CSID Journal of Infrastructure Development

Volume 6 | Issue 2 Article 5

12-31-2023

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Recommended Citation
Pratama, M., & Constantine, D. (2023). A Spatiotemporal Analysis of Organic Pollutants Contamination in Ciliwung River, Indonesia. *CSID Journal of Infrastructure Development, 6*(2). https://doi.org/10.7454/jid.v6.i2.1119

CSID Journal of Infrastructure Development (6) 2: 198-210
ISSN 2407-4438

A SPATIOTEMPORAL ANALYSIS OF ORGANIC POLLUTANTS CONTAMINATION IN CILIWUNG RIVER, INDONESIA

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(Received: August 2023 / Revised: October 2023 / Accepted: December 2023)

ABSTRACT

Indonesia's DKI Jakarta province faces the ongoing issue of river pollution in the Ciliwung River, stemming from a variety of sources including domestic, commercial/industrial, and agricultural activities, exacerbated by the region's rapid population growth and associated shifts in land use patterns. Therefore, this study aims conduct a comprehensive spatiotemporal analysis of pollutant concentrations within the Ciliwung River and explore their correlation with land use changes to identify the predominant factors influencing river pollution. The investigation focuses on key organic pollutant parameters particularly focusing on Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Dissolved Oxygen (DO), and Total Suspended Solids (TSS) and utilizes flow and water quality data sourced from Ciliwung-Cisadane River Basin Center. Spatially, the findings of this study indicate that there is an increasing concentration of organic pollutants from the river's upstream to downstream segments. Temporally, concentrations of organic pollutants, particularly BOD and COD, reached their peak in 2018 and subsequently exhibited a declining trend until 2020. The study also reveals a moderate to strong correlation between residential land use and increased pollution levels. These findings highlight the urgent need for integrated river basin management and policy implications to mitigate the environmental risks posed by escalating urbanization.

Keywords: Ciliwung organic pollutant; Spatial analysis; Temporal analysis

1. INTRODUCTION

The Ciliwung River, flowing through the heart of Jakarta, the Capital City of Indonesia, is a vital natural resource for the city, providing water for various needs such as drinking, industry, fishery, and agriculture (Hendrawan, 2007). Several reports highlighted that the river's water quality has deteriorated despite its critical role. A rising trend of water pollution in the Ciliwung River from upstream to downstream has been observed, with domestic activities identified as the dominant source of pollution due to high concentrations of Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), ammonia, phosphate, detergent, and coliform bacteria (Ratnaningsih et al., 2019; Yudo, 2010).

Building upon previous studies, which have shown that factors like stream flow, soil moisture, antecedent streamflow, vegetation cover, and water temperature significantly affect the temporal water quality of rivers (Guo et al., 2018), this study aims to extend the analysis to more recent trends and deeper correlations.

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DOI: 10.7454/jid.v6.i2.1119

Baba and Gunduz (2017) indicated that geogenic alteration zones and anthropogenic intervention influence the temporal variability of river water quality. The land use change in the watershed, closely associated with human activities, has led to significant changes in river water quality. It is supported by Pratama et al. (2020) that stated that significant correlations between land use and water quality in the Code River in Yogyakarta, Indonesia. Furthermore, hydrological processes affect the spatial distribution of organic pollutants in a river and cause a decline in quality at the river delta are also influenced by land use characteristics in a particular area.

In recent decades, the condition of the Ciliwung watershed in Jakarta has worsened due to uncontrolled land use changes, notably the increase in residential and built-up areas at the expense of agricultural land (Fachrul et al., 2007). The land use composition in the catchment area is strongly correlated with the amount of water runoff that flows into the water body (Qin et al., 2010), and changes in this composition, such as decreases in recharge areas and agricultural land, can greatly influence runoff and soil erosion (Dunjó et al., 2004).

Given its critical roles, it is essential to understand the spatial and temporal variability of the Ciliwung River's quality. While several studies have reported the water quality trend from upstream to downstream of the river, there remains a gap in the temporal analysis of river quality, particularly in recent years. Although Ratnaningsih et al. (2019) reported a low-significance trend of river quality through the 2011-2014 period, updating the analysis to recent years is important. Therefore, this study aims to analyze the spatiotemporal trend of the organic pollutant concentration in the Ciliwung River and its correlation with the trend of land use changes, focusing on the last five years (2016-2020). Water quality monitoring data from five stations provided by the Ciliwung–Cisadane River Basin Center (BBWS) were collected for this period. Land use changes through the same period were analyzed using geographic information system (GIS) tools, allowing for more accurate visualization and in-depth analysis of the impacts of these changes on water quality.

2. METHODS

2.1. Study Area

The Ciliwung River, which flows through several administrative areas, including Bogor Regency, Bogor City, Depok City, and Jakarta Province Capital City, displays diverse geographical characteristics. From its mountainous origins in Bogor to the low-lying plains in Jakarta, these varying landscapes significantly influence the river's water quality and flow patterns. According to DKI Jakarta Provincial Environmental Service, the river extends over a length of approximately 120 kilometers (km), encompassing a river basin area of 387 km^2.

