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The Influence of Rainfall and ENSO Phenomenon on The Water Quality Status of Jakarta Rivers in 2021-2023

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Abstract

This study investigates the influence of rainfall and the El Niño-Southern Oscillation (ENSO) phenomenon on river water quality in Jakarta, focusing on pollution index (PI) values as a measure of water quality. As a densely populated urban area, Jakarta is susceptible to waste production from domestic activities, which impacts its water quality. In addition to anthropogenic factors, external influences such as rainfall and ENSO events, represented by the Oceanic Niño Index (ONI), are believed to affect water quality status. Data was collected at 120 river sites across DKI Jakarta from 2021 to 2023, covering four seasonal periods: rainy, first transition, dry, and second transition seasons. The PI value (Y) was the dependent variable, while rainfall (X_1) and ONI value (X_2) were the independent variables. The results revealed a negative correlation between rainfall and PI value (-0.2654) and a positive but weak correlation between ONI value and PI value (0.0490). The regression model ($Y = 12.1546 – 0.0137\ X_1 – 0.1857\ X_2$) showed that increased rainfall decreased PI values, whereas higher ONI values correlated with higher PI values. Despite the correlation, the effect of rainfall and ENSO on PI value was statistically insignificant, suggesting that other factors, notably anthropogenic influences, have a more significant impact on river water quality. Efforts to reduce pollution from surrounding areas are crucial for maintaining ecosystem stability.

Keywords: El Niño-Southern Oscillation, Jakarta, pollution index, rainfall, river

1. Introduction

The watershed area in the Special Capital Region of Jakarta Province (DKI Jakarta) is situated in the middle to downstream regions of a river. There are 23 river flows including Ciliwung, Cipinang, Angke, Sekertaris, Sepak, Mookervart, Grogol, Sunter, Krukut, Cengkareng, Buaran, Petukangan, Jati Kramat, Kalibaru Barat, Kalibaru Timur, Kanal Timur, Cakung, Cideng, Mampang, Tarum Barat, Kamal, Pesanggrahan, dan Blencong rivers. Water quality in Jakarta Rivers has deteriorated over the years because of urban development. High population growth with low watershed management is suspected to trigger a decrease in river water quality [1]. Jakarta Municipality Statistics (2024) mentioned that the population growth in 2021 to 2023 reached 66,663 people; therefore, the total population reached 10,672,100 in 2023. On the other hand, Indonesia's Ministry of Environment and Forestry (2024) mentioned the generated wastes in the province from 2020 to 2022, respectively, were 3.054.812,22 tons, 2,354,345.24 tons, and 3,112,381.40 tons. High population growth and community behaviors that degrade river health contribute to declining water quality, leading to river pollution [2]. This condition can be visually observed from the presence of waste in the river flow and the decrease in dissolved oxygen concentration [3–5].

The rainfall that occurs is influenced by the change of seasons, especially the movement of the monsoon winds [6]. Generally, the seasons in Indonesia are divided into the rainy, dry, and transition seasons. The rainy season is characterized by a decadal rainfall amount of more than 50 mm. During the dry season, water quality parameters tend to decrease. However, during the rainy season, runoff from the river catchment area and high river discharge from the upstream river cause these water quality parameters to improve [7,8]. Rainfall is generally caused by climatic factors, including the El Niño-Southern Oscillation (ENSO) phenomenon, which is divided into two conditions: El Niño and La Niña [6]. The El Niño phenomenon occurs due to an increase in normal water temperature in the Pacific Ocean, causing an increase in heat, whereas La Niña occurs when the temperature decreases, thus increasing rainfall [9]. Seasonal changes, which can be measured through rainfall and ENSO, are suspected to influence changes in water quality status in the river flow area of Jakarta.

The declining water quality during the dry and rainy seasons increases the risk of degradation in urban freshwater ecosystems. Currently, fish species in Jakarta's rivers are largely dominated by invasive species due to deteriorating water quality. In addition to human-led introductions, invasive species thrive because of their ability to adapt to poor environmental conditions [10]. The loss of native species in urban ecosystems can disrupt the food chain and affect the populations of both predators and prey. From an economic and social perspective, the disappearance of native fish species in Jakarta's waters may reduce local food sources and lead to the loss of traditional culinary culture [11]. If this continues, the river's ability to provide essential ecosystem services in urban areas will decline.

Given the strong connection between the ENSO phenomenon and freshwater ecosystems, a study is needed to analyze this relationship. The period from 2021 to 2023 marks a transition from the COVID-19 pandemic to the new normal and post-pandemic phases, making water quality trends particularly interesting. Additionally, a time-series analysis of atmospheric conditions is expected to help predict future weather patterns, allowing for preventive measures to mitigate water quality deterioration caused by climatic events. This study aims to analyze the impact of rainfall and the ENSO phenomenon on river water quality in DKI Jakarta from 2021 to 2023. The findings are expected to serve as a scientific reference for improving watershed management, particularly in Jakarta, during seasonal transitions.

2. Methods

2.1. Time and Location of Research

This research was conducted based on river water quality monitoring activities by the Environmental Agency for the Special Capital Region of Jakarta Province (DLH DKI Jakarta) from 2021 to 2023. Monitoring was carried out based on the seasons that occur each year, namely, the rainy season, first transition season, dry season, and second transition season. Monitoring was carried out at 120 monitoring points spread across five city regions in the DKI Jakarta Province (Figure 1).

