

# Land cover dynamics and surface water quality conditions in the Upper Wampu Watershed, Indonesia

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Manuscript received: 4 December 2025. Revision accepted: 16 March 2026.

**Abstract.** Darnianti, Rauf A, Rahmawaty, Mulya MB, Delvian, Rahmanta. 2026. Land cover dynamics and surface water quality conditions in the Upper Wampu Watershed, Indonesia. *Asian J For* 10 (1): r100121. <https://doi.org/10.13057/asianjfor/r100121>. Land cover variation in upstream watersheds is spatially associated with differences in observed surface water quality characteristics. This study evaluates land cover dynamics between 2017 and 2024 and examines surface water quality conditions in the Upper Wampu Watershed, Karo District, North Sumatra, Indonesia. Land cover mapping utilized pre-classified 10 m Sentinel Land Cover datasets, validated using 10 independent points which yielded a localized accuracy of 90%. Water quality was assessed at 10 spatially distributed sampling stations using physicochemical and microbiological parameters and evaluated against Class II surface water standards set forth in Government Regulation No. 22 of 2021, serving as a raw water source for drinking water treatment. Forest cover increased slightly (+1.91%), built-up areas expanded markedly (+29.04%), cropland increased moderately (+4.72%), and grassland declined substantially (-36.80%), while water bodies remained relatively stable. Exceedances were observed for Total Suspended Solids (TSS), color, Chemical Oxygen Demand (COD), ammonia, and iron, whereas microbiological parameters remained below regulatory limits. Using Exploratory Spatial Data Analysis (ESDA), specifically spatial overlay and Local Indicators of Spatial Association (LISA) clustering, the study identified spatial patterns in which settlement-dominated areas coincided with higher microbiological concentrations, while agriculturally dominated areas coincided with elevated organic indicators. These findings describe spatial associations rather than causal effects and are interpreted within the exploratory scope of the study. The river remains suitable as a source for drinking water treatment under current conditions, although continued monitoring is recommended to account for ongoing land-use change.

**Keywords:** Exploratory Spatial Data Analysis, land cover dynamics, Sentinel land cover, surface water quality, watershed management

## INTRODUCTION

Land cover and land use change are universally recognized as major drivers of watershed degradation, influencing hydrological processes, sediment transport, and surface water quality (Mashala et al. 2023). Foundational watershed studies (Sliva and Williams 2001; Allan 2004; Liu et al. 2024) have long established the theoretical basis that the conversion of forests and natural vegetation into agricultural land and settlements increases surface runoff and soil erosion while reducing infiltration capacity. This ultimately degrades water quality and accelerates sedimentation in river systems. Contemporary research confirms that these impacts remain particularly pronounced in upstream tropical watersheds, such as the Wampu River in Karo District, North Sumatra, Indonesia, where land cover plays a critical role in regulating hydrological functions and sustaining downstream water availability (Wagesho and Claire 2016).

In Indonesia, rapid population growth and agricultural expansion have intensified land-use change across many upstream watersheds, increasing pressure on water

resources. Previous studies have examined watershed characteristics using parameters such as morphometry, topography, soil conditions, vegetation cover, land use, and hydrology (Lan et al. 2024; Vasić et al. 2024). However, most previous research has focused predominantly on general watershed characterization or hydrological quantity.

In the Indonesian context, upstream watersheds are increasingly affected by agricultural expansion and settlement growth, placing greater pressure on watershed sustainability and water resources management. Sustainable watershed management, therefore, requires not only hydrological assessment, but also spatially explicit evaluation of land cover dynamics and their environmental consequences (Aynalem and Liben 2020; Narendra et al. 2021). Recent studies also indicate that water quality degradation is influenced by land use patterns across multiple spatial scales, suggesting that riparian observations alone may be insufficient to explain watershed conditions comprehensively (Jaywant and Arif 2024; Shekar and Mathew 2024). This highlights the need for integrated spatial studies linking land cover change with

observed surface water quality in tropical upstream watersheds.

While the theoretical link between land use and watershed health is established (Alciaturi and Gil 2025), spatially explicit studies in tropical regions remain limited. To address this gap, the scientific novelty of this study is anchored in three key aspects: (i) the integration of remote sensing-derived land cover change trajectories with empirical water quality indicators; (ii) the execution of a multi-parameter water quality analysis encompassing both physicochemical and microbiological parameters in a dynamic upstream tropical watershed; and (iii) the application of an exploratory spatial analysis to map the correspondence between specific land cover types and water quality degradation patterns. The Wampu Watershed serves as an ideal case study for this approach. Its upper catchment area, Lau Biang, originates from Gunung Leuser National Park and functions as a primary source of clean water. In recent years, this area has experienced increasing ecological pressure due to plantation expansion and settlement development. Vegetation alteration in these upstream areas has been associated with reduced infiltration capacity, increased erosion, and elevated sediment loads, which may influence surface water quality (Desrita et al. 2018; Chen et al. 2024).