The Ciliwung River passages through numerous villages, dense residential areas, and slum settlements. The level of sanitation in these areas directly impacts the river's health. As of 2021, data from the Central Statistics Agency revealed that in West Java and DKI Jakarta Province, the percentage of households with access to adequate sanitation facilities stood at 71.66% and 95.17%, respectively. Adequate sanitation is defined as having individual or communal defecation facilities, using a gooseneck toilet, and a final disposal site for feces in a septic tank, Wastewater Treatment Plant (WWTP), or in a hole in the ground for rural areas.

Apart from domestic activities, land-based activities such as agriculture play a significant role in the catchment area's environmental dynamics. Using fertilizers and pesticides in extensive agricultural lands along the Ciliwung River Basin can increase nutrient levels and pollutants in the river water. According to the 2015-2019 Agricultural Land Statistics Report, the total agricultural land in the Province of DKI Jakarta, Depok City, Bogor City, and Bogor Regency in 2019 amounted to 46,648 hectares, most of which falls within the Ciliwung River watershed.

2.2. Data Collection

2.2.1. River Water Quantity and Quality

In this study, river discharge and water quality data were compiled from the BBWS report for the 2016 – 2020 period. Five strategic monitoring points were selected to measure river discharge and water quality, namely: Katulampa (TP 1), Kampung Kelapa (TP 2), Panus Bridge Depok (TP 3), MT Haryono (TP 4), and Manggarai Gate (TP 5). These points were chosen as they represent the river's upstream, midstream, and downstream sections, providing a comprehensive overview of the water quality changes along the river's course, as shown in Figure 1.