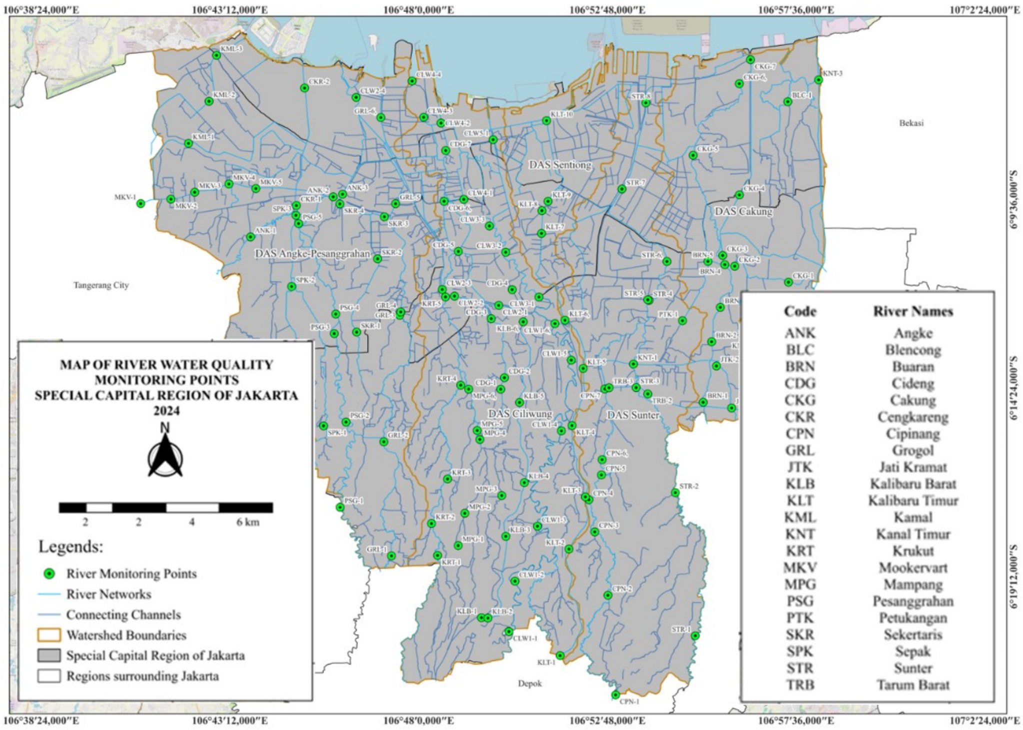

Figure 1. Map of river water quality monitoring location in DKI Jakarta. This figure depicts the distribution of water quality monitoring points across the Jakarta metropolitan area, encompassing various major river systems and canals.

2.2. Data Collection

2.2.1. Water Quality

Water data were acquired to determine river water quality based on SNI 8995:2021 on water sampling methods for physical and chemical testing for water sampling and in-situ parameter testing. The water samples were analyzed at the Regional Environmental Laboratory of the Special Capital Region of Jakarta. The water quality parameters tested in this study are shown in Table 1. The quality standard used was based on Government Regulation of the Republic of Indonesia Number 22 of 2021, Appendix VI, regarding class II river water quality standards.

2.2.2. Rainfall

Rainfall data were obtained based on daily rainfall monitoring data from the Meteorology, Climatology, and Geophysics Agency (BMKG) at the Kemayoran Meteorological Station, Central Jakarta, from October 2020 to January 2024. The rainfall data can be accessed through the following address: https://dataonline.bmkg.go.id/. The data were then calculated on a decadal scale to display the rainfall conditions during that period. Meanwhile, the ENSO phenomenon was measured using the Oceanic Niño Index (ONI) value obtained from monthly monitoring by the National Weather Service-National Oceanic and Atmospheric Administration (NWS-NOAA) from 2020 to 2024. The ONI value data can be accessed through the following address: https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php.

Table 1. Water quality parameters for physical, chemical, and biological components: Quality standards, units, and measurement methods (in situ and laboratory) for river monitoring.

Num.	Parameters	Units	Standard Quality*	Descriptions
A. Physics Components				
1	Temperature	°C	Dev 3	Insitu
2	Salinity	‰	-	Insitu
3	Water brightness	cm	-	Insitu

Num.	Parameters	Units	Standard Quality*	Descriptions
4	Turbidity	NTU	-	Insitu
5	Water colour	Ini-Co Unit	50	Laboratory
6	Total Dissolved Solid (TDS)	mg/l	1000	Laboratory
7	Total Suspended Solid (TSS)	mg/l	50	Laboratory
B. Chemical Components				
1	pH	-	6-9	Insitu
2	Dissolved Oxygen (DO)	mg/l	4	Insitu
3	BOD (20°C, 5 hari)	mg/l	3	Laboratory
4	COD (dichromat)	mg/l	25	Laboratory
5	Total Phosphate (Total P)	mg/l	0.2	Laboratory
6	Nitrate (INI_3)	mg/l	10	Laboratory
7	Nitrite (INI_2)	mg/l	0.06	Laboratory
8	Ammonia (NH_3)	mg/L	0.2	Laboratory
9	Total Nitrogen (Total N)	mg/l	15	Laboratory
10	Fluoride (F^-)	mg/l	1,5	Laboratory
11	Hydrogen Sulphide (H_2S)	mg/l	0.002	Laboratory
12	Sulphate (SO_4^{2-})	mg/l	300	Laboratory
13	Free Chlorin	mg/l	0.03	Insitu dan Laboratory
14	Chloride (Cl^-)	mg/l	300	Laboratory
15	Cyanide (CN^-)	mg/l	0.02	Laboratory
16	Mercury (Hg)	mg/l	0.002	Laboratory
17	Cadmium (Cd)	mg/l	0.01	Laboratory
18	Zinc (Zn)	mg/l	0.05	Laboratory
19	Copper (Cu)	mg/l	0.02	Laboratory
20	Lead (Pb)	mg/l	0.03	Laboratory
21	Hexavalent Chrome (Cr^{6+})	mg/l	0.05	Laboratory
22	Nickel (Ini)	mg/l	0.05	Laboratory
23	Arsenic (As)	mg/l	0.05	Laboratory
24	Cobalt (Co)	mg/l	0.2	Laboratory
25	Barium (Ba)	mg/l	-	Laboratory
26	Boron (B)	mg/l	1.0	Laboratory
27	Selenium (Se)	mg/l	0.05	Laboratory
28	Iron (Fe)	mg/l	-	Laboratory
29	Manganese (Mn)	mg/l	-	Laboratory
30	Oil and Fat	mg/l	1	Laboratory
31	Methylene Blue Active Surfactant (MBAS)	mg/l	0.2	Laboratory
32	Phenol	mg/l	0.005	Laboratory
C. Biological Components				
1	Fecal Coliform	total/100 ml	1000	Laboratory
2	Total Coliform	total/100 ml	5000	Laboratory

*Class II river water quality standards are based on Government Regulation of the Republic of Indonesia Number 22 of 2021.

