
5.0 < IPj ≤ 10	Moderately polluted
IPj > 10	Heavily polluted

Limitations

While the sampling design and analytical procedures provide robust insights into water quality dynamics, several limitations are acknowledged:

1. Temporal coverage: The study spanned six months covering dry and rainy seasons, providing only a short-term perspective. Long-term trends, inter-annual variability, and extreme hydrological events (floods, droughts) were not captured.
2. Spatial coverage: Seventeen monitoring stations were strategically distributed across upstream, midstream, and downstream zones, but finer-scale variability within some sub-catchments may not be fully resolved.
3. Parameter variability: Certain parameters, such as pesticide residues, may exhibit episodic spikes that were not captured by monthly sampling.

These limitations indicate that while this study provides a solid assessment of seasonal and spatial patterns and their relationship to land use, extended temporal coverage, higher-frequency sampling, and expanded spatial resolution would strengthen understanding of watershed dynamics and improve generalizability of the findings.

RESULTS AND DISCUSSION

Land use change dynamics

Land use change analysis in the Jeneberang Watershed between 2015 and 2025 indicates a substantial transformation of natural landscapes into anthropogenic land uses. Forest and shrubland areas declined significantly due to conversion into agricultural land and settlements. Agricultural expansion was dominant in the midstream region, while built-up areas increased notably in downstream zones influenced by urban development. This transformation reduces infiltration capacity and increases surface runoff, which contributes to higher sediment and pollutant transport into the river system. To better illustrate the spatial distribution and transformation of land use between 2015 and 2025, a land use change map is presented in Figure 4.