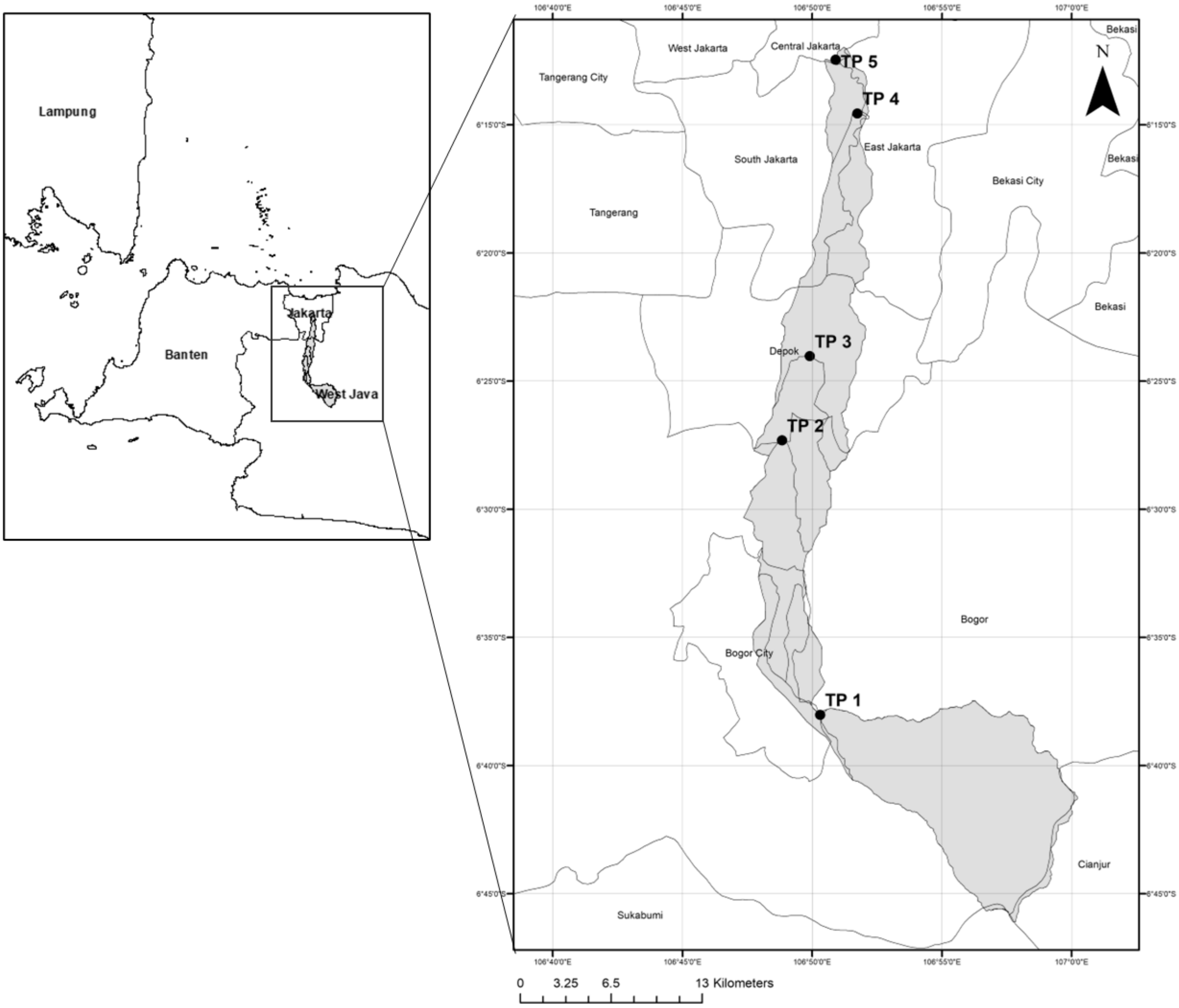


Figure 1 Study area and monitoring stations

The river discharge and water quality data were collected during the second semester (July – December) of each year from 2016 to 2020. Although the discharge measurement and water quality sampling were not conducted simultaneously each year, this methodology ensures consistency and accuracy in data collection. Four water quality parameters were analyzed to indicate the presence of organic pollutants, namely BOD, COD, DO, and TSS. The measurement methods for these parameters are detailed in Table 1.

Table 1 Water Quantity and Quality Parameter Measurement Method

Parameter	Method	Code
Discharge	Current meter	SNI 8066 2015
BOD	Five days incubation	SNI 6989.72:2009
COD	Spectrophotometric	SNI 6989.02:2019
DO	Potentiometric	SNI 06989.14-2004
TSS	Gravimetric	SNI 6989.3:2019

2.2.2. Land Use

For land use data, this study utilized shapefile data resulting from land cover recalculations from digital data available at the Directorate of Forest Resources Inventory and Monitoring and the Directorate General of Forestry Planning and Environmental Management under the Indonesia's Ministry of Environment and Forestry. On a scale of 1:250,000 accuracy, the data is used to obtain the percentage of each land cover type from 2016 – 2020. This detailed and accurate data will be instrumental in correlating land use changes with water quality trends, providing insights into the impacts of human activities on the Ciliwung River.

2.3. Data Analysis

The data analysis in this study was conducted using IBM SPSS Statistics 26. Prior to the correlation analysis, the data underwent a comprehensive cleaning process that included removing incomplete entries, correcting measurement errors, and handling outliers, ensuring the integrity and reliability of the dataset.The selection of the trendline type was based on a thorough analysis of the data distribution, which involved visually examining the data and statistical methods to ensure that the chosen trendline accurately reflected the observed trends.

Correlation analysis was then carried out to examine the relationship between pollutant concentration values and land cover percentage. This was done using the Pearson Correlation Coefficient (r), which measures the strength and direction of the relationship between two variables, x and y, in the sample. The Pearson r value was calculated to determine the degree to which changes in land use correlate with changes in the concentration of pollutants in the river.

The results of the correlation analysis will be presented in tables and graphs for interpretation and of how land use influences the water quality of the Ciliwung River, providing insights into the dynamics between human activities and environmental impacts.

3. RESULTS AND DISCUSSION

3.1. Data Summary

Tables 2 and 3 provide a descriptive statistical summary of the water quality of the Ciliwung River from 2016 to 2020 at each monitoring station and for each year of the study. These tables highlight critical areas with BOD concentrations exceeding class II water quality standards 27 times, according to the Republic of Indonesia Government Regulation Number 22 of 2021 regarding Implementation of Environmental Protection and Management. COD, DO, and TSS concentrations exceeded the standards 13, 9, and 2 times. These summaries underscore areas and times where focused environmental management interventions are needed.

Table 2 Spatial Summary of Wtaer Quality of Ciliwung River in 2016 – 2020

Parameter		Concentration (mg/L)				
		TP 1	TP 2	TP 3	TP 4	TP 5
BOD	Mean	4.1	4.6	5.2	7.2	6.2
	Median	3.3	3.2	5.0	7.0	5.0
	St. Dev	1.7	2.3	2.4	0.4	3.1
	n > QS	3	3	4	5	4
COD	Mean	18.5	19.1	25.1	30.4	24.4
	Median	17.0	14.0	23.0	30.8	18.8
	St. Dev	6.7	10.6	5.9	3.4	11.7
	n > QS	1	1	2	4	2
DO	Mean	4.8	4.7	4.8	4.5	3.9
	Median	4.7	4.4	4.6	4.0	3.6
	St. Dev	1.3	1.9	1.3	1.8	1.7
	n > QS	1	1	1	2	3
TSS	Mean	18.2	14.8	16.8	22.0	31.8
	Median	14.0	14.0	15.0	18.0	20.0
	St. Dev	8.9	7.7	9.1	11.4	23.6
	n > QS	0	0	0	0	1

Spatially, TP4 exhibited the highest BOD and COD concentrations, whereas TP5 showed the most significant pollution in DO and TSS. TP1 appeared to be the least polluted, with the lowest BOD and COD concentrations and the highest DO levels. However, there were occasions (1-3 times) when water quality at this station exceeded quality standards. Temporally, 2018 emerged as the most polluted year, with average BOD, COD, and DO concentrations of 7.6 mg/L, 34.4 mg/L, and 3.8 mg/L, respectively (see Table 3). In contrast, the TSS concentration was lowest in 2018, suggesting a lower impact of rainfall on sediment transport.