2.2.3. Freshwater Biodiversity

Freshwater biodiversity data were obtained from secondary sources by analyzing plankton composition at several Jakarta River locations over the past three years. By understanding the plankton composition in a body of water, it becomes possible to predict both primary productivity and fisheries productivity, as plankton serves as an essential food source for fish. Additionally, changes in plankton composition can indicate shifts in water quality and ecosystem health, making it a crucial parameter in freshwater biodiversity studies.

2.3. Data Analysis

2.3.1. Pollution Index (PI)

Water quality in rivers is analyzed using a pollution index (PI), which determines the pollution level against the quality standard parameters of water that are allowed [12]. This index is determined based on the average index representing the average pollution level of all parameters and the maximum index showing one main type of parameter that causes a decrease in water quality at one observation. The PI calculation used in this study is shown in Equation 1. The tools used in this analysis are Microsoft Excel 365 data processing software. The water quality classification based on the PI value is based on the Decision of the Minister of Environment Number 115 of 2003, which is an evaluation of the IP value, as shown in

.

$$PI_j = \sqrt{\frac{\left(\frac{C_i}{L_{ij}}\right)_M^2 + \left(\frac{C_i}{L_{ij}}\right)_R^2}{2}} \tag{1}$$

Descriptions:

PI_j = Pollution index for designation j;

C_i = Concentration of parameter test result;

L_{ij} = Concentration of parameter according to water quality standards j;

$(C_i/L_{ij})_M$ = Maximum C_i/L_{ij} value; and

$(C_i/L_{ij})_R$ = Average $C_i/L_{ij.}$ value.

Table 2. Water quality status based on pollution index. The PIj value range is divided into four categories: meeting quality standards (good condition), lightly polluted, moderately polluted, and heavily polluted. This classification refers to water quality assessment guidelines commonly used in aquatic environmental management in Indonesia.

Value	Quality Status
$0 \le PI_j \le 1.0$	Meets quality standards (good condition)
$1.0 < PI_j \le 5.0$	Lightly polluted
$5.0 < PI_j \le 10$	Moderately polluted
$PI_j > 10$	Heavily polluted

2.3.2. Correlation Analysis and the Influence of Rainfall and ENSO on Water Quality Status

The independent variables in this analysis are rainfall based on decadal and ONI values, whereas the dependent variable is water quality status. Correlation analysis uses statistical methods to measure the strength of the linear relationship among the three variables used [13]. This determines the level of change among the three analyzed variables. In contrast, the influence analysis used is a linear regression analysis between decadal rainfall and ONI values with the monitored PI value based on the ongoing season [14]. The seasons are divided into rainy, dry, and transitional seasons from 2021 to 2023. The regression model used in this study is presented in Table 3. The classical assumption test was carried out using the normality test through the Liliefors Test and the heteroscedasticity test through the Glejser Test. Data processing in both analyses was performed using Microsoft Excel 365 data processing software.

Table 3. Linear regression model for analyzing the influence of decadal rainfall and ONI value on water quality status (PI value) across different seasons (2021-2023).

Test type	Model Equation	Variables	Descriptions
Linear regression	$Y = a + b_1X_1 + b_2X_2 + \varepsilon$	X_1	Rainfall
		X_2	ONI value

Y	PI value

3. Results and Discussion

3.1. Result

3.1.a Water Quality Status of Jakarta River in 2021-2023

The rivers spreading across the Jakarta region are generally classified as lightly to heavily polluted (Figure 2). River sections that tended to have a light pollution status from 2021 to 2023 included Tarum Barat, the upper Pesanggrahan, and the upper Ciliwung. Meanwhile, river sections classified as heavily polluted during the same period were Cideng, Sekertaris, Kalibaru Timur, Grogol, and Sepak. High population density, coupled with low public awareness among communities living near the river basin areas, is suspected to be the main cause of river pollution in Jakarta [1,15]. The findings of high levels of total coliform and fecal coliform parameters support this. These parameters are closely related to the feces of living beings, indicating that the primary source of pollution in this area stems from domestic waste. This condition threatens the sustainability of the river's aquatic environment and can lead to the death of aquatic organisms [16]. This situation can be mitigated by reorganizing urban spaces and supporting the development of communal wastewater treatment plants to ensure that domestic wastewater does not flow directly into the rivers.