This study examines land cover change trajectories in the Wampu Watershed between 2017 and 2024, with particular attention to forest, plantation, and settlement dynamics, and evaluates surface water quality conditions. Rather than inferring causal relationships, this research adopts an exploratory and spatially descriptive approach to examine the correspondence between land cover change patterns and variations in selected physicochemical and microbiological water quality parameters. By integrating supervised classification of Sentinel-2A imagery with regulation-based water-quality assessment (Government Regulation No. 22 of 2021), this study provides empirical baseline information to support sustainable watershed management and conservation-oriented land-use planning aimed at maintaining clean water availability in Karo District (Javed et al. 2009; Jung and Kim 2023).

This study addresses the research question of whether recent land cover changes in the Upper Wampu Watershed are associated with variations in surface water quality. Specifically, it examines whether the expansion of built-up

areas and cropland, together with the reduction of grassland or savanna, corresponds to changes in key physicochemical and microbiological water quality parameters. Given the exploratory design, the analysis aims to identify spatial and temporal patterns rather than to establish causal relationships.

## MATERIALS AND METHODS

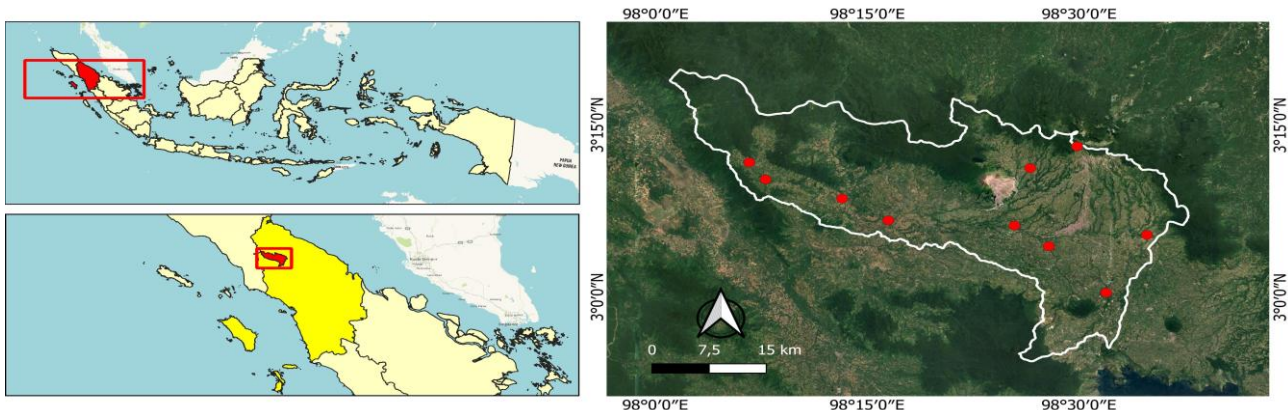
### Study area

The study was conducted in the Upper Wampu Watershed, Karo District, North Sumatra, Indonesia (3°00'–3°30' N; 98°10'–98°40' E) from January to April 2025 (Figure 1). The watershed originates from forested slopes adjacent to Gunung Leuser National Park and includes the Lau Biang, Bahorok, and Berkail Sub-watersheds. The total watershed area is approximately 227,000 ha ( $\approx 2,270$  km<sup>2</sup>), with elevations ranging from 400 to 2,500 m above sea level and annual rainfall between 2,500–3,800 mm.

### Land cover data acquisition and accuracy assessment

To analyze land cover dynamics between 2017 and 2024, this study utilized the pre-classified, high-resolution (10 m) Sentinel land cover dataset. Because this study adopted a ready-to-use land cover product generated by the provider's automated algorithms, primary satellite data processing steps such as atmospheric correction, cloud filtering, training sample extraction, and raw classification were not applicable and thus not performed by the authors. The dataset inherently categorizes the study area into six distinct land cover classes: forest, plantation, cropland, grassland/savanna, built-up area, and water body.

Although the global dataset has its own native accuracy, an independent, localized accuracy assessment was conducted to ensure its reliability within the specific context of the Upper Wampu Watershed. A total of 10 validation points were selected and cross-referenced with ground truth observations and high-resolution imagery. The validation assessment showed that 9 out of the 10 points were correctly classified, yielding a localized overall accuracy of 90%, which is considered highly acceptable for the subsequent spatial analysis.



**Figure 1.** Distribution of water sampling locations and land cover in the Wampu Watershed, Karo District, North Sumatra, Indonesia

### Water quality sampling and laboratory analysis

Surface water sampling was conducted to evaluate physicochemical and microbiological parameters. A total of 10 sampling stations were established across the watershed. The spatial distribution of these 10 points was strategically designed to capture the runoff from various major land cover types across the Lau Biang, Bahorok, and Berkail Sub-watersheds.