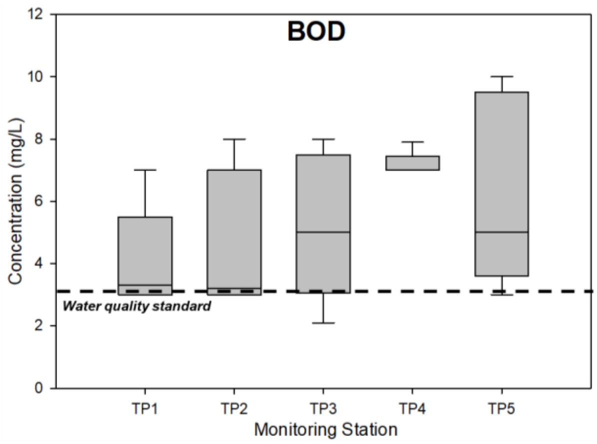
Table 3. Temporal Summary of Water Quality of Ciliwung River in TP1 – TP5

Parameter		Concentration (mg/L)				
		2016	2017	2018	2019	2020
BOD	Mean	4.4	7	7.6	4.2	4.1
	Median	4	7	7	3	3.3
	St. Dev	1.7	2.2	0.9	1.8	2.3
	n > QS	3	5	5	2	4
COD	Mean	18.2	24.8	34.4	18.4	21.5
	Median	18	25	34	14	22.3
	St. Dev	8.4	6.5	4.5	7.8	6.4
	n > QS	1	2	5	1	1
DO	Mean	5.2	6.8	3.8	4.2	2.7
	Median	5	6.8	4	4.4	2.6
	St. Dev	0.9	0.3	0.4	0.6	0.6
	n > QS	0	0	1	2	5
TSS	Mean	17.2	30.8	14.6	17.2	23.8
	Median	13	17	15	12	26
	St. Dev	15.9	22.6	1.7	9.8	7.4
	n > QS	0	1	0	0	0

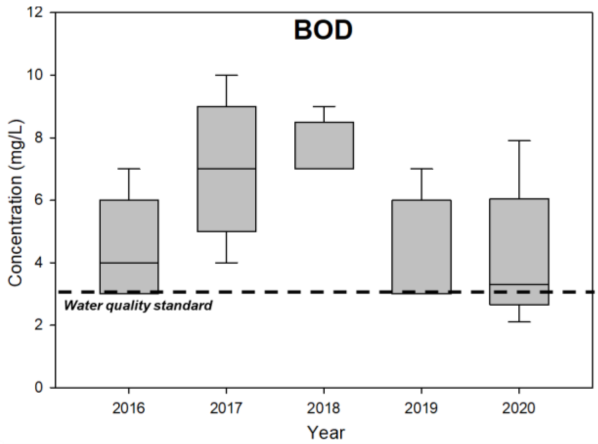
3.2. Biological Oxygen Demand (BOD)

Figure 2a displays boxplots of BOD concentrations at each monitoring station. The trend of increasing BOD concentrations from upstream to downstream is evident, with the median values indicating the lowest concentration in TP1 and TP2, at 3.3 mg/L and 3.2 mg/L, respectively. The highest median value was at TP4, at 7.0 mg/L. Dissolved oxygen levels can influence BOD concentrations, suggesting varying self-purification capacities along the river (Wahyuningsih et al., 2019).

This explains why there is a turbulent flow at TP5, with a high discharge exceeding 300 m^3/second, likely enhances the reaeration rate, as indicated by the lower BOD concentration compared to previous stations. The fluctuating BOD concentrations from upstream to downstream may reflect the river's self-purification capability, as long as there is sufficient dissolved oxygen (Moersidik & Widhiasari, 2015). Figure 2b shows the temporal trend of BOD concentrations, peaking in 2017 and 2018 reaching 7 mg/L, and then declining in subsequent years to 3 mg/L and 3.3 mg/L, in 2019 and 2020, respectively. The overall increase in BOD concentrations from 2016 to 2020 was 11%, highlighting the need for a closer examination of specific changes or events during these years that may have impacted water quality.



(a)

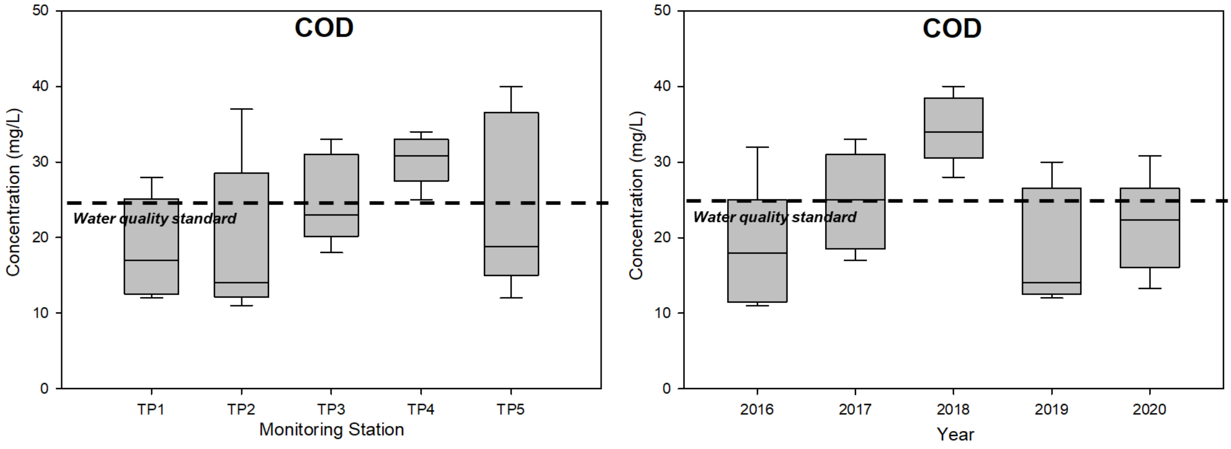


(b)