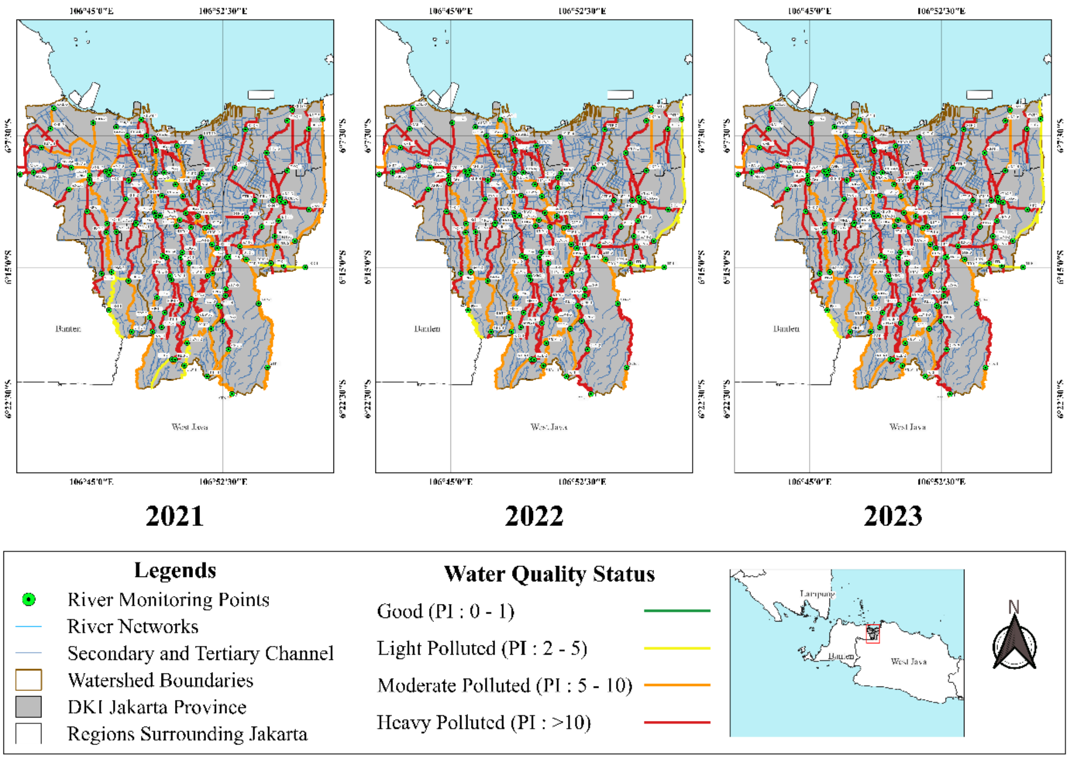

Figure 2. Map of Water Quality Status of Jakarta River in 2021-2023. Water quality status is divided into four categories: good, lightly polluted, moderately polluted, and heavily polluted. The map shows that most river segments in DKI Jakarta are in a state of light to heavy pollution, with relatively consistent variations in pollution distribution throughout the observation period.

3.1.b. Comparison of Rainfall and River Water Quality Status

Rainfall from 2020 to 2022 showed a change in conditions that tended to be consistent each month (Figure 3). However, in 2023, there was an inconsistent change in rainfall conditions, which was a significant increase in February; however, it tended to decrease to very low rainfall in July to October. This is suspected to be caused by a shift in the dry season conditions, making it longer than that of the previous year.

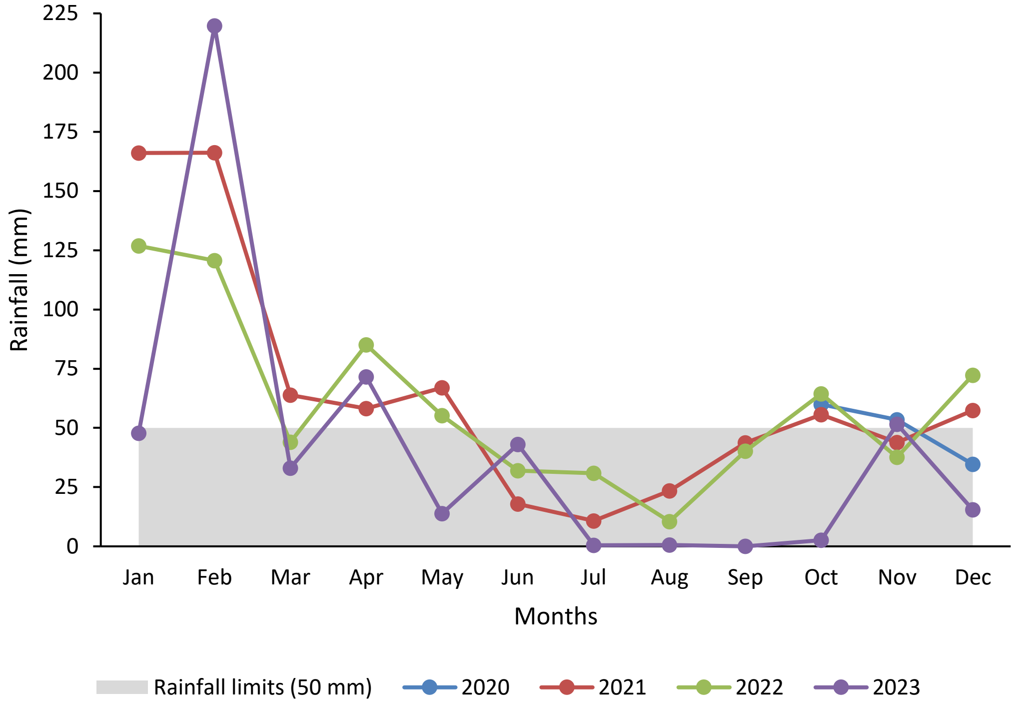

Figure 3. Rainfall that occurred in 2020 to 2023 that was observed in Kemayoran Meteorology Station, Central Jakarta. Source: Meteorology, Climatology, and Geophysics Agency (BMKG). Available at: https://dataonline.bmkg.go.id/.

Rainfall tends to fluctuate; however, it is in line with the seasons based on the rainfall limit of 50 mm, which is the boundary of the tendency for the rainy season (more than 50 mm) and dry season (less than 50 mm) [7]. The highest rainfall occurred during the rainy season in 2021, which was 89.0684 ± 17.9827 mm, while the lowest occurred during the dry season in 2023, which was 11.025 ± 6.0757 mm. The monitored precipitation index (PI) value of water tends to fluctuate between seasons, where the highest value occurred in the rainy season in 2022, which was 13.1165 ± 0.3117, while the lowest occurred during the dry season in 2023, which was 9.6927 ± 0.3019 (Figure 4). Rainfall that occurs in the South-East Asia (SEA) region is caused by atmospheric pressure, topography, wind patterns, ocean currents, moisture in the air, air currents, storm dynamics, and ENSO [6].

The correlation between rainfall and PI values was negative, indicating that an increase in rainfall by one unit would decrease the PI value by 0.0091 (Figure 5). Based on the coefficient of determination (R^2) value, it can be said that rainfall affected only 7.05% of the PI value, with the remainder influenced by other factors. Nevertheless, it should be noted that the PI value calculated in this study was obtained from the value of water quality parameters that were tested according to quality standards with a dominance of maximum levels. Therefore, the decrease in the PI value at high rainfall was proportional to the decrease in the concentration of measured parameter values [18].