Sampling was conducted as a snapshot measurement (one-time sampling) to represent the specific conditions during the study period. Water samples were collected in sterilized bottles, preserved in cool boxes, and immediately transported to the laboratory of Politeknik Kesehatan Kementerian Kesehatan Indonesia, Medan, Indonesia, for analysis. The laboratory analysis followed standard national health and environmental protocols to determine the concentrations of parameters such as TSS, COD, and coliforms. Measured parameters were then evaluated against the Indonesian Government Regulation No. 22 of 2021 regarding Class II surface water standards.

### Spatial and statistical analysis

Land cover change was quantified by applying spatial overlay analysis on the classified maps from 2017 and 2024 in a GIS environment to calculate area transitions for each class. To evaluate the spatial associations between land cover distribution and water quality parameters, Exploratory Spatial Data Analysis (ESDA) was performed using GeoDa software. The methodology involved several explicit steps:

**Spatial Overlay:** Land cover percentages within the specific catchment area of each of the 10 water sampling stations were extracted using spatial overlay tools.

**Global Moran's I:** This statistic was utilized to measure global spatial autocorrelation, determining whether specific water pollutants exhibited clustered, dispersed, or random patterns across the watershed.

**Hotspot Analysis (LISA):** Bivariate Local Indicators of Spatial Association (LISA) were applied to map statistically significant spatial clusters. This identified "High-High" hotspots (e.g., areas where a high percentage of built-up area spatially coincides with high microbiological concentrations) and "Low-Low" coldspots. A first-order Queen contiguity spatial weight matrix was applied to construct the spatial relationships.

## RESULTS AND DISCUSSION

### Land cover classification accuracy and spatial distribution (2017-2024)

Prior to analyzing the land cover dynamics, the reliability of the spatial data was verified. Field visits were conducted to visually verify selected land cover classes. To quantitatively assess the reliability of the spatial data, an accuracy assessment was performed using 10 ground-truth sampling points distributed across the watershed. Cross-validation between the spatial map and actual field

conditions demonstrated that 9 out of 10 points were correctly classified, yielding an overall localized accuracy of 90%. This high accuracy confirms that the land cover data is highly reliable for subsequent spatial association analysis. The field observations are presented in Figure 2 as photographic documentation of representative land cover types, including built-up areas, cropland, grassland, and forest.

The spatial distribution of land cover in the Wampu Watershed is illustrated in Figure 3. In 2017, forest and cropland represented the dominant land cover types. Forest areas were primarily located in the northern and western parts of the watershed adjacent to Gunung Leuser National Park, while cropland occupied most of the central and eastern regions. Built-up areas were dispersed with higher density in the eastern section, whereas grassland or savanna occurred mainly in the central-southern areas. Water bodies and barren land occupied relatively limited areas.



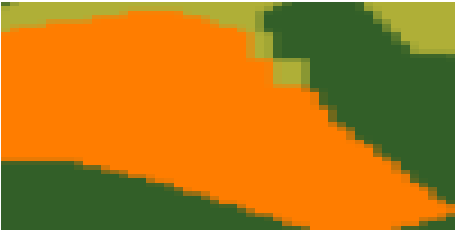



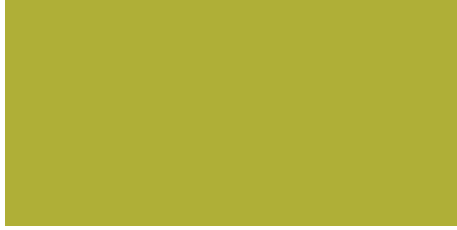





By 2024, the spatial configuration remained generally consistent; however, several directional changes were observed. Built-up areas expanded toward the eastern and southeastern parts of the watershed, while grassland or savanna became increasingly fragmented. Barren land showed a declining spatial presence, whereas forest cover remained concentrated in the northern and western zones. Cropland continued to dominate the middle and downstream areas of the watershed.