Figure 2 Boxplots of BOD concentrations by monitoring stations (a) and by year (b)

3.3. Chemical Oxygen Demand (COD)

COD concentrations at each monitoring station are illustrated in Figure 3a through boxplots. The median COD concentration was lowest at TP2 (14 mg/L), indicating relatively better water quality at this upstream location. In contrast, the highest median value of 30.8 mg/L was recorded at TP4, suggesting significant organic pollution in this part of the river. Figure 3b, showing COD concentrations for each monitoring year, reveals a peak in pollution levels during 2017 and 2018, with concentrations reaching up to 34 mg/L. A subsequent decrease in 2019 and 2020 to 14 mg/L and 22.3 mg/L, respectively, was noted. Overall, there has been an 18% increase in COD concentration over the study period, indicating a rising trend in organic pollutant load each year.



(a) (b)

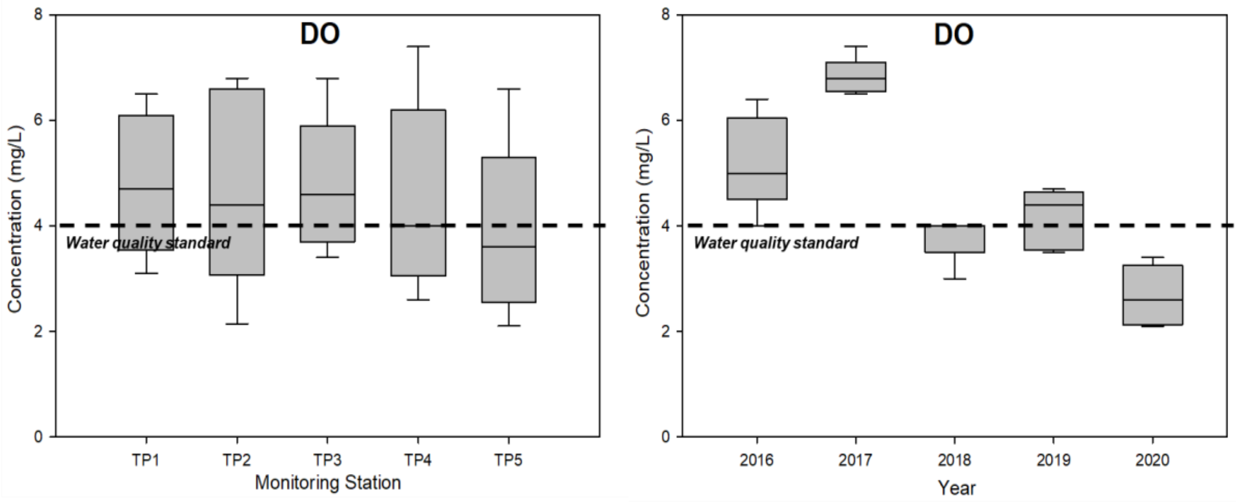
Figure 3 Boxplots of COD concentrations by monitoring stations (a) and by year (b)

High COD levels in river water indicate a substantial amount of organic pollutants, encompassing both biodegradable and non-biodegradable substances (Islam et al., 2019). This study reveals a heavier pollution load in the downstream segment of the Ciliwung River, particularly in the DKI Jakarta area, compared to the upstream segments. This suggests that urbanization and industrial activities in these regions significantly contribute to the deterioration of water quality. COD, along with BOD, is a critical parameter for assessing wastewater characteristics. The decline in water quality in the Ciliwung River is not only a result of domestic waste but also due to commercial and industrial activities. Industries in the catchment area, especially those without adequate wastewater treatment facilities, contribute to the pollution load. The Ciliwung River, functioning as an open ecosystem, receives various pollutants through water channels. Industrial effluents discharged into these channels, which do not meet environmental standards, exacerbate the decline in water quality (Hasibuan, 2019).

This trend highlights the urgent need for integrated wastewater management strategies, encompassing domestic and industrial sources, to mitigate the impact on the river's ecosystem. Strengthening regulations and monitoring systems for industrial discharges, alongside promoting effective wastewater treatment solutions, will be crucial in improving the overall health of the Ciliwung River.