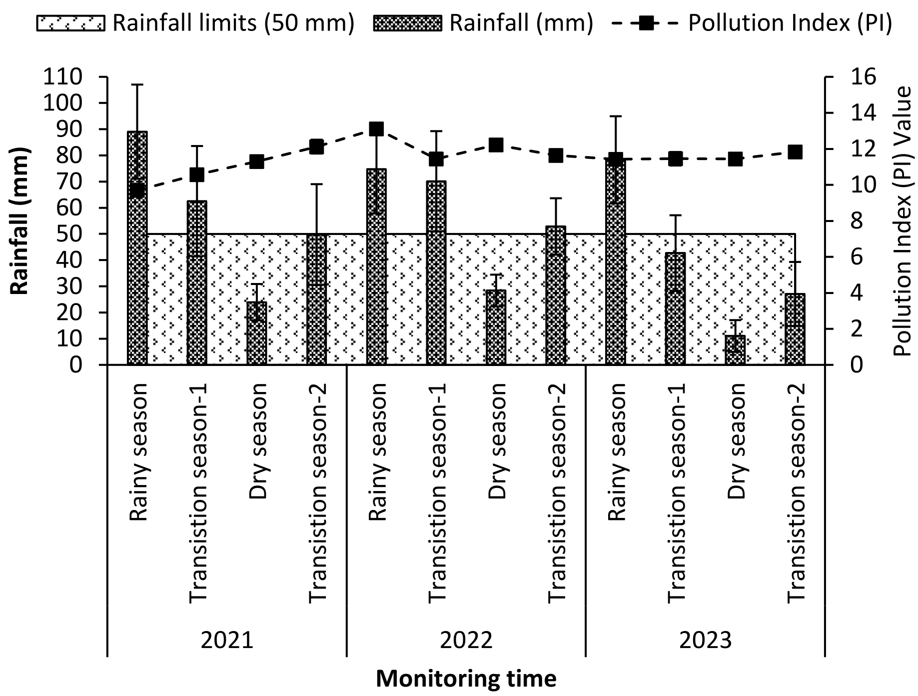

Figure 4. Rainfall and PI value Jakarta River based on seasons from 2021 to 2023. The data provide a temporal context to assess how seasonal rainfall patterns influence river water quality conditions. The figure indicates that fluctuations in rainfall are associated with changes in PI values, suggesting a potential relationship between hydrological conditions and pollution levels in Jakarta's river system.

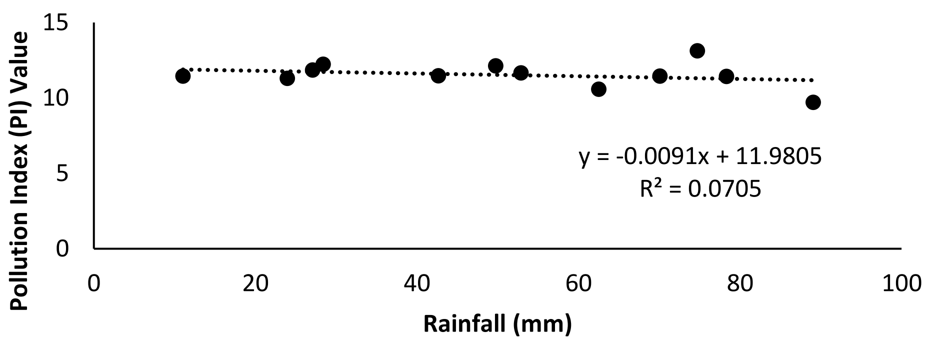

Figure 5. Correlation between rainfall and PI value of the Jakarta River. This figure shows the relationship between rainfall (mm) and pollution index (PI) values based on river water quality monitoring data in DKI Jakarta. These results indicate that rainfall has a limited influence on river water quality, suggesting that other factors are likely more dominant in determining pollution levels.

3.1.c. Comparison of ENSO and River Water Quality Status

ENSO which consists of El Niño and La Niña, has the opposite effects on rainfall patterns [19]. During El Niño events, rainfall decreases from normal levels. El Niño is associated with warmer sea surface temperatures in the central and eastern tropical Pacific Ocean, leading to changes in atmospheric circulation patterns that can result in drought conditions in some regions. In contrast, La Niña events typically increase rainfall compared to normal levels. La Nina is characterized by cooler sea surface temperatures in the central and eastern tropical Pacific Ocean, which can lead to enhanced rainfall in certain areas [20,21]. Recent studies have highlighted the significant influence of the El Niño Southern Oscillation (ENSO) on river water quality. For instance, research on South Africa's Crocodile River revealed that during El Niño phases, there was an increase in *Escherichia coli* (*E. coli*) concentrations, with levels reaching between 70 and 80 cfu/100 mL in 2016 and 2020, surpassing the effluent discharge quality limit of 0 cfu/100 mL. In contrast, during La Niña and neutral periods, *E. coli* levels were generally lower, though still above acceptable limits [22].

Fluctuations in water quality parameters due to ENSO events pose challenges to the sustainability of riverine environments, as they can disrupt aquatic ecosystems and biodiversity. The ONI is a key tool for monitoring and characterizing the ENSO phenomenon [23]. The ONI helps identify the presence and intensity of El Niño (warmer than average SST) and La Niña (cooler than average SST) events. Figure 6 shows El Niño and La Niña events based on ONI values, in which a negative value indicates a La Niña event and a positive value indicates an El Niño event. During 2020–2021 and 2021–2022, the ONI values depict a La Niña event (low to moderate), while in early 2023, El Niño occurred and prolonged in 2024.