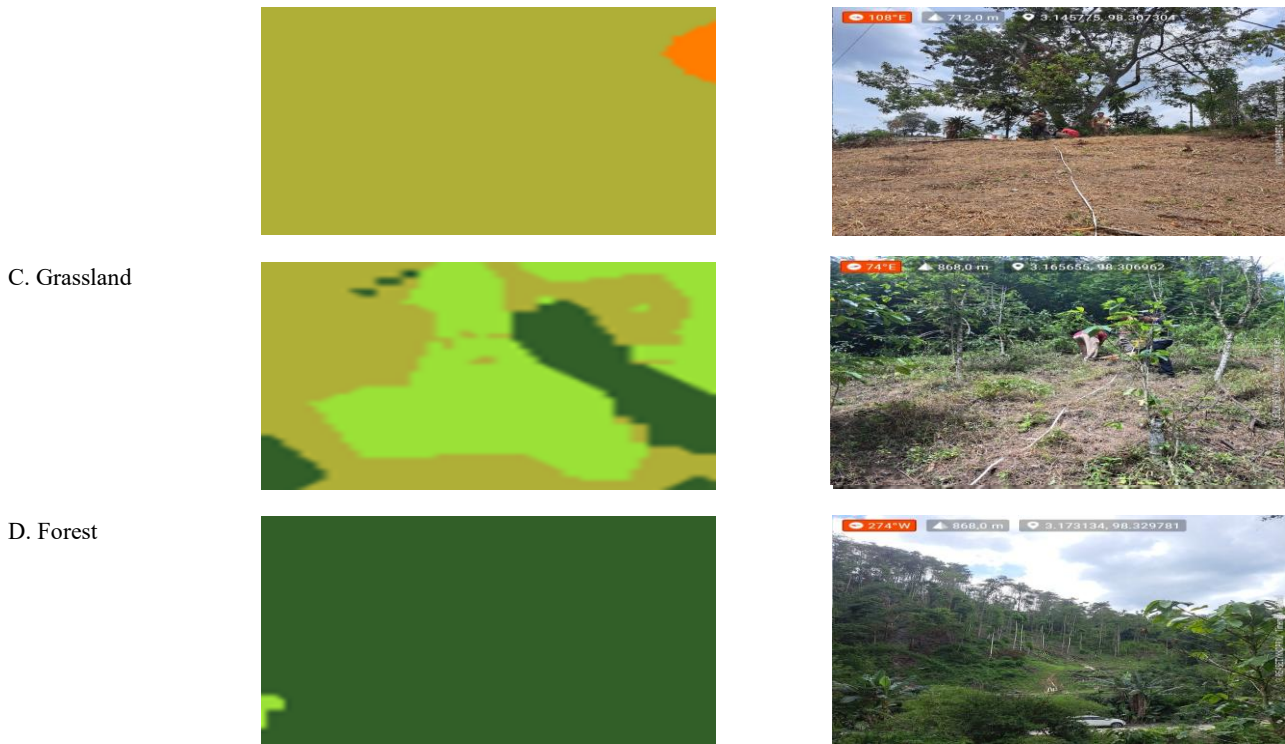
Quantitative analysis of land cover change between 2017 and 2024 is summarized in Table 1. Forest area increased from 668.45 km<sup>2</sup> in 2017 to 683.46 km<sup>2</sup> in 2024 (+2.25%). In contrast, grassland or savanna decreased from 98.32 km<sup>2</sup> to 57.08 km<sup>2</sup> (-41.95%). Built-up areas increased from 63.00 km<sup>2</sup> to 78.54 km<sup>2</sup> (+24.67%), while cropland increased from 428.95 km<sup>2</sup> to 448.60 km<sup>2</sup> (+4.58%). Barren land decreased from 11.34 km<sup>2</sup> to 2.70 km<sup>2</sup> (-76.19%). Water bodies showed a slight decrease from 2.07 km<sup>2</sup> to 1.94 km<sup>2</sup> (-6.28%). To further illustrate temporal trends, Figure 4 presents a comparative visualization of land cover changes between 2017 and 2024, highlighting the spatial expansion of built-up and cropland areas, and the contraction of grassland and barren land.

**Table 1.** Land cover area and percentage changes in the Wampu Watershed, Karo District, North Sumatra, Indonesia, between 2017 and 2024