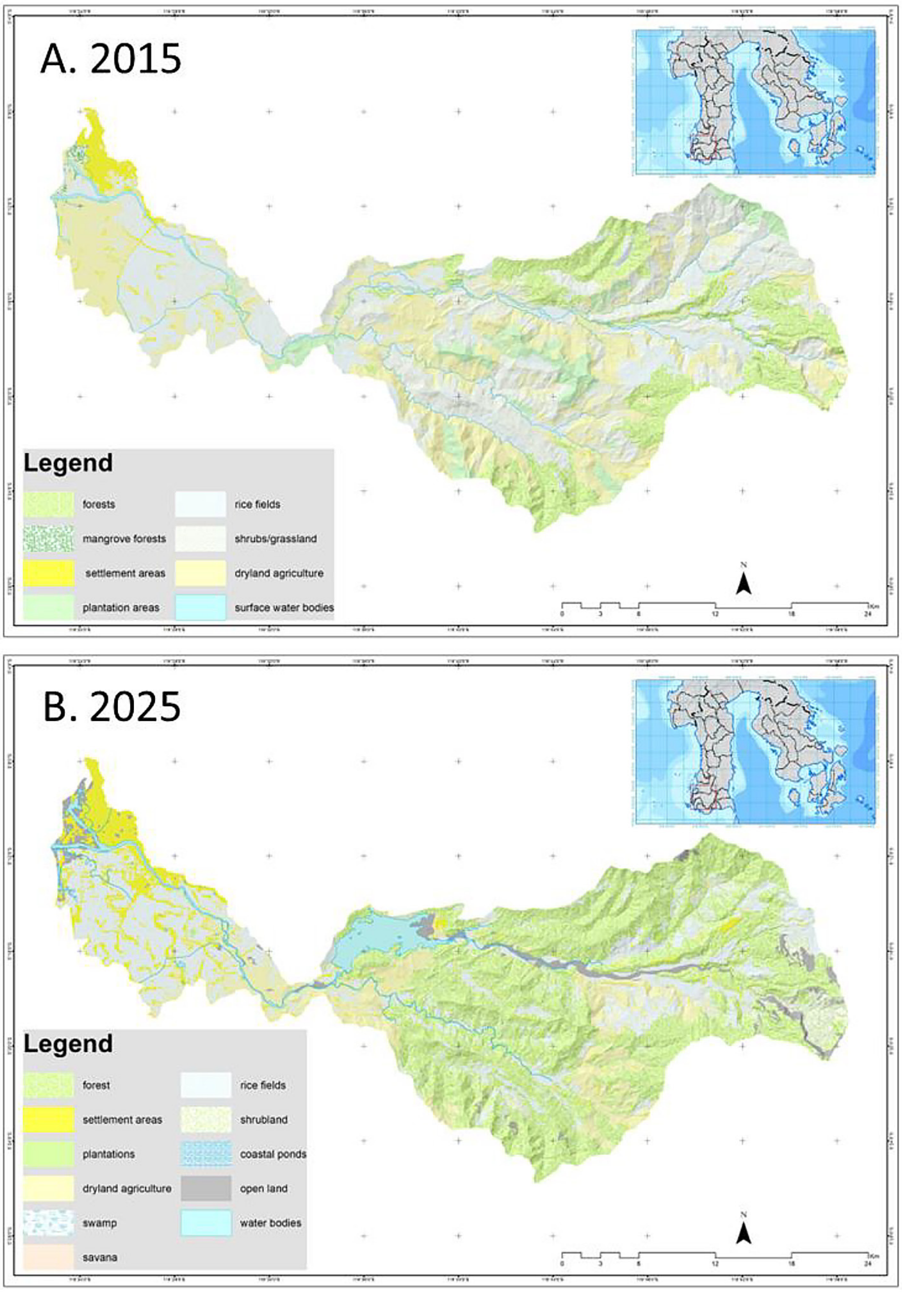

Figure 4. Land use change

Water quality analysis

Dry season conditions

Water quality during the dry season was generally within Class II standards. TSS ranged from 3–10 mg/L, BOD from 0.4–0.56 mg/L, and COD from 1.5–2 mg/L. Dissolved oxygen (DO) remained stable at 4.8–4.9 mg/L, indicating good oxygenation conditions. Nutrient concentrations were also low, with total nitrogen averaging 0.30 mg/L and total phosphorus around 0.02 mg/L, indicating minimal pollutant input during low-flow conditions. A detailed summary of water quality parameters during the dry season across all monitoring stations is presented in Table 3.

PI values ranged from 0.35 to 0.41, with a mean of 0.37 ± 0.02, indicating all stations met water quality standards (good). Low variability reflects stable environmental conditions.

Rainy season conditions

In contrast, the rainy season showed a significant deterioration in water quality. TSS increased drastically, reaching up to 948 mg/L at downstream stations. BOD ranged from 9–43 mg/L and COD from 16–290 mg/L, exceeding regulatory limits at several locations. This increase is attributed to surface runoff transporting sediments, nutrients, and organic pollutants into the river system. The complete results of water quality measurements during the rainy season are summarized in Table 4.

PI ranged from 1.70 to 8.50 (mean = 4.45 ± 2.05), confirming a substantial increase in pollution levels during the rainy season, with most stations classified as lightly polluted and several downstream stations reaching moderate pollution levels.

Statistical analysis

To evaluate the variability and reliability of the data, descriptive statistical analysis was conducted.

Descriptive statistics

To better understand the distribution and variability of water quality parameters between seasons, descriptive statistics are presented in Table 5.

The results indicate significantly higher variability during the rainy season, particularly for TSS, reflecting strong hydrological influence.