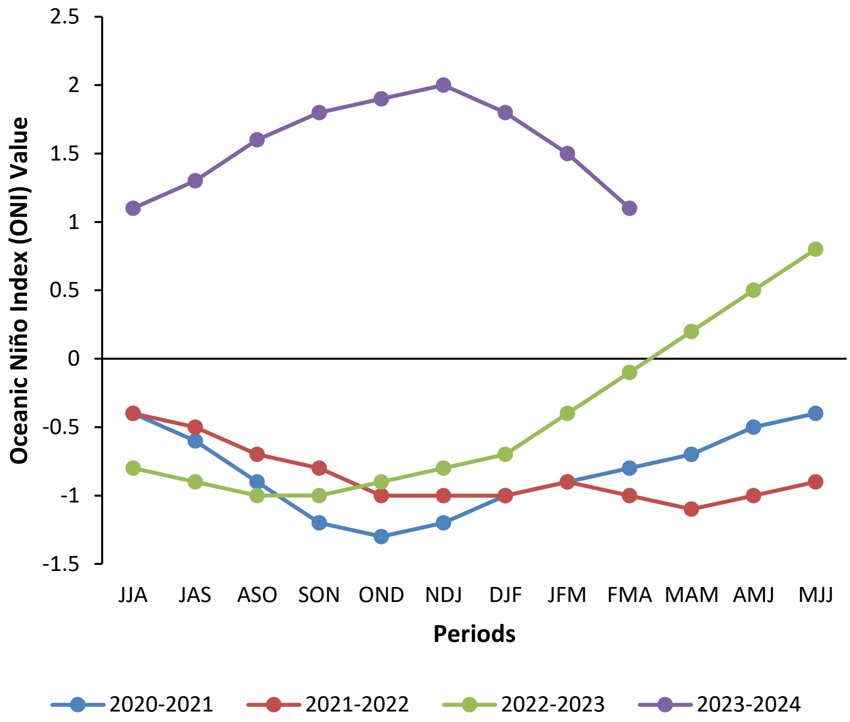

Figure 6. Oceanic Nino Index (ONI) from 2021 to 2024. Source: https://origin.cpc.ncep.noaa.gov/products/analysis_ monitoring/ensostuff/ONI_v5.php. Note: JJA: June July August; JAS: July August September; ASO: August September October; SON: September October November; OND: October November December; NDJ: November December January; DJF: December January February; JFM: January February March; FMA: February March April; MAM: March April May; AMJ: April May June; MJJ: May June July.

The ONI value that occurred from 2020 to the rainy season in 2023 was dominated by negative values, thus experiencing more conditions leading to the La Nina phenomenon with the lowest condition occurring in the Rainy Season in 2021, reaching -1.0666 ± 0.0802 (Figure 7). However, since the first transitional season in 2023, the ONI value has shown a significant increase, even for the next three seasons, with the highest value at 1.85 ± 0.0499 in the second transitional season in 2023. This indicates the beginning of the El Niño phenomenon, which lasts until the following year.

When reviewed based on the observed PI value, the value tended to fluctuate with respect to the ONI value. The correlation between the two values is positive, which means that an increase of one unit in the ONI value will increase the PI value by 0.0429 (Figure 8). Based on the R^2 value obtained, it can be known that the influence of the ONI value on the PI value is only 0.24%, whereas the remainder is influenced by other factors. Despite having a small influence, the influence of the ONI value is in line with previous research, which shows an influence, namely that an increase in the ONI value can increase the PI value in river water environments through river water discharge [6].

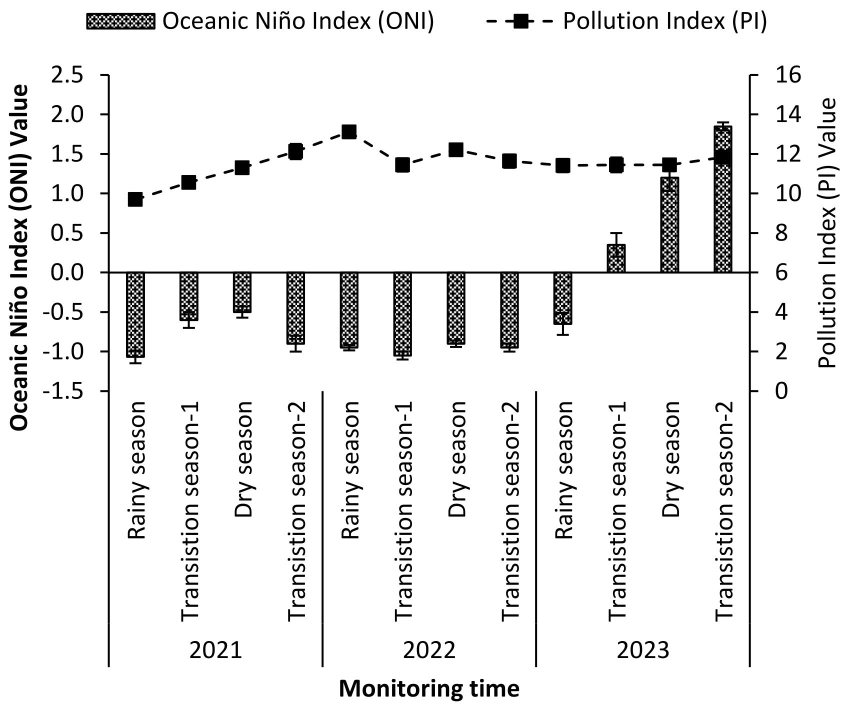

Figure 7. ONI and PI values of the Jakarta River are based on the occurring seasons from 2021 to 2023. This figure shows the variation of Oceanic Niño Index (ONI) and pollution index (PI) values in various seasonal periods, namely the rainy season, dry season, and transitional season, during 2021 to 2023.

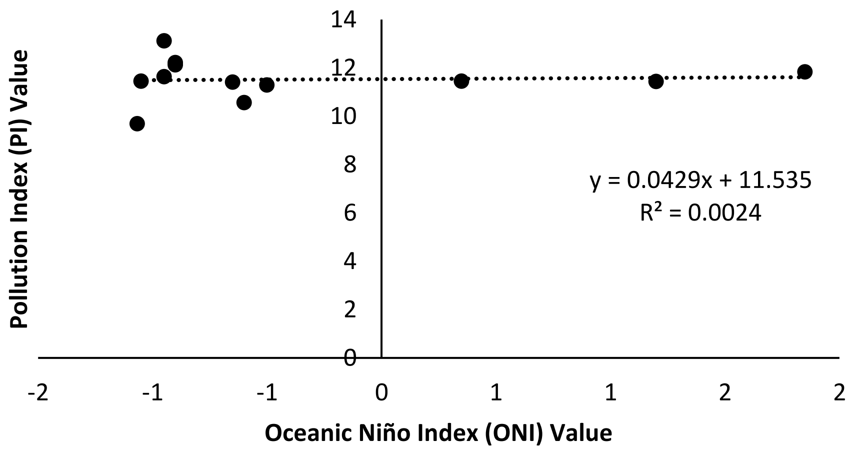

Figure 8. Correlation between the ONI value and the PI value of the Jakarta River. This figure shows the relationship between the Oceanic Niño Index (ONI) as an indicator of global climate variability and the pollution index (PI) based on river water quality monitoring data in DKI Jakarta.