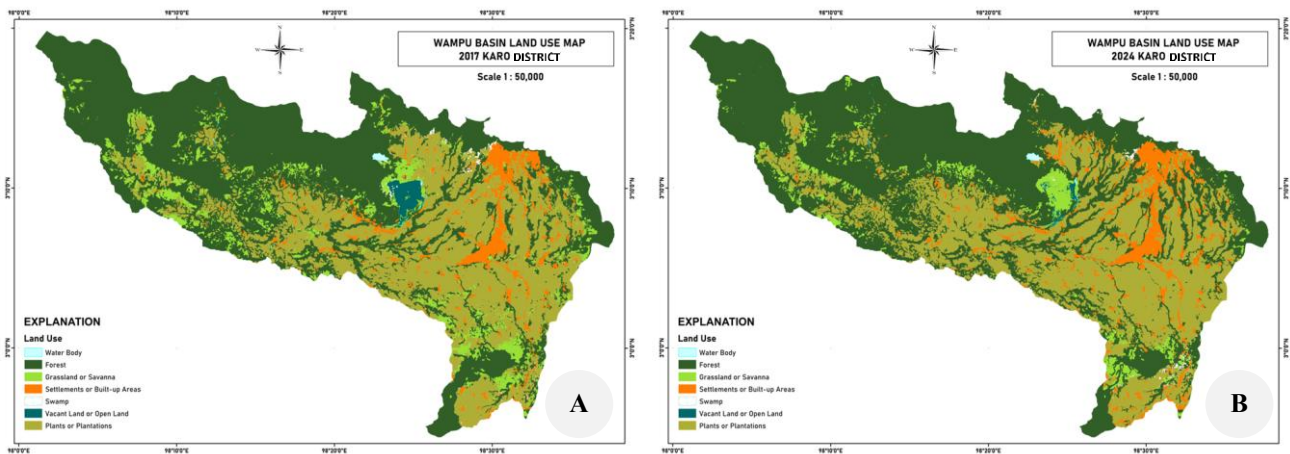
Land Cover	Area (km <sup>2</sup> )		Changes (%)
	2017	2024	
Water	2.07	1.94	-6.28%
Forests	668.45	683.46	+2.25%
Grassland or Savanna	98.32	57.08	-41.95%
Built-up	63	78.54	+24.67%
Barren Land	11.34	2.7	-76.19%
Cropland	428.95	448.6	+4.58%

Source: Data Processing (2025)

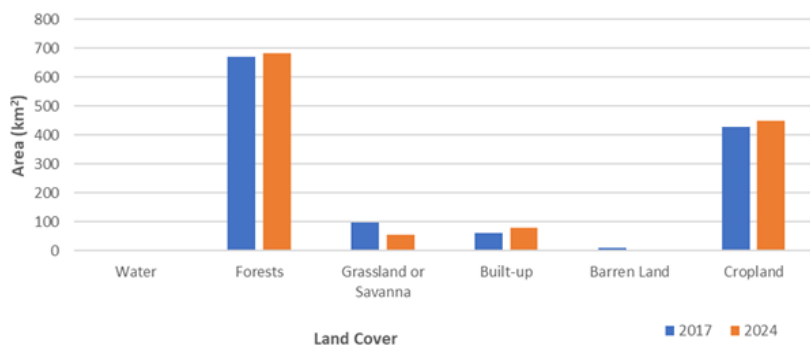
Class	Sentinel 2	Field condition
A. Build-up		
		
B. Cropland		
		
		
		



**Figure 2.** Qualitative field verification of land cover classes in the Upper Wampu Watershed, Karo District, North Sumatra, Indonesia. A. Built-up area, B. Cropland, C. grassland, D. forest



**Figure 3.** Spatial distribution of land cover classes in the Wampu Watershed, Karo District, North Sumatra, Indonesia, in A. 2017 and B. 2024 based on Sentinel-2 land cover



**Figure 4.** Trends in land cover area changes in the Wampu Watershed, Karo District, North Sumatra, Indonesia, from 2017 to 2024

### Surface water quality in the Wampu Watershed (2017-2024)

Baseline water quality measurements in 2017 are presented in Table 2 for the Bahorok and Berkail rivers. Temperature ranged from 24.73°C to 25.53°C, Dissolved Oxygen (DO) values exceeded 7 mg/L, and pH ranged from 6.86 to 8.40. Fecal coliform and total coliform were not detected in either river.

More recent water quality measurements from 2023-2024 for the Lau Biang River are summarized in Table 3. Several parameters exceeded Class II water quality standards (Government Regulation No. 22 of 2021), including Total Suspended Solids (TSS), color, Chemical Oxygen Demand (COD), fecal coliform, and total coliform. This indicates a noticeable decline in surface water quality coinciding with the period of land cover alteration.

**Table 2.** Water quality parameters of the Bahorok and Berkail Rivers, Karo District, North Sumatra, Indonesia, in 2017

Parameter	Unit	Bahorok (mean ± SD)	Berkail (mean ± SD)
Physical			
Temperature	°C	25.53 ± 0.23	24.73 ± 0.35
Current	m/s	1.06 ± 0.29	1.20 ± 0.35
Depth	cm	62.04 ± 27.38	86.31 ± 38.27
Transparency	cm	62.04 ± 27.38	86.31 ± 38.27
Chemical			
pH	-	6.86 ± 0.06	8.40 ± 0.13
DO	mg/L	7.64 ± 0.34	8.09 ± 0.44
Fecal Coliform	MPN/100 mL	ND	ND
Total Coliform	MPN/100 mL	ND	ND

**Table 3.** Water quality assessment of the Lau Biang River, Wampu Watershed, Karo District, North Sumatra, Indonesia, in 2023-2024