Significance testing (ANOVA)

To evaluate whether seasonal variation significantly influences water quality parameters, a one-way analysis of variance (ANOVA) was conducted. The analysis compared parameter values between the dry season and rainy season across all 17 monitoring stations. Prior to

Table 3. Water quality parameters during dry season

Station	PI	Status
1	0.39	Good
2	0.38	Good
3	0.38	Good
4	0.41	Good
5	0.37	Good
6	0.36	Good
7	0.38	Good
8	0.36	Good
9	0.39	Good
10	0.37	Good
11	0.35	Good
12	0.35	Good
13	0.36	Good
14	0.37	Good
15	0.4	Good
16	0.37	Good
17	0.36	Good

Table 4. Water quality parameters during rainy season

Station	PI	Category
1	1.97	Lightly polluted
2	2.15	Lightly polluted
3	3.2	Lightly polluted
4	1.7	Lightly polluted
5	4.15	Moderately polluted
6	3.95	Lightly polluted
7	4.1	Moderately polluted
8	3.9	Lightly polluted
9	3.3	Lightly polluted
10	4.25	Moderately polluted
11	5.8	Moderately polluted
12	6.3	Moderately polluted
13	5.1	Moderately polluted
14	5.4	Moderately polluted
15	6.9	Moderately polluted
16	8.5	Moderately polluted
17	5.2	Moderately polluted

Table 5. Descriptive statistics of water quality parameters

Parameter	Season	Mean	Std. Dev	Min	Max
TSS	Dry	6.2	2.8	3	10
TSS	Rainy	138	245	2	948
BOD	Dry	0.41	0.05	0.4	0.56
BOD	Rainy	30.2	9.5	9	43
COD	Dry	1.6	0.2	1.5	2
COD	Rainy	132	85	16	290

ANOVA, data normality was assessed using the Shapiro–Wilk test, and homogeneity of variance was evaluated using Levene's test. Since the data met the required assumptions ($p > 0.05$), ANOVA was applied at a 95% confidence level ($\alpha = 0.05$). For parameters that showed non-normal distribution, log transformation was performed to stabilize variance.

The ANOVA results indicated statistically significant differences between seasons for major water quality parameters (Table 6).

A one-way ANOVA test was conducted to evaluate differences between seasons. The results show statistically significant differences ($p < 0.05$) for TSS, BOD, and COD, confirming that seasonal variation strongly influences water quality (Table 6). These results confirm that seasonal variation has a significant effect on water quality, with higher pollutant concentrations observed during the rainy season.

Spatial analysis (IDW)

To visualize the spatial distribution of water quality conditions during the dry season, the PI values were interpolated using the IDW method. The

Table 6. Analysis of variance (ANOVA)

Parameter	F-value	p-value	Interpretation
TSS	18.72	< 0.001	Significant
BOD	22.15	< 0.001	Significant
COD	19.87	< 0.001	Significant