3.4. Dissolved Oxygen (DO)

The boxplots detailing DO concentration values across both monitoring stations and years was presented in Figures 4a and 4b. These plots reveal a discernible trend of decreasing DO concentration as we move downstream. Examining the median values, TP5 exhibits the lowest DO concentration at 3.6 mg/L, while the highest median value is observed at TP1 at 4.7 mg/L. Notably, the boxplots depict variations in DO concentration in the upstream river, with compliance with class II water quality standards as stipulated by the Government Regulation Number 22 of 2021. However, it's important to highlight that certain DO concentration data points at TP4 and TP5 exceed these standards. Additionally, the boxplots underscore that the most significant variation in DO concentration occurred in 2017, peaking at 6.8 mg/L, while the lowest median DO concentration value was recorded in 2020 at 2.6 mg/L. The fluctuations in both DO and BOD concentrations imply that the river's self-purification capacity varies at each monitoring point and in each year, a phenomenon likely influenced by hydrodynamic conditions. The process of gas transfer from air to water bodies, known as river hydraulic factors, significantly affects the reaeration process. Overall, the trend in DO concentration reveals a decrease of -9%, indicating a decline in the water quality of the Ciliwung River over the study period.



(a) (b)

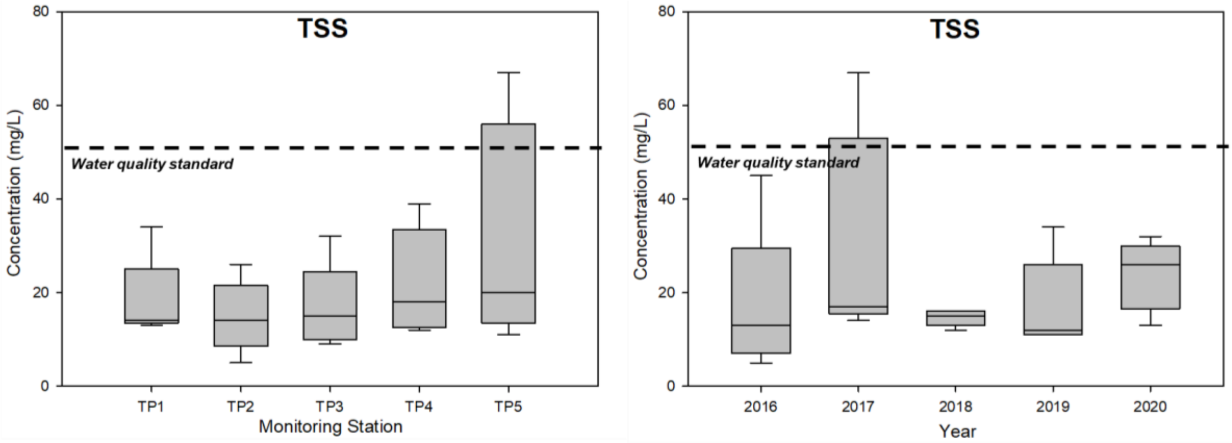
Figure 4 Boxplots of DO concentrations by monitoring stations (a) and by year (b)

DO is a crucial parameter for assessing water quality and ecosystem health. Insufficient oxygen levels can harm aquatic life, often resulting in fatalities not directly from pollutant toxicity but due to oxygen depletion caused by the biodegradation process of pollutants (Manahan, 2000). This trend suggests that the downstream segments of the Ciliwung River are increasingly unsuitable for sustaining freshwater ecosystems. High levels of BOD, indicative of organic waste, further exacerbate DO depletion in these water bodies (Penn et al., 2009).

The relatively better DO concentration in the river's upstream segments can be attributed to a lower deoxygenation rate than the reaeration rate. This balance is crucial for maintaining water quality, where a high deoxygenation rate is typically driven by the concentration of organic pollutants and their decomposition rate. Conversely, the reaeration rate, indicating the speed at which oxygen diffuses into the water, is essential for replenishing oxygen levels. A study on the Bedadung River in Jember Regency corroborates these findings, showing lower deoxygenation rates in rural areas compared to urban settings (Wahyuningsih et al., 2019). These findings underscore the critical need for effective management strategies to mitigate pollution sources, particularly in urban areas, to preserve the ecological integrity of the Ciliwung River.

3.5. Total Suspended Solids (TSS)

Figure 5a presents boxplots of TSS concentrations at each monitoring station along the Ciliwung River. These plots reveal an increasing trend in TSS concentration from upstream to downstream, with the lowest median concentrations observed at TP1 and TP2 (14 mg/L) and the highest at TP5 (20 mg/L). Despite this increase, all stations have TSS levels within class II water quality standards per the Government Regulation Number 22 of 2021, indicating a relatively stable water quality in suspended solids. The temporal analysis of TSS concentrations, illustrated in Figure 5b, shows the highest variation in 2020, reaching a median of 26 mg/L and the lowest in 2016 at 13 mg/L. Overall, there has been a 45% increase in TSS concentration over the study period, signifying a growing load of suspended solids entering the river each year.



(a) (b)

Figure 5 Boxplots of TSS concentrations by monitoring stations (a) and by year (b)

This rising trend in TSS is corroborated by the record rainfall in Jakarta since early 2020, as reported by the Meteorology, Climatology, and Geophysics Agency of Indonesia (BMKG). The highest recorded rainfall reached 377 mm/day, aligning with the increased river discharge data from Ciliwung–Cisadane River Basin Center, where the discharge at TP7 peaked at 386 m^3/second. Such high rainfall events, especially in urban areas like Jakarta, often result in elevated river TSS levels due to enhanced soil erosion and runoff, as river conditions during heavy rains typically lead to cloudier water with higher sediment content (Nurjanah, 2018).