Parameter	Unit	Water quality standard	Water quality result	
			2023	2024
Temperature (Deviation)	°C	≤±3°C	24.70	23.70
Total Dissolved Solids (TDS)	mg/L	1000	97	108
Total Suspended Solids (TSS)	mg/L	40	47	41
Color	Pt-Co	15	45.20	40.60
Acidity / pH	-	6-9	7.20	6.83
Biochemical Oxygen Demand (BOD)	mg/L	2	2	2
Chemical Oxygen Demand (COD)	mg/L	10	20.67	20.35
Dissolved Oxygen (DO)	mg/L	6	6.42	6.74
Sulfate (SO <sub>4</sub> <sup>2-</sup> )	mg/L	300	1.73	2.11
Chloride (Cl <sup>-</sup> )	mg/L	300	32.14	54.60
Nitrate (as N)	mg/L	10	1.02	1.15
Nitrite (as N)	mg/L	0.06	<0.004	<0.004
Ammonia (as N)	mg/L	0.1	0.12	0.15
Total Nitrogen	mg/L	15	1.17	1.30
Total Phosphate (as P)	mg/L	0.2	0.13	0.13
Fluoride (F <sup>-</sup> )	mg/L	1	0.24	0.28
Sulfur (as H <sub>2</sub> S)	mg/L	0.002	<0.002	<0.002
Cyanide (CN <sup>-</sup> )	mg/L	0.02	<0.01	<0.01
Free Chlorine	mg/L	0.03	<0.03	<0.03
Dissolved Barium (Ba)	mg/L	1.0	<0.1	<0.1
Dissolved Boron (B)	mg/L	1.0	<0.06	<0.06
Dissolved Mercury (Hg)	mg/L	0.001	<0.001	<0.001
Dissolved Arsenic (As)	mg/L	0.05	<0.002	<0.002
Dissolved Selenium (Se)	mg/L	0.01	<0.005	<0.005
Dissolved Iron (Fe)	mg/L	0.2	0.27	0.29
Dissolved Cadmium (Cd)	mg/L	0.003	<0.001	<0.001
Dissolved Manganese (Mn)	mg/L	0.1	<0.02	<0.02
Dissolved Nickel (Ni)	mg/L	0.07	<0.05	<0.05
Dissolved Zinc (Zn)	mg/L	3	<0.02	<0.02
Dissolved Copper (Cu)	mg/L	2	<0.02	<0.02
Dissolved Lead (Pb)	mg/L	0.01	<0.01	<0.01
Hexavalent Chromium (Cr <sup>6+</sup> )	mg/L	0.05	<0.01	<0.01
Total Detergents (Surfactants)	mg/L	200 µg/L (0.2 mg/L)	<0.05	<0.05
Phenols	mg/L	1 µg/L (0.001 mg/L)	<0.001	<0.001
Fecal Coliform	MPN/100 mL	1000 MPN/100 mL	2	2
Total Coliform	MPN/100 mL	5000 MPN/100 mL	220	540

Source: Water quality laboratory analysis conducted at Sucofindo Laboratory, Indonesia; data provided by PDAM Tirta Malem (2024)

### Spatial relationship between land cover change and surface water quality

The exploratory spatial data analysis using GeoDa revealed the spatial structure of pollutants in the Upper Wampu Watershed. To provide a quantitative basis for the spatial patterns, Global Moran's I statistics were calculated for key pollutants as summarized in Table 4.

Global Moran's I values for both Chemical Oxygen Demand (COD) and *Escherichia coli* indicate a random global spatial pattern (N=23). For COD, the Moran's I value was 0.042 (z-score=0.6036; p-value=0.257), while for *E. coli*, the Moran's I was -0.367 (z-score=-0.9901; p-value=0.162).

Despite the random global pattern, the Bivariate Local Indicators of Spatial Association (LISA) revealed a distinct and significant local dynamic regarding the spatial distribution of water quality parameters. To visualize this spatial relationship, Figure 5 presents the spatial maps generated from the GeoDa analysis, illustrating the clustering of specific pollutants in relation to land cover expansion.

To explicitly address the spatial association between specific land cover dynamics and water quality degradation, the Bivariate LISA results are summarized in Table 5. The analysis demonstrated that areas experiencing significant cropland expansion spatially coincide with elevated COD levels, creating significant High-High spatial clusters (p<0.001). Similarly, the growth of settlement (built-up) areas exhibited a strong spatial correspondence with increased *E. coli* concentrations, also resulting in significant High-High clusters (p<0.001).

### Discussion

Water quality conditions in the Upper Wampu Watershed show a contrast between baseline observations in 2017 and comparative assessments conducted in 2024 (Tables 2 and 3). Given the exploratory design of this study, the following discussion interprets observed patterns as spatial associations rather than statistically inferred causal relationships. Measurements from the Bahorok and Berkail rivers in 2017 are comparable to ranges reported for forest-dominated and low-disturbance watersheds, where vegetative cover is associated with reduced pollutant transport into river systems (Helsel et al. 2020). Differences between the Bahorok and Berkail rivers correspond to variations in physical and geomorphological characteristics. Greater depth, flow velocity, and transparency observed in the Berkail River are consistent with differences in channel morphology and flow conditions reported for upland rivers in North Sumatra (Helsel et al. 2020).