3.1.d. Correlation of Rainfall and ENSO on River Water Quality Status

The results of the correlation test show that there is a negative correlation of 0.2654 between rainfall and PI values, a positive correlation of 0.0490 between the ONI value and PI value, and a negative correlation of 0.6481 between rainfall and the ONI value (Table 4). Based on these results, it can be known that an increase in rainfall decreases the PI value, whereas an increase in the ONI value increases the PI value. The results of the linear regression test show that the influence between the three variables through the equation model Y = 12,1546 – 0.0137 X_1 – 0.1857 X_2, the R^2 value was 9.65% (

). This shows that the influence given by rainfall and ONI value tends to be smaller than that of other factors. If reviewed based on the F value of 0.4811, it is a value that is smaller than the inverse F value. The results of the classical assumption test for normality using the Liliefors test indicate that the test statistic value (Lo) is 0.841, which is greater than the critical value from the table (Ltable) of 0.242. This condition (Lo > Ltable) implies that the data are not normally distributed. Furthermore, the results of the heteroskedasticity test using the Glejser test show that the p-value is 0.9130, which is greater than the significance level (α = 0.05) (Table 6). Therefore, it can be concluded that there is no indication of heteroskedasticity in the tested model. This proves that at a 95% confidence interval, the influence between rainfall and ONI value on PI value shows a condition that is not significant. The PI value in the river water environment tends to be more influenced by anthropogenic factors that occur around the watershed area, such as waste generation, domestic waste, and industrial waste [1,5,24].

Table 4. Results of Correlation Analysis Between Rainfall, ONI Value, and PI Value in River Water Quality. This table presents a correlation matrix between rainfall, ONI values, and pollution index (PI) based on river water quality monitoring data in DKI Jakarta.

	Rainfall	ONI value	PI value
Rainfall	1		
ONI value	-0.6481	1	
PI value	-0.2654	0.0490	1

Table 5. Results of Linear Regression Analysis for the Influence of Rainfall and ONI Value on PI Value in River Water Quality. This table presents the results of the linear regression analysis used to evaluate the effect of rainfall (X_1) and ONI value (X_2) on the pollution index (PI) value based on monitoring data in DKI Jakarta.

	df	SS	MS	F	F inverse
Regression	2	0.7573	0.3786	0.4811	2.8962
Residual	9	7.0835	0.7871		
Total	11	7.8408			

	Coefficients	Standard Error	t Stat	P-value
Intercept	12.1546	0.6959	17.4657	0.0000
X_1 (Rainfall)	-0.0137	0.0142	-0.9686	0.3580
X_2 (ONI value)	-0.1857	0.3641	-0.5101	0.6222

Table 6. Results of Heteroskedasticity Test using the Glejser Test as the classical assumption test of the Linear Regression Analysis for the Influence of Rainfall and ONI Value on PI Value in River Water Quality.

	df	SS	MS	F	F inverse
Regression	2	0.6916	0.3458	1.118	0.3684
Residual	9	2.7873	0.3093		
Total	11	3.4753			

	Coefficients	Standard Error	t Stat	P-value
Intercept	0.0104	0.4362	0.0240	0.9813
X_1 (Rainfall)	0.0107	0.0088	1.2083	0.2577
X_2 (ONI value)	0.0256	0.2282	0.1120	0.9130

3.2. Discussion

3.2.a. Influence of ENSO on Climate Variability in Southeast Asia

The SEA region, including Indonesia, is vulnerable to climate change. The ENSO phenomenon affects this region in terms of decreased rainfall and drought that impact agriculture, social aspects, and water resources. Projection results show that some SEA regions, such as the Philippines and the Malaysian Peninsula, experience drier conditions during the El Niño summer and wetter conditions during La Niña. In spring, ENSO amplification results in increased flooding in various SEA regions due to high rainfall during La Niña [25]. Indonesia is one of the maritime countries that has a high potential for precipitation and can influence the climate conditions in the surrounding region. During the El Niño period, the sea surface temperature is warmer in the central and eastern tropics and colder in the western Pacific tropics. During the La Niña period, high rainfall occurs in island nations in the eastern tropics [26]. The complexity of ENSO in the maritime region results in an asymmetry in El Niño and La Niña events. El Niño tends to end after the peak phase, whereas La Niña tends to persist until the following year.

An increase in rainfall during the La Niña period can increase the volume and discharge of river water. This condition affects the quality of river water. Increased rainfall can dilute pollutant concentrations and improve the quality status of river water towards a better direction. On the other hand, high rainfall will increase runoff which impacts the increase in sediment, turbidity, and phosphorus [27]. This condition can be exacerbated by the use of high agricultural and built-up land around the river. In addition to the parameters mentioned above, bacteria and color also worsen water quality at high rainfall and increased runoff [28]. *Escherichia coli* is a bacterium often associated with increased rainfall and runoff. High concentrations of coliform bacteria in bodies of water can increase the risk of bacterial contamination in humans, which can decrease health [29]. Poor sanitation systems in urban areas can trigger an increase in coliform bacteria in bodies of water during the rainy season. If not handled properly, the increase in various pollutants during the rainy season can decrease the quality of river water.

3.2.b. Plankton Taxa Composition in Jakarta Rivers as Indicators of Water Quality

The taxa identified from the eDNA samples in some Jakarta Rivers indicated that the order *Thalassiosirales* from the class *Mediophyceae* (eukaryotic phytoplankton) and the order *Ploima* from the class *Monogononta* (zooplankton) were the most frequently detected plankton across all sampled sites [30]. *Thalassiosirales* thrive in nutrient-rich waters, particularly those with high concentrations of nitrogen and phosphorus. Their abundance may indicate eutrophic conditions, often caused by agricultural runoff or wastewater discharge. Some species of *Thalassiosirales* are tolerant of pollution and can thrive in degraded environments, whereas others are sensitive and decline in response to contamination. *Ploima* species are often found in nutrient-rich (eutrophic) waters, where they feed on phytoplankton and organic detritus. Both *Thalassiosirales* (a diatom order from *Mediophyceae*) and *Ploima* (a rotifer order from *Monogononta*) play essential roles in aquatic food webs and directly influence fish productivity.

3.2.c. Dominance of Invasive Fish Species and Their Ecological Implications

In addition to indicating high fisheries productivity, these two orders signal excessive nutrient enrichment and eutrophication in various water bodies across Jakarta. This is further supported by the dominance of invasive fish species, such as tilapia, three-spot gourami, striped snakehead, and pleco (*Hypostomus pardalis*), in Jakarta's freshwater ecosystems. Some invasive species can survive under poor water quality and low dissolved oxygen levels, allowing them to outcompete native species [31]. The high abundance of invasive species poses a significant threat to native aquatic species and disrupts ecosystem balance. Therefore, optimal efforts are needed to reduce pollutant inflow, ensuring that the composition of plankton and fish in river ecosystems remains stable. Implementing effective water management strategies, restoring natural habitats, and strengthening regulations on invasive species are crucial steps for mitigating these environmental challenges.

3.2.d. Land Use and Sanitation Systems as Determinants of River Pollution

The use of land in the watershed area is a major determinant of the flow of pollutants entering the river. Increasing conservation areas, especially in the upstream region, can reduce the risk of sedimentation rates and runoff into bodies of water. Vegetated areas can also store rainwater during the La Niña period. Efficient use of fertilizers in agricultural areas can also reduce the excessive runoff of nutrients, such as N and P, into bodies of water [32,33]. Controlling the flow of nutrients from agricultural areas can also prevent eutrophication of water bodies. In addition to land use, pollutant flows at the source can also be prevented through improvements in sanitation systems and the provision of Communal Wastewater Treatment Plants (CWWTP). This is important considering that *E. coli* bacteria are one of the pollution parameters that are quite high in the rivers of Jakarta. Research has shown that improving water quality can be achieved through the use of CWWTP [34]. However, in some areas, *E. coli* bacteria are found to be high in water that has been treated at CWWTP. This indicates the need for improvements in household septic systems so that *E. coli* bacteria are not easily released into the environment. Public awareness regarding defecation in appropriate places also needs to be improved, considering that adequate sanitation facilities in Jakarta only reached 92.79% in 2022 [35].

3.2.e. Role of Riparian Buffer Zones in Runoff and Pollutant Control

The high influence of runoff on pollutant increases in bodies of water makes buffer areas play a major role in regulating water quality. The provision of a buffer area in the form of pollutant-absorbing plants is predicted to reduce the flow of pollutants, runoff, and soil erosion into bodies of water [27]. A buffer strip in the form of grass is more effective than trees in absorbing pollutants. However, trees are believed to be more effective at reducing the impacts of climate change [36]. Therefore, combining these two types of vegetation is expected to improve the quality of riparian ecosystems. Grass species with dense tillers and deep roots absorb pollutants very effectively.

Riparian buffer zones serve as ecological barriers that filter pollutants before they reach water bodies. Vegetation, such as grasses and trees, contributes differently to pollution control: grasses with dense tillers and deep roots effectively absorb nutrients and suspended pollutants, whereas trees provide broader benefits by mitigating the effects of climate change through carbon sequestration. Combining both vegetation types enhances riparian ecosystem health and improves water quality. Establishing and maintaining effective vegetated buffer strips along riverbanks is therefore a key strategy for reducing runoff, erosion, and pollutant inflow from agricultural and urban areas.

3.2.f. Integrated Management Strategies to Address Climate Variability and Water Pollution

Regardless of the correlation between rainfall and river water quality, the management of pollutants entering bodies of water must be undertaken in every region. Various efforts to reduce incoming pollutants, such as buffer strips and CWWTPs, can be utilized locally. However, pollutant flows originating from sources such as agricultural land, industry, and household waste need to be prevented. This must involve strong political will and appropriate policies from both the central and regional governments. With the control of pollutant flows, each region will be ready to face the uncertainty of climate conditions [37]. Especially in regions that are included in tropical island countries that have high weather variability.

Given the complex interactions between climate variability and water pollution, an integrated management approach is essential. This includes controlling pollutant sources, improving environmental infrastructure, restoring riparian habitats, and promoting collaboration between central and local governments. Strategic measures, such as strengthening wastewater policies, enhancing public awareness, and implementing sustainable water treatment technologies, are vital to maintaining water quality. Through comprehensive pollutant control and adaptive management, Indonesia can build resilience against the uncertainty of tropical climate conditions and ensure the sustainability of its freshwater resources.

4. Conclusions

An increase in rainfall decreases the PI value, whereas an increase in the ONI value increases the PI value. When El Niño conditions occur, the PI value tends to increase, whereas under La Niña conditions, it decreases. The influence of rainfall and the ENSO phenomenon on the quality status has no significant effect. Another factor that causes an increase in PI value is the anthropogenic factor found around the watershed area. Thus, comprehensive efforts are essential to minimize pollutant inflow and maintain the stability of plankton and fish populations in river ecosystems. Key measures include implementing effective water management strategies, restoring natural habitats, and enforcing stricter regulations on invasive species to address these environmental challenges.

Author Contributions

JZA: Conceptualization, methodology, software, investigation, writing, review, and editing**.** **LFA:** Software, Investigation, Writing - Review & Editing**. PAP:** Investigation, Writing - Review & Editing**. YSF:** Software, Writing - Review & Editing**. GPR:** Investigation, Writing - Review & Editing, Supervision**. FSF:** Software, Writing - Review & Editing**. LAS:** Writing - Review & Editing. **RAH:** Supervision**.**

Conflicts of interest

There are no conflicts to declare.

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