Managing the Manggarai Sluice Gate, including the Ciliwung Lama and West Flood Canal, is crucial in controlling water overflow and sediment transport during these high rainfall events (Sari, 2020). The increased TSS levels in 2020 can be attributed to these extreme weather conditions, highlighting the need for effective sediment and stormwater management strategies, particularly in light of increasing urbanization and climate change impacts.

3.6. Land Use Trend Analysis

The land use map of the Ciliwung watershed from 2016 to 2020 is depicted in Figure 6 that clearly shows that the further downstream one goes, particularly in the MT Haryono watershed and Manggarai Gate areas, the more dominant residential areas become. This trend aligns with the urbanization patterns that Lambin (2001) identified, where urban agglomeration and suburban settlements that need to be expanded led in significant landscape changes. However, city centers that are already densely populated only experience a change from residential to commercial areas (Sari & Dewanti, 2018). This study includes industrial and commercial areas in the residential land classification, reflecting a nuanced perspective on urban land use. Thus, in the downstream segment of the Ciliwung River, the percentage of residential land has only experienced a small or even constant increase.

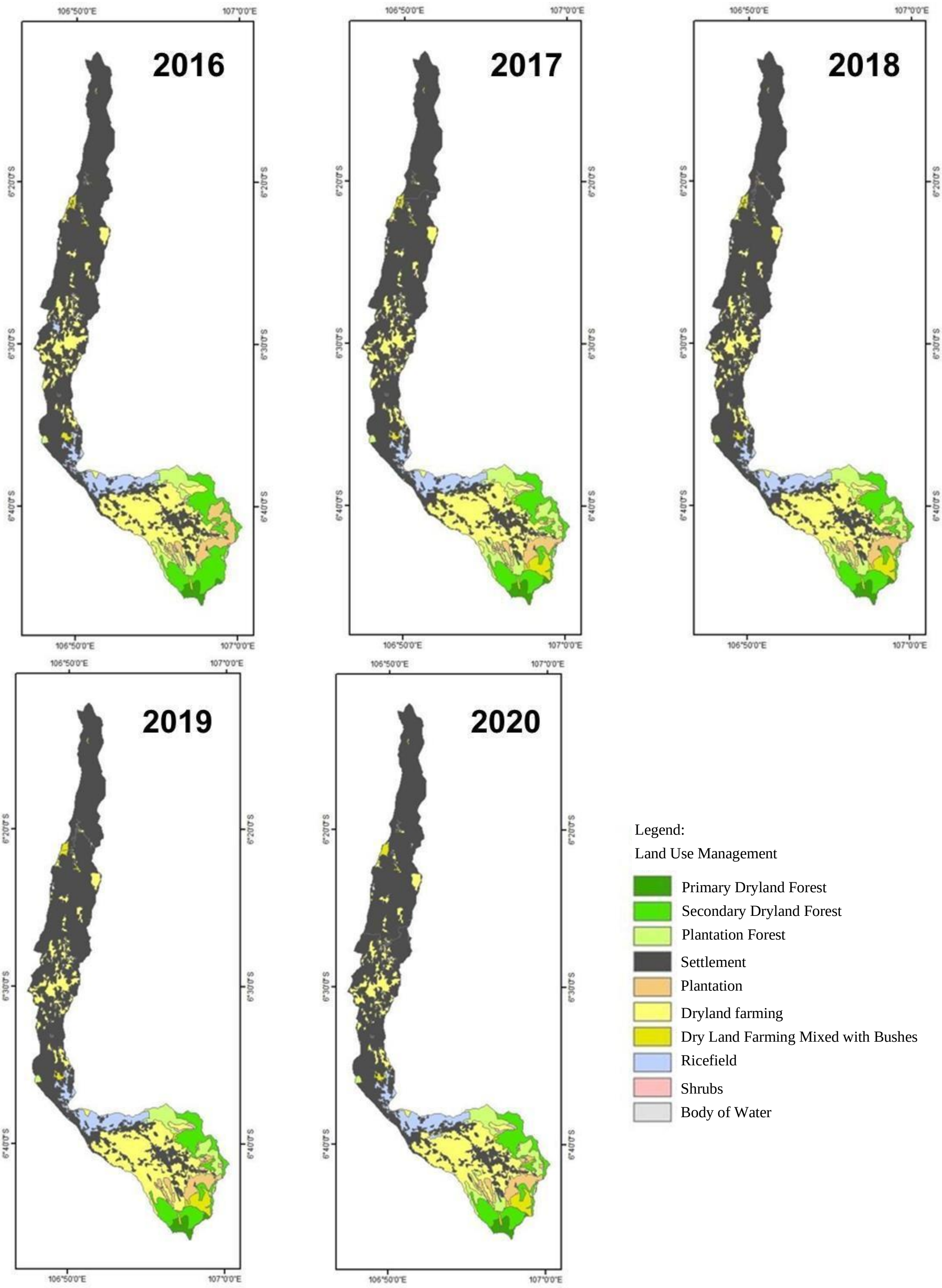


Figure 6 Land use change in the Ciliwung River watershed in 2016-2020

The percentage of residential land from 2016 to 2020 for each monitoring point river basin can be seen in Table 4. Residential areas in the Katulampa watershed only increased by 0.9% in 2017 and remained constant until 2020. The residential area in the Kampung Kelapa watershed increased by 2.8% in 2017, 0.2% in 2018, and 0.5% in 2019, and it remained constant until 2020. Residential land in the Panus Depok Bridge watershed increased by 2.5% in 2017 and remained constant until 2020. Residential land in the MT Haryono watershed increased by 0.1% from 2017 and remained constant until 2020, whereas residential land in the Manggarai Watershed did not increase from 2016 to 2020.

Table 4 Pearson Correlation Coefficient between Water Quality in each Monitoring Station versus Percentage of Residential Area in the Catchment Area of each Monitoring Station.

Parameter	**2016**	**2017**	**2018**	**2019**	**2020**
BOD	0.664	0.861	0.466	0.405	0.364
COD	0.568	0.796	0.834	0.381	0.066
DO	-0.555	0.516	-0.447	-0.728	-0.482
TSS	0.377	0.649	-0.422	-0.891	0.676

Table 4 presents the Pearson Correlation Coefficients between water quality parameters at each monitoring station and the percentage of residential areas in their respective catchments. The findings reveal a moderate to strong correlation across all parameters, emphasizing the significant impact of residential land use on water quality. For example, BOD, commonly resulting from decomposable organic carbon from various sources including human activities, notably correlates with residential areas. This indicates the impact of domestic and commercial/industrial wastewater, which typically lacks proper treatment and directly contributes to river pollution (Penn et al., 2009; Putri, 2021). The strong positive correlation observed between residential areas and river COD concentrations (Suharyo, 2019) further underscores the need for comprehensive wastewater management.

The significance of the correlation between water quality in each monitoring station versus the percentage of residential area in the catchment area of each monitoring station may indicate the importance of a centralized wastewater treatment system. Although only around 4.83% – 28.34% of households do not have access to proper sanitation in Jakarta and West Java, only a few households have managed their greywater, as the common practice is direct discharge to drainage systems, which eventually ends up in water bodies. The current lack of proper sanitation in some areas of Jakarta and West Java, where direct discharge into water bodies is common, calls for urgent action.

Currently, the Ministry of Public Works and Housing, through the Directorate General of Human Settlements, in collaboration with the Japan International Cooperation Agency (JICA) assists the government of DKI Jakarta province to address the sanitation and wastewater issues by developing a Domestic Wastewater Treatment Plant system in key zones across Jakarta called the Jakarta Sewerage Development Project (JSDP). This project is a critical step towards mitigating river pollution and enhancing urban water quality.

In accordance with the 2012’s master plan outlined in the Project for Capacity Development in the Wastewater Sector in DKI Jakarta, the strategic development of the wastewater sector in DKI Jakarta is organized into fifteen designated zones. Among these, Zone 1 and Zone 6, encompassing areas in Central Jakarta, West Jakarta, and North Jakarta, have been identified as the foremost priorities for development by the Ministry of Public Works and Housing. JSDP was planned to be built within DKI Jakarta's Zone 1. The estimated cost for this undertaking amounts to 185 billion Indonesian Rupiah (Kementerian PUPR, 2022). Commencing in 2023, the construction of Zone 1's wastewater treatment infrastructure is slated for completion in 2027.

4. CONCLUSION

This study conducted a comprehensive spatial and temporal analysis of organic pollutant concentrations in the Ciliwung River at five monitoring stations: Katulampa (TP1), Kampung Kelapa (TP2), Panus Bridge Depok (TP3), MT Haryono (TP4), and Manggarai Gate (TP5). Spatially, there is a discernible increase in the concentrations of BOD, COD, and TSS from upstream to downstream, with a range of 14-29%. Conversely, DO concentration exhibited a negative trend, decreasing by 9%. Temporally, the study period of 2016-2020 revealed a general decline in water quality. Specifically, an increasing trend in BOD, COD, and TSS concentrations was noted, ranging from 11-45%, while DO levels showed a decrease of 9%.

A key finding from the correlation analysis is the moderate to strong relationship between water quality at each monitoring station and the percentage of residential land in the corresponding catchment areas. This correlation underscores the significant impact of residential development and associated wastewater on river pollution. It highlights the urgent need to develop and implement centralized wastewater management infrastructure to address the increasing pollution load, particularly in urban areas.

The results of this study emphasize the critical role of integrated water resource management that considers land use changes and urbanization patterns. Effective wastewater treatment and management, especially in densely populated urban areas, are essential to mitigate the adverse effects on river ecosystems. The ongoing initiatives, such as the Jakarta Sewerage Development Project, are steps in the right direction and should be supported and expanded to improve water quality in the Ciliwung River and other similar urban river systems.

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