In contrast, recent assessments of the Lau Biang River show several parameters exceeding Class II standards (Table 3), occurring concurrently with documented land cover dynamics (Table 1). Exploratory spatial analysis illustrates a strong spatial correspondence between specific

land cover patterns and surface water quality degradation. Sub-watersheds with higher proportions of built-up areas spatially coincide with higher fecal coliform concentrations, forming significant High-High clusters. Mechanistically, this association is driven by the increase in impervious surfaces (e.g., roads, housing roofs) and inadequate domestic wastewater infrastructure. In expanding rural and peri-urban settlements, greywater and domestic sewage are often discharged directly into drainage networks or leach from unlined septic tanks, contributing directly to organic and microbiological pollution in the river system. Comparable observations have been reported in other developing watersheds, where organic indicators spatially coincide with areas of dense anthropogenic activity (Dou et al. 2016; Ojha et al. 2023).

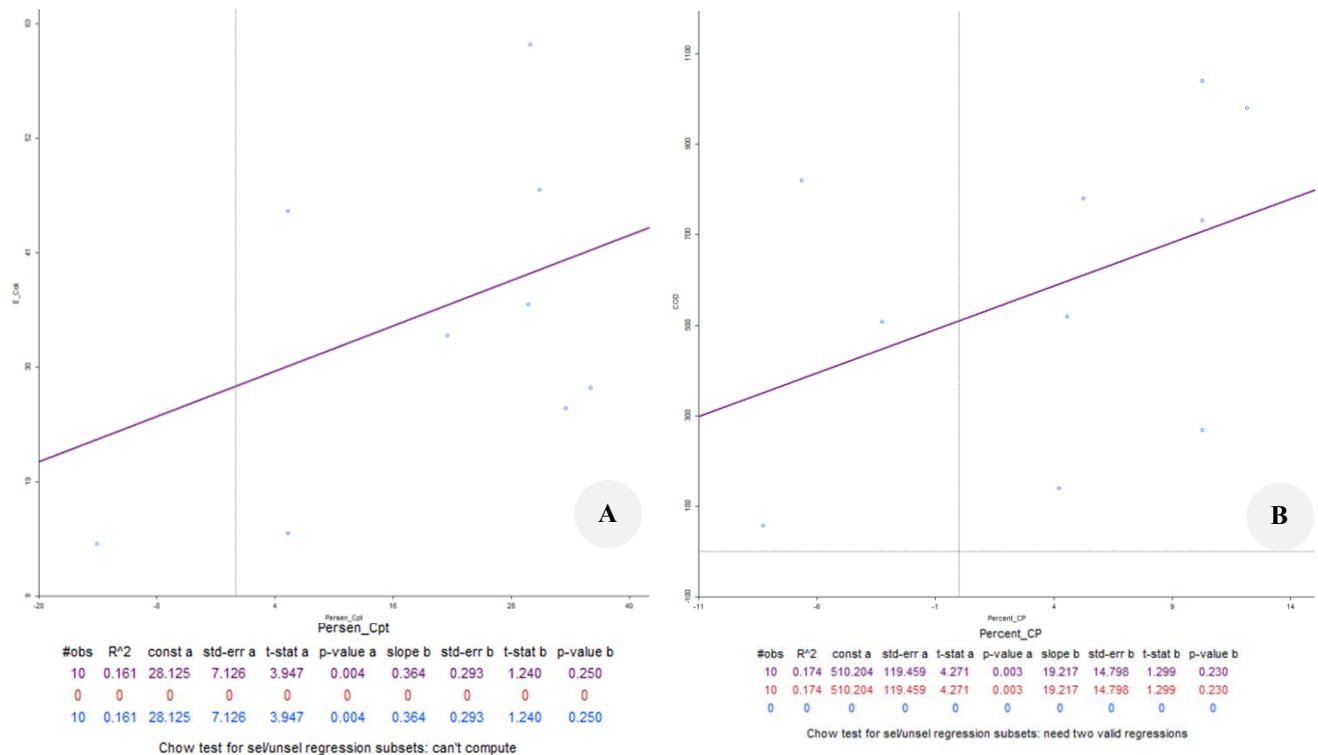
Conversely, the clustering of Chemical Oxygen Demand (COD) and elevated sediment-related parameters (TSS) occurs predominantly in areas characterized by intensive agricultural activity and grassland reduction. The mechanism behind this involves the removal of deep-rooted natural vegetation, which reduces soil cohesion and infiltration capacity. Consequently, surface runoff increases significantly, accelerating the transport of topsoil, unabsorbed agricultural fertilizers, and pesticide residues into the river network. This process explains the elevated organic loads and nutrient runoff observed in agricultural sub-catchments. Similar spatial patterns have been prominently documented in other tropical Indonesian watersheds, such as the Rejoso Watershed (Tamjidillah et al. 2021), where reduced vegetative cover under steep topography and high rainfall conditions consistently corresponded to higher sediment and organic indicators (Markum and Rahman 2024; Papadopoulou et al. 2025).

**Table 4.** Global Moran's I statistics for water quality parameters (N=23)

Parameter	Moran's I	Z-score	P-value	Spatial pattern
COD	0.042	0.6036	0.257	Random
<i>E. coli</i>	-0.367	-0.9901	0.162	Random

**Table 5.** Bivariate spatial association between land cover change and water quality (LISA)

Land cover variable	Water quality parameter	Spatial clustering pattern (LISA)	Significance level (p-value)
Settlement growth (Built-up)	<i>E. coli</i>	High-High cluster	<0.001
Cropland expansion	Chemical Oxygen Demand (COD)	High-High cluster	<0.001



**Figure 5.** Spatial clustering of: A. Fecal coliform and B. Chemical Oxygen Demand (COD) in relation to settlement expansion in the Upper Wampu Watershed based on GeoDa analysis

Despite the expansion of settlements, microbiological indicators showed localized occurrences and did not universally or persistently exceed extreme regulatory standards across the entire watershed. Several environmental factors may explain why these microbiological parameters remain relatively low or localized. First, the high natural river discharge and frequent intense rainfall typical of the tropical Wampu Watershed likely create a strong dilution effect, lowering the overall concentration of bacterial loads. Second, high exposure to natural ultraviolet (UV) radiation from tropical sunlight accelerates the die-off of coliform bacteria in open surface waters. Finally, the observed values might reflect the timing of the grab sampling, which can miss peak "first-flush" contamination events during early heavy rains (Wright et al. 2004; Pratama and Marodiyah 2024). Therefore, these observations suggest localized spatial occurrence rather than persistent, uniform microbiological pollution.

Overall, the findings show that different land use types correspond to different surface water quality characteristics. Agricultural areas correspond to sediment-related and organic (COD) parameters, whereas settlement areas correspond to microbiological indicators. These relationships are consistent with land use-hydrology interaction frameworks in which vegetation cover and land use alterations dictate variations in runoff generation and pollutant occurrence (Chawla et al. 2020).

Several limitations should be considered when interpreting these findings. The temporal mismatch between land cover datasets and water quality observations limits direct interpretation of specific linkages. In addition,

the absence of inferential statistical analysis and land cover transition matrices restricts quantitative attribution of specific water quality variations to individual land use conversions. Therefore, the relationships identified should be interpreted as spatial associations rather than causal linkages. Future research should incorporate statistical modeling, land cover conversion matrices, and integrated hydrological approaches such as the Soil and Water Assessment Tool (SWAT) to evaluate these relationships more rigorously (Grey et al. 2014; Liu et al. 2023).

In conclusion, land cover dynamics in the Upper Wampu Watershed between 2017 and 2024 were characterized by the expansion of built-up and cropland areas and a substantial reduction of grassland. Surface water assessments showed that several parameters exceeded Class II standards, while most physicochemical and microbiological parameters remained within permissible limits. Exploratory spatial analysis identified clustering of fecal coliform in settlement-dominated sub-watersheds and clustering of COD in agriculturally dominated areas. These findings represent spatial associations rather than causal relationships. This study is based on spatial comparison between land cover maps (2017-2024) and limited-period water quality observations and therefore cannot establish causal relationships. Differences in observation timing and sampling frequency may influence the strength of detected associations.

The observed degradation in specific water quality parameters, driven by the expansion of built-up and agricultural areas, highlights significant implications for future integrated watershed management. To ensure the sustainability of the Upper Wampu Watershed as a raw

water source, continuous and systematic land cover monitoring is highly recommended to track rapid land-use transitions and prevent uncontrolled encroachment. Furthermore, proactive mitigation strategies must be implemented, specifically the establishment and strict protection of riparian buffer vegetation along the river networks. Restoring these natural vegetative buffers is crucial to intercept agricultural runoff, stabilize riverbanks, and naturally filter non-point source pollutants before they enter the main water bodies. Future research should implement consistent monitoring locations, long-term datasets, and quantitative hydrological or statistical modeling approaches (e.g., SWAT) to evaluate land cover–water quality interactions more rigorously.

### ACKNOWLEDGEMENTS

The authors thank the staff of PDAM Tirta Malem and BBWS Sumatera II, Indonesia, for their contribution to hydrological and water quality data collection, and for the use of management strategies.

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