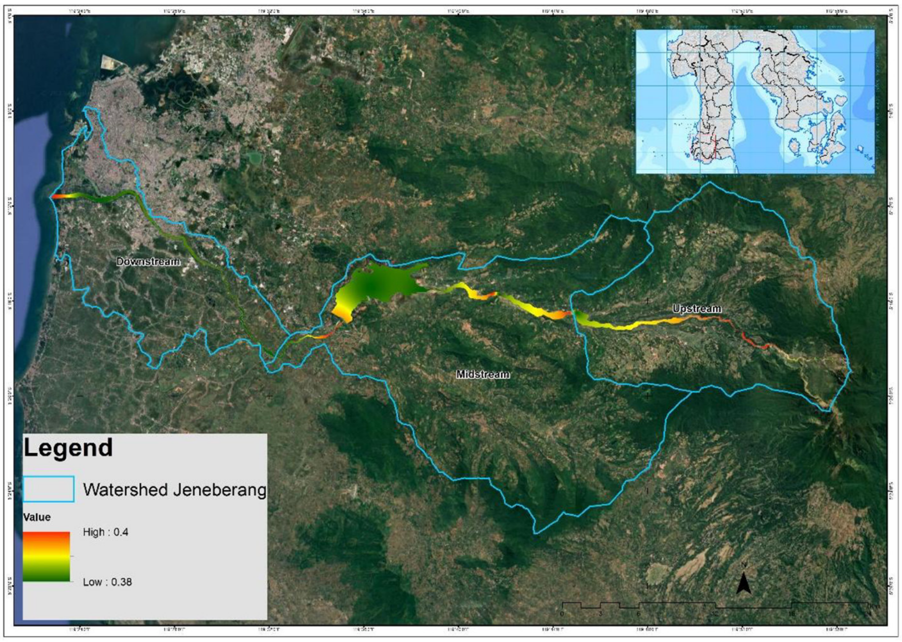

Figure 5. Spatial distribution of pollution index (IDW) dry season

resulting spatial pattern is presented in Figure 5. To further examine the spatial variation of water quality during the rainy season, the PI values were interpolated using the IDW method. The resulting spatial distribution, which reflects increased pollution levels across several parts of the watershed, is presented in Figure 6.

Correlation analysis

To quantify the relationship between land use patterns and water quality, Pearson correlation analysis was performed between land use categories (forest, agriculture, settlements) and key pollution indicators (TSS, BOD, COD, and PI values).The analysis revealed strong and statistically significant correlations (Table 7).

All correlations were statistically significant at $p < 0.05$, indicating that land use changes strongly influence water quality. These findings provide quantitative evidence supporting the study hypothesis, confirming that increased anthropogenic land use leads to higher pollution levels.

Reliability and uncertainty analysis

To ensure the reliability and reproducibility of the results, strict quality control procedures were implemented throughout the sampling and analysis process.

Instrument calibration:

- all field instruments (DO meter, pH meter, TDS meter) were calibrated daily before sampling,
- calibration used standard buffer solutions (pH 4, 7, 10) and certified reference standards,
- laboratory instruments were calibrated following APHA standard procedures.

Sampling consistency:

- sampling conducted monthly over 6 months,
- each station sampled using consistent depth and location protocol,
- duplicate samples were collected at selected stations for validation.

Analytical accuracy:

- laboratory analysis followed standard methods (APHA, 2017),

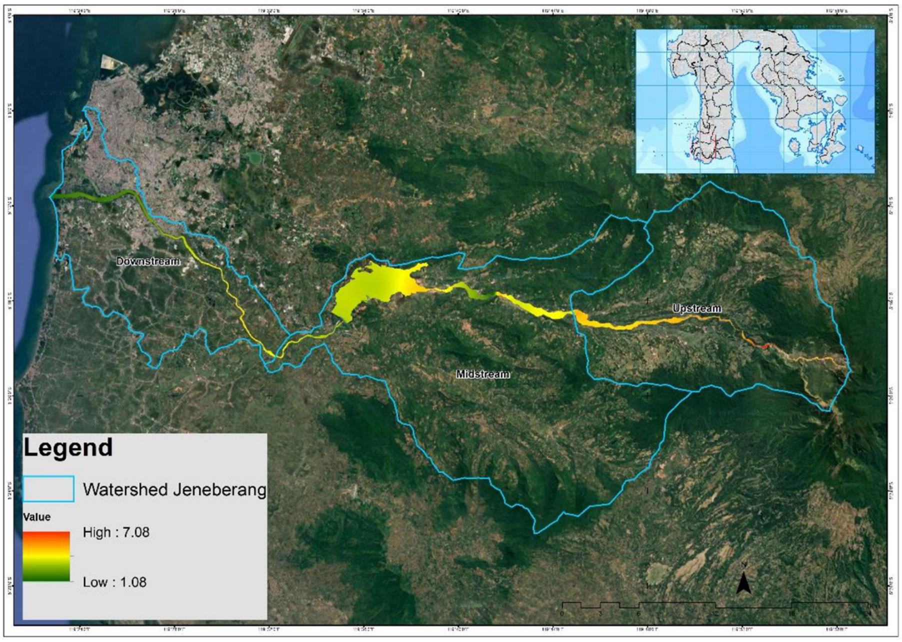

Figure 6. Spatial distribution of pollution index (IDW) rainy season

Table 7. Correlation analysis

Variable pair	Correlation (r)	Strength	Interpretation
Agriculture vs TSS	0.78	Strong	High sediment from farming runoff
Settlement vs COD	0.72	Strong	Organic pollution from domestic waste
Built-up area vs PI	0.75	Strong	Urbanization increases pollution
Forest vs PI	-0.65	Moderate (negative)	Forest reduces pollution

- Detection limits:
  - BOD: ±0.1 mg/L
  - COD: ±2 mg/L
  - TSS: ±1 mg/L
- Analytical precision maintained within ±5% relative error.

Uncertainty sources

Potential sources of uncertainty include:
1. Hydrological variability (rainfall intensity and river discharge fluctuations).
2. Sampling disturbances during high-flow conditions.
3. Instrument sensitivity limitations.
4. Temporal variability between sampling intervals.

Despite these uncertainties, the integration of statistical analysis, spatial modeling, and pollution index calculations demonstrates strong consistency in the results. Overall, the uncertainty level is considered low to moderate, and does not significantly affect the interpretation of spatial and seasonal trends.

The results clearly demonstrate that land use change and seasonal rainfall significantly influence water quality in the Jeneberang Watershed. Increased pollutant concentrations during the rainy season are primarily driven by runoff transporting sediments and nutrients into the river system. Unlike previous studies that rely mainly on descriptive analysis, this study provides quantitative evidence through statistical testing and correlation analysis. The findings confirm that areas experiencing rapid land use change exhibit higher pollution levels. These findings highlight the critical importance of integrated watershed management. The expansion of agricultural and urban land without adequate environmental controls may significantly accelerate water quality degradation in the future.

CONCLUSIONS

This study demonstrates that seasonal variation and land use change are statistically significant drivers of water quality degradation in the Jeneberang watershed. The results of the ANOVA test confirmed that key parameters, including TSS, BOD, and COD, differ significantly between dry and rainy seasons ($p < 0.05$), indicating that hydrological conditions strongly control pollutant dynamics.

During the dry season, water quality remained stable and met Class II standards across all monitoring stations, reflecting low runoff conditions and the buffering role of upstream vegetation. However, the rainy season revealed a systematic spatial shift in pollution levels, with PI values increasing from "good" (≤1.0) to "lightly–moderately polluted" (1.5–4.5), particularly in midstream and downstream areas. This indicates that seasonal runoff acts as a key mechanism for transporting pollutants from land surfaces into the river system.

Importantly, this study identifies a clear spatial pattern of vulnerability:
- upstream areas remain relatively resilient due to remaining forest cover, but show early signs of degradation where land conversion occurs;
- midstream zones represent the most critical transition areas, where mixed land use (agriculture and settlements) significantly increases sediment and organic pollution loads;
- downstream areas exhibit the highest pollution accumulation, driven by urban activities and cumulative upstream inputs.

Correlation analysis further confirms that land use change is a dominant factor influencing water quality, with strong positive relationships between agricultural and built-up areas and pollution indicators (r = 0.72–0.78), and a negative relationship with forest cover (r = -0.65). These findings provide quantitative evidence supporting the hypothesis that increased anthropogenic land use leads to higher pollution levels.

From a management perspective, the results highlight that intervention priorities should focus on midstream and downstream zones, where pollution levels and variability are highest. Specifically, erosion control and agricultural runoff management are critical in midstream areas, while wastewater management and urban land-use regulation are essential in downstream regions. In upstream areas, maintaining and restoring forest cover is crucial to preserve the watershed's natural buffering capacity.

Overall, this study provides a spatially explicit and statistically supported assessment of water quality dynamics, demonstrating that the interaction between land use change and seasonal hydrology governs pollution patterns in tropical watersheds. These findings offer a robust scientific basis for integrated watershed management strategies, particularly in rapidly developing regions where land transformation continues to intensify.

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