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Investigation of Deoxygenation Rate Determination in Cikakembang River, West Java, Indonesia

Finna Fitriana, Doddi Yudianto*, Andrea Polisar, S Sanjaya
Department of Civil Engineering, Parahyangan Catholic University, Bandung, INDONESIA
Jalan Ciumbuleuit No 94 Bandung
*Corresponding author: doddi_yd@unpar.ac.id

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ABSTRACT Cikakembang River, a tributary of Citarum River, is situated in the densely populated Majalaya District, renowned for textile production. Direct discharges of domestic and industrial pollutants into the river contribute to substantial pollution, making it crucial to manage pollution levels. This implies that controlling pollution is crucial, as it significantly impacts the condition of Citarum River, already infamous as one of the world most polluted rivers. A key indicator for assessing river water quality is Biological Oxygen Demand (BOD), representing the oxygen required for microorganism-mediated decomposition. This parameter is influenced by deoxygenation rate, denoted as k_d. Therefore, this study aimed to analyze the most suitable k_d value for Cikakembang River using various empirical methods, including Simple, Fujimoto, Sawyer, Thomas, Fair, and Hydroscience. The result showed that Thomas method provided the most accurate prediction for BOD concentration of the river. In rainy season, Root mean square error (RMSE), mean absolute percentage error (MAPE), and coefficient of determination (R^2) values were 0.542, 0.035, and 0.981, respectively, and in dry season, the values were 0.117, 0.009, and 0.999. Additionally, k_d value effectively simulated the river water quality using HEC-RAS, yielding satisfactory results. RMSE, MAPE, and R^2 values for BOD concentration were 3.551, 0.162, and 0.331 in rainy season and 1.071, 0.100, and 0.812 in dry season. Finally, the modeling result showed that Cikakembang River did not meet the Class 2 Water Quality Standard during both rainy and dry seasons. This finding is critical, as it underscores the severity of the pollution problem in the river and the urgent need for comprehensive and effective management strategies to improve its water quality.

KEYWORDS Cikakembang River; Deoxygenation Rate; Water Quality Modeling; Pollution; Biological Oxygen Demand

1 INTRODUCTION

The fast increase in Indonesian population is causing significant industrial development, specifically in Java Island, where 56.10% of the country total population lives (Statistics Indonesia, 2021). West Java, the most populous province on the island, has the highest concentration of industries (Ministry of Industry Indonesia, 2014). Consequently, the province has gained the distinction of being recognized as the country largest source of hazardous and toxic waste (National Geographic Indonesia, 2011). Citarum River, which is the longest river in this location, has been declared one of the world most polluted rivers, affecting more than 5 million people due to the discharge of chemical contaminants into its flow (Blacksmith Institute, 2013). Ministry of Environment and Forestry data reveals that 54% of Citarum River water is heavily polluted, 23% is moderately polluted, 20% is slightly polluted, and only 3% meets water quality standards (Ministry of Environment and Forestry, 2018). Majalaya textile industry location, situated upstream of Citarum River, remains the largest and densely populated textile-producing hub, contributing up to 40% of the country textile production (Kompas, 2011). This situation has led the location to become a significant contributor of both domestic and industrial waster (Fitriana et al., 2023).

Cikakembang River is a tributary of Citarum River that receives direct pollutants from domestic and industrial sources in Majalaya District. A prior study showed that Cikakembang River failed to meet class II water quality standards in both rainy and dry seasons (Polisar, 2023). Therefore, there is a need to control pollution in the river since it significantly impacts the condition of Citarum River. The key indicators in assessing river water qual-

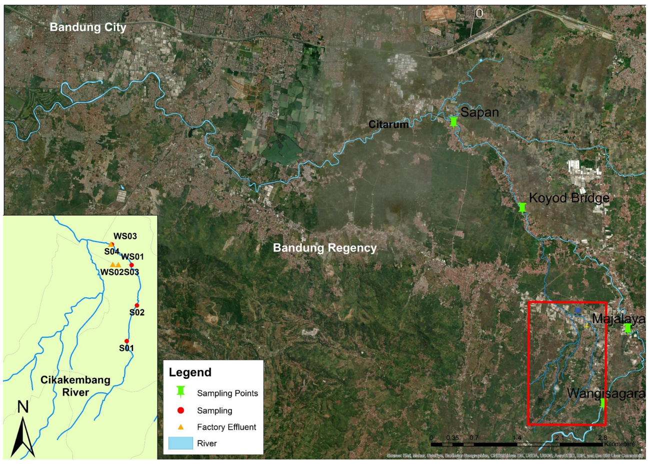


Figure 1 Study location (ESRI et al., 2023)

Table 1. Sampling point locations

Sampling points	Latitude coordinates	Longitude coordinates
S01	107.745523	-7.061088
S02	107.747027	-7.055850
S03	107.746237	-7.049933
S04	107.743346	-7.046913
WS01	107.744287	-7.049856
WS02	107.743483	-7.049824
WS03	107.743199	-7.046848

ity include Dissolved Oxygen (DO) and Biological Oxygen Demand (BOD) (Atima, 2015). BOD reflects the oxygen required for aerobic decomposition, oxidation, and the breakdown of organic pollutants by microorganisms (Nas et al., 2008). Water quality modeling considers the increase in BOD influenced by deoxygenation rate (k_d), representing the decrease in DO due to microbial decomposition in water (Yustiani et al., 2021). The Ultimate BOD parameter (L_0) describes the total oxygen used by microorganisms in the reaction (Dhage et al., 2012). This implies that both k_d and L_0 values are crucial in assessing water quality and organic matter-induced pollution (Astuti and Pratiwi, 2016). Therefore, an analysis is necessary to determine accurate k_d and L_0 values for simulating the conditions of Cikakembang River.

This study estimates k_d and L_0 values using various empirical equations to achieve accuracy, in line with prior studies on Citarum River that consistently applied Hydroscience equation (Yustiani et al., 2021, 2019; Chapra, 2008). Subsequently, Hydrologic Engineering Center River Analysis System (HEC-RAS) software is used for water quality evaluation in Cikakembang River. HEC-RAS is chosen for its versatility in water quality modeling, easy integration of hydraulic and water quality parameters, thereby ensuring precise pollutant transport representation (Brunner, 2016). Additionally, HEC-RAS accommodates multiple water quality parameters, providing a comprehensive assessment.

Table 2. Climatological conditions during samplings

Parameters	Units	23 February 2022 (10:00 AM GMT+07)	24 August 2022 (10:00 AM GMT+07)
Air temperature	(°C)	25	24
Wind velocity	(m s^{-1})	3	1
Air pressure	(mmHg)	760	760
Humidity	(%)	50	60
Cloud cover	(%)	30	20

Table 3. Water quality measurement methods

Parameter	Units	Measurement methods
pH	-	pH sensor (Sealed, gel-filled, polycarbonate body, Ag or AgCl)
DO	mg l^{-1}	Dissolved oxygen probe (Clark-type polarographic electrode)
BOD	mg l^{-1}	Manometric, mercury-free, and electronic pressure sensor
Flow velocity	m s^{-1}	Flowmeter

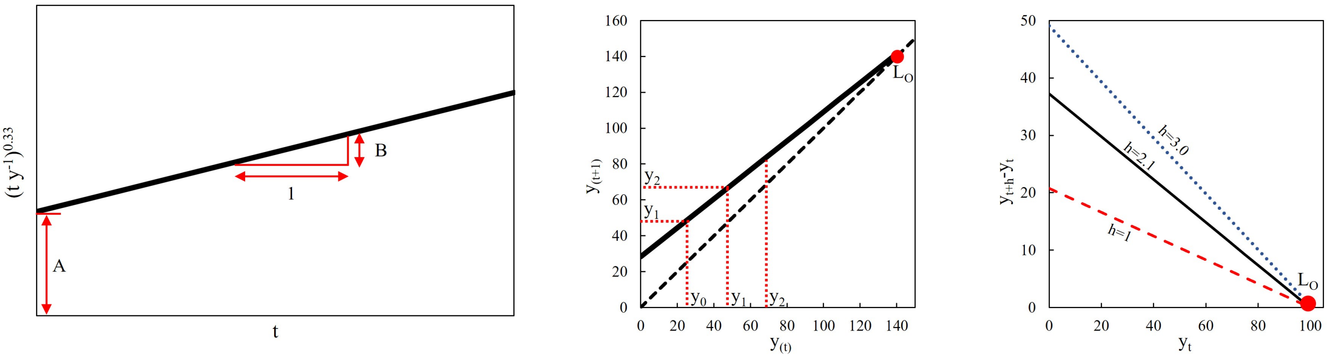
2 STUDY METHODOLOGY

2.1 Study Location

This study was carried out in Cikakembang River, which is a tributary of Citarum River, with a length of 2,360 m, as shown in Figure 1. The observed river section was predominantly surrounded by textile industry and residential locations. Upstream, the river condition was rocky, while downstream, the riverbanks were lined with brickwork, and the channel bottom was composed of slightly rocky soil. In addition, there were four water quality monitoring points, S01-04, and three industrial waste disposal points, WS01-03, with the locations detailed in Table 1.

2.2 Sampling and Laboratory Analysis

To ensure representative monitoring results, samples were collected using the grab sampling method during both rainy and dry seasons. The climatic conditions during the field sampling were presented in Table 2, followed by laboratory analysis to measure various water quality parameters using the methods outlined in Table 3. BOD concentration measurements were conducted for 5 days in the laboratory, while DO, flow velocities,



(a) Simple Method

(b) Fujimoto Method

(c) Sawyer Method

Figure 2 Calculation of k_d and L_0

and pH values were obtained through direct field measurement.

2.3 Deoxygenation Rate Calculation

Based on the laboratory BOD measurement results, k_d and L_0 values were calculated using several empirical methods. These parameters were then used to estimate BOD concentration, which was compared with the laboratory measurement results. The most suitable k_d value was used as input data in water quality model. Several of the empirical methods applied included the following:

1. Simple Method (Thomas Jr., 1950)

This method estimated k_d and L_0 values by plotting BOD measurements (y) for several days (t). Calculation was performed by drawing a straight line that best fits the $(ty^{-1})^{0.33}$ versus t plotting, as shown in Figure 2a. From the straight line, the intercept point (A) on the y-axis and the line slope (B:1) were obtained. The values of k_d and L_0 were then calculated using Equations 1 and 2.

$$\mathrm{k_d} = \frac{(2.61B)}{A} \tag{1}$$

$$\mathrm{L_0} = \frac{1}{2.3k_\mathrm{d}A^3} \tag{2}$$

2. Fujimoto (Fujimoto, 1964)

In this approach, k_d and L_0 values were calculated by plotting the results of BOD measurements for several days (yt) against the value (yt+1), as shown in Figure 2b. k_d value was estimated using Equation 3, calculating the slope of the line. L_0 value was calculated using Equation 4, showing the intersection between the plotting results and the x=y linear line.

$$10^{\mathrm{-kd}} = \text{slope of the line} \tag{3}$$

$$\mathrm{L_0} = \frac{1}{2.3k_\mathrm{d}A^3} \tag{4}$$

3. Sawyer (Bagchi and Chaudhuri, 1970)

k_d and L_0 values were estimated by plotting BOD measurement results for several days (yt) against the (yt+h-yt) value, as presented in Figure 2c. In this context, h represented the time interval determined based on the availability of measurement data. The value of L_0 was the intersection of the three lines with the x-axis, while k_d was obtained by calculating the weighted mean using Equation 5.

$$k_\mathrm{d} = log10\frac{L_0}{L_0 - y_1} \tag{5}$$

4. Thomas “Slope” (Bagchi and Chaudhuri, 1970)

In this approach, the estimation of k_d and L_0 values was conducted using BOD (y) measurements for several days (t). Calculations were performed using Equations 6, 7, 8 and 9 with n representing the amount of data.

$$\mathrm{na} + \mathrm{b}\sum \mathrm{y} - \sum \mathrm{y'} = 0 \tag{6}$$

$$\mathrm{a}\sum \mathrm{y} + b\sum \mathrm{y}^2 - \sum \mathrm{yy'} = 0 \tag{7}$$

$$\text{-b} = k_\mathrm{d} \tag{8}$$

$$\mathrm{L_0} = \frac{a}{k_\mathrm{d}} \tag{9}$$

Table 4. Performance evaluation of water quality modeling

Empirical methods	RMSE		MAPE		R^2	
	Rainy season	Dry season	Rainy season	Dry season	Rainy season	Dry season
Simple Method	1.755	0.276	0.090	0.026	0.894	0.999
Fujimoto	1.307	0.017	0.065	0.001	0.895	1.000
Sawyer	9.813	5.145	0.489	0.442	0.003	0.372
Thomas	0.542	0.117	0.035	0.009	0.981	0.999
Fair	1.810	0.017	0.071	0.001	0.983	1.000

Table 5. Performance evaluation of water quality modeling

Sampling points	Rainy season			Dry season		
	RMSE	MAPE	R^2	RMSE	MAPE	R^2
BOD	3.551	0.162	0.331	1.071	0.100	0.812
DO	0.138	0.024	0.999	0.220	0.081	0.841

5. Fair (Fair, 1936)

Similar to the previous method, the determination of k_d and L_0 values used BOD measurements for several days (yt). Calculations incorporated Equations 10 and 11, with n denoting the amount of data, and d representing the difference between y_{t+1} and y_t.

$$k_d = \frac{6}{(n^{2-1})}[(n+1)\sum \log d - 2\sum t \log d] \quad (10)$$

$$L_0 = \frac{\sum(1 - 10^{k_d t})y_t}{n - 2 \times 10^{k_d}\frac{1-10^{nk_d}}{1-10^{k_d}} + 10^{-2k_d}\frac{1-10^{-2nk_d}}{1-10^{-2k_d}}} \quad (11)$$

6. Hydroscience (Chapra, 2008)

When compared with the preceding five graphical methods, this method showed that deoxygenation rate was contingent on the flow depth (h). As the river flow deepened, fewer microorganisms could inhabit the river due to lower oxygen content (Wahyuningsih et al., 2021). Based on these assumptions, k_d was calculated using Equations 12 and 13.

$$k_d = 0.3(\frac{h}{2.4})^{-0.434} \text{ if } 0 \leq h \leq 2.4 \text{ m} \quad (12)$$

$$k_d = 0.3 \text{ if } h < 2.4 \text{ m} \quad (13)$$

2.4 Performance Indicators

Root mean square error (RMSE), mean absolute percentage error (MAPE), and coefficient of determination (R^2) evaluated the accuracy of calculations (Band et al., 2021). Predicted values with smaller RMSE and MAPE typically showed more accurate predictions, while higher R^2 values signified better-correlated results (Hossain,et.al, 2022). The following Equations 14, 15, and 16 were the expressions for each of the metrics:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=q}^{n}(\text{actual}_i \text{ - predicted}_i)^2} \quad (14)$$

$$\text{MAPE} = \frac{1}{n}\sum_{i=q}^{n}\left|\frac{(\text{actual}_i \text{ - predicted}_i)}{(\text{actual}_i)}\right| \quad (15)$$

$$R^2 = 1 - (\frac{\sum_{i=1}^{n}(\text{actual}_i \text{ - precdicted}_i)^2}{\sum_{i=1}^{n}(\text{actual}_i \text{ - precdicted}_i)^2}) \quad (16)$$

2.5 Water Quality Modeling

Water quality modeling used HEC-RAS software, as shown in Figure 3. In addition to the previously identified sewerage channels (WS01-03), various residential and industrial zones around Cikakembang River were modeled to assess the impact on river water quality. These locations were selected based on an accurate representation of modeled river conditions resulting from wastewater discharge at the upstream section of each monitoring point, originating from both domestic and industrial wastewater sources.

3 RESULTS AND DISCUSSION

3.1 Measurement Results

The results for both seasons generally showed a similar trend, with higher concentrations of BOD

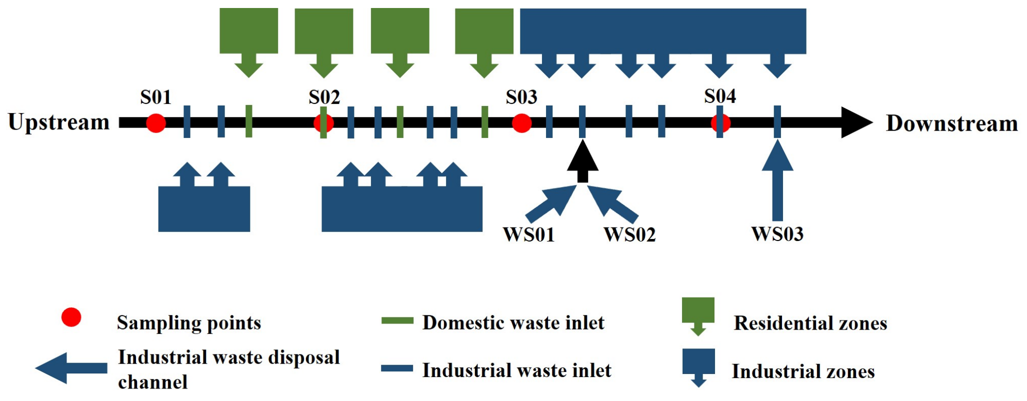
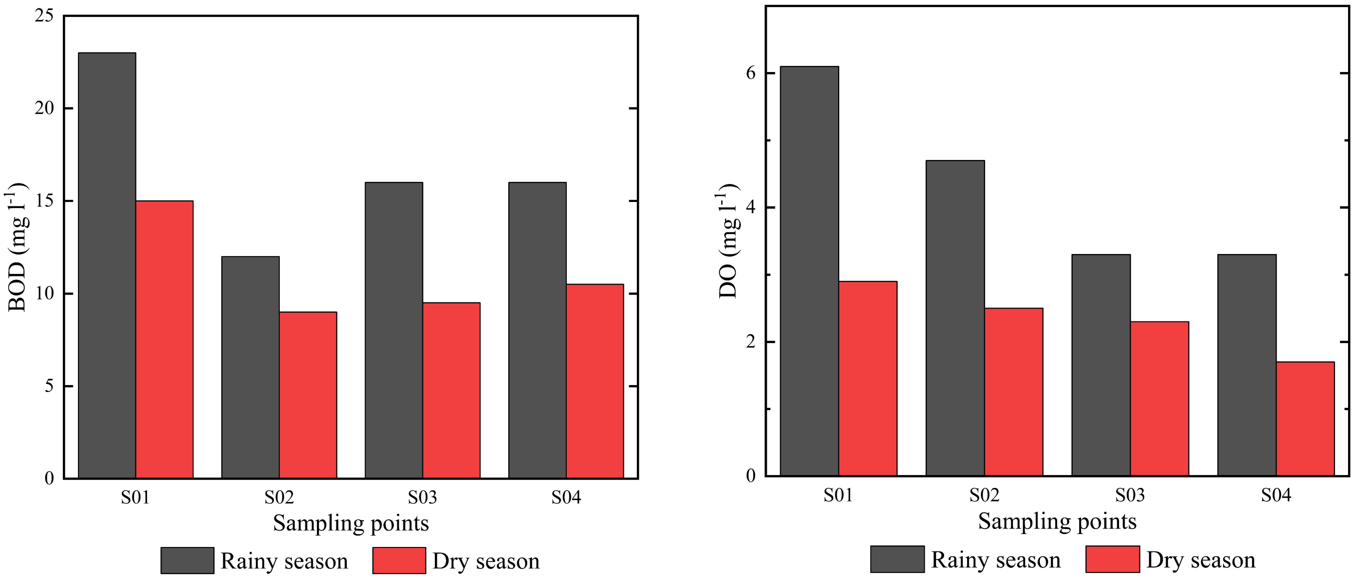
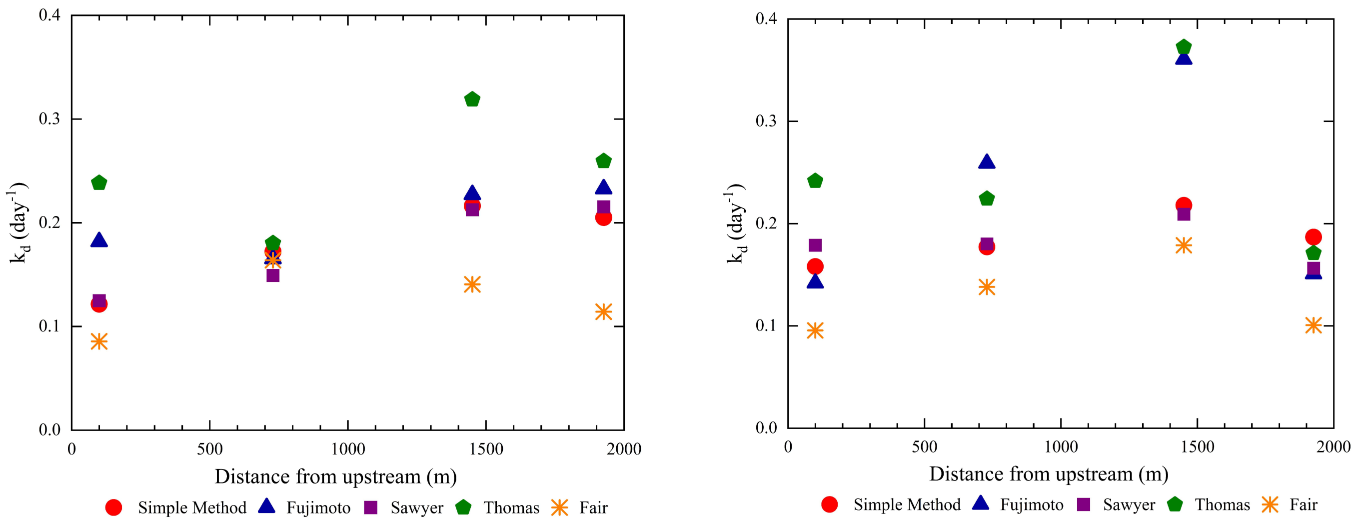


Figure 3 River Schematization



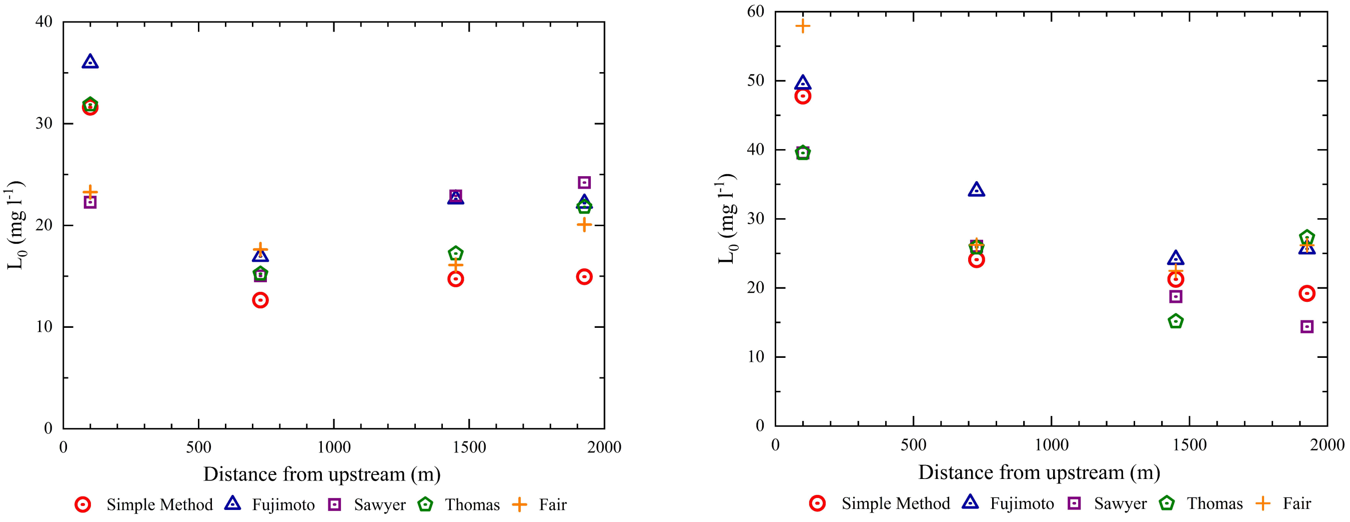
(a) (b)

Figure 4 Measurement results of (a) BOD and (b) DO concentrations during rainy and dry seasons



(a) (b)

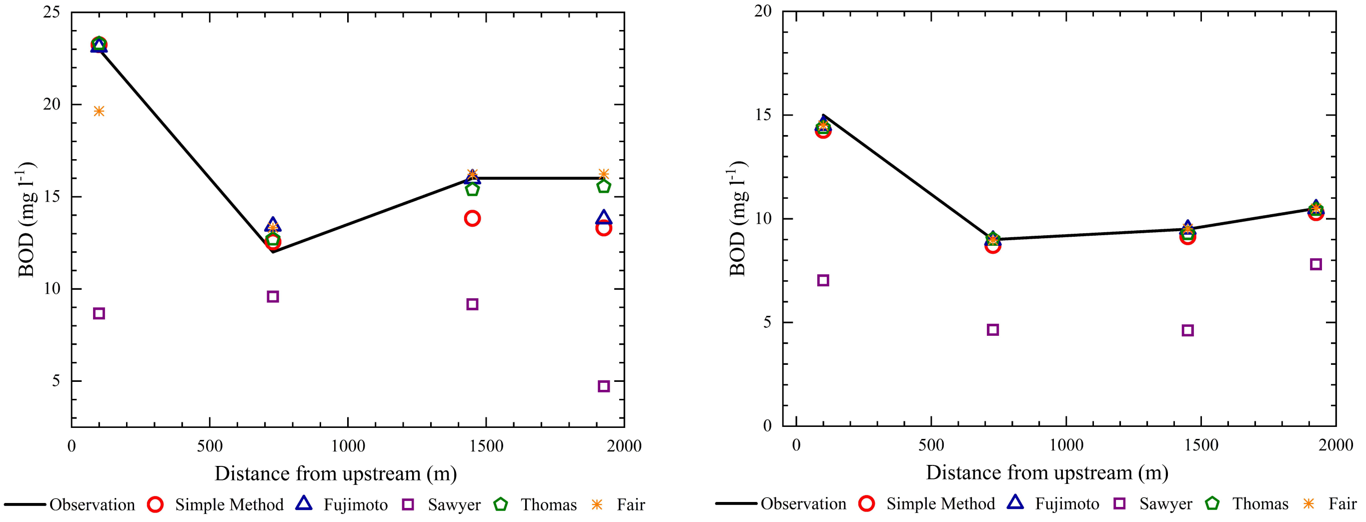
Figure 5 The variation of k_d values during (a) rainy and (b) dry seasons from various empirical methods



(a)

(b)

Figure 6 Calculations of L_0 during (a) rainy and (b) dry seasons from various k_d values



(a)

(b)

Figure 7 Comparison of the estimated BOD concentration with the observation data during (a) rainy and (b) dry seasons

and DO during rainy season compared to dry season. A fluctuation in BOD values from upstream to downstream was observed, with the highest concentration found at S01, followed by a decrease at S02, and subsequent increases at S03 and S04. Meanwhile, the measurements of DO showed a gradual decrease from upstream to downstream, with the lowest concentration observed at S04. In more detail, Cikakembang River water quality test results were shown in Figure 4.

3.2 Deoxygenation Rate Calculations

k_d value was estimated for both rainy and dry seasons using 5-day BOD measurement data. Calculations were performed for each water quality monitoring point, as detailed in the previous section, and plotted against the distance upstream, according to Figure 5. Subsequently, the computation of L_0 value for each k_d value was shown in Figure 6. The shown graphs represented variations in L_0 value for both seasons, calculated using various empirical equations.

The estimation of BOD concentration was carried out using the previously obtained k_d value. The comparison between the calculated BOD results and the measured concentration was shown in Figure 7. Generally, values obtained from Simple, Fujimoto, Thomas, and Fair methods showed satisfactory results and were relatively close to the measurement results. However, Sawyer method

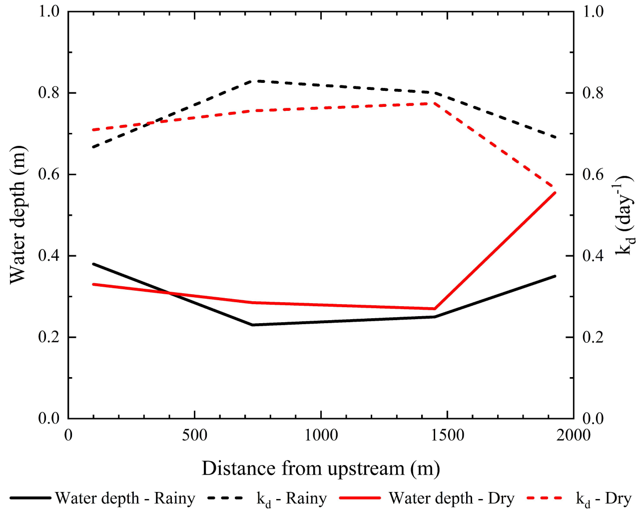
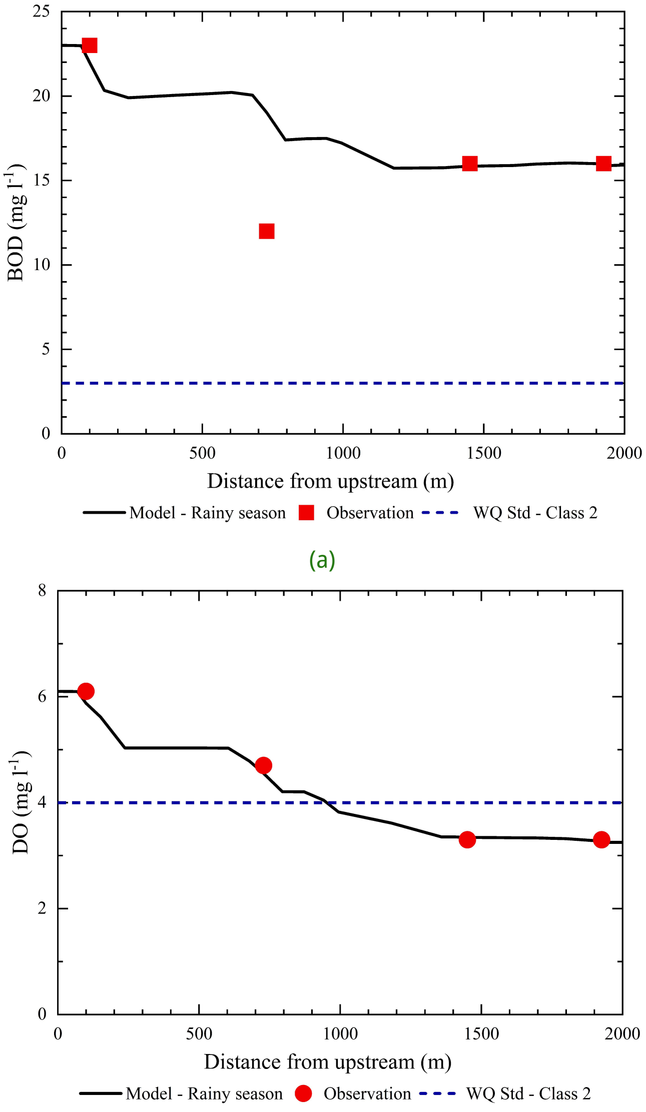


Figure 8 Estimation of k_d values using Hydroscience Method



(a)

(b)

Figure 9 Water quality modeling in rainy season

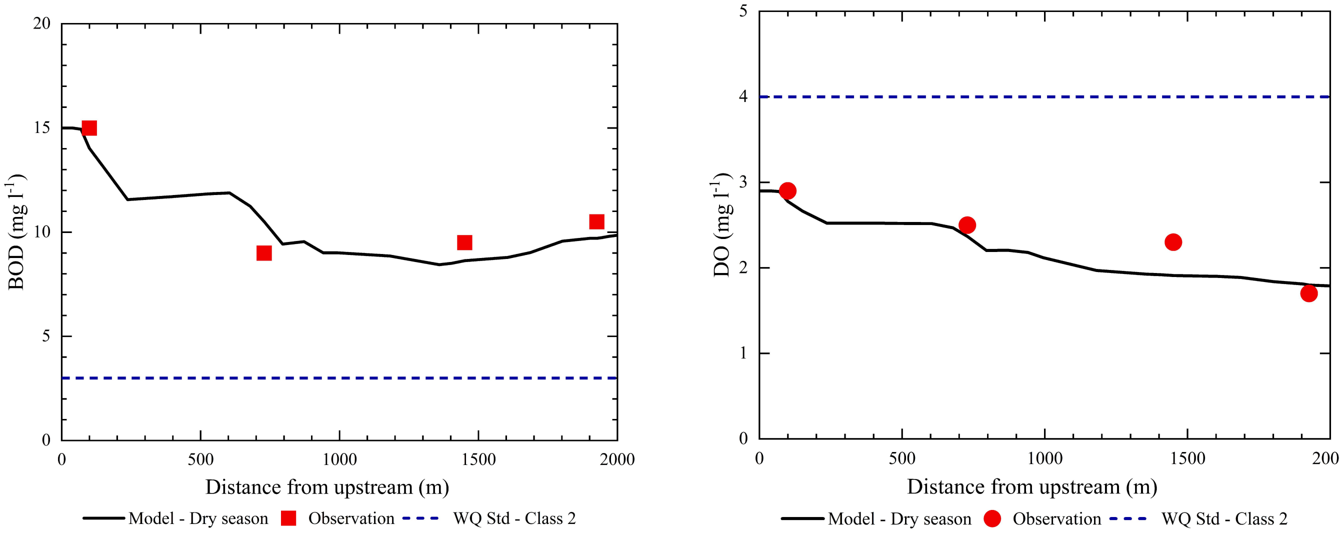
did not provide fitting results for both seasons. Considering the lowest RMSE and MAPE values of the two seasons, Thomas method, with a considerably high R^2 value, was selected as the most suitable value for Cikakembang River, with k_d value of 0.25. More details regarding the performance evaluation for k_d value of each method can be seen in Table 4.

Aside from the graphical method using BOD measurement data, k_d value was also estimated by considering water depth in the river section under review. Water depth was measured simultaneously with sampling during each rainy and dry season for each water quality monitoring point. The results of k_d value calculation could be seen in Figure 8, but the value obtained was higher when compared to the results of calculations using other empirical methods. As a result, the method was considered unsuitable for Cikakembang River, implying that the value obtained from Thomas method was preferable.

3.3 Water Quality Modelling

After obtaining k_d value, quality modeling was conducted to evaluate water quality of Cikakembang River. BOD and DO concentrations were simulated during rainy and dry seasons. River discharge was obtained through calculations using flow velocity data, yielding values of 0.86 m^3 s^{-1} during rainy season and 0.252 m^3 s^{-1} during dry season. In this model, the value of the reaeration coefficient (k_a) used the equation from Jha et al. (2004), while the dispersion coefficient (Ex) used the equation from Iwasa and Aya (1991); Jain and Jha (2005); Peruzzi et al. (2021). Based on previous studies, combining these two coefficients provided adequate analysis results and was suitable for Cikakembang River (Polisar, 2023). This implied that the modeling results shown in Figures 9 and 10, were satisfactory.

Water quality of Cikakembang River was assessed against the Class 2 Water Quality Standard (Government Regulation No.22 of 2021 concerning the implementation of Environmental Protection and Management, 2021). It was evident that, during rainy season, the concentration of BOD exceeded the permissible limit. Specifically, BOD value at S02 obtained from the simulation showed significantly higher values than those determined



(a)

(b)

Figure 10 Water quality modeling in dry season

through field measurements. This difference could result from a potential setback during the sample collection at S02 or during laboratory testing. To enhance confidence in the obtained results, it was crucial to conduct water quality measurements and modeling for a more extended period. Meanwhile, DO concentration in the upper river met the required minimum level, but further downstream, the concentration continued to decrease below the standard. During dry season, BOD and DO concentrations did not meet the quality standards permitted by the government. Additionally, the performance evaluation of the two models was shown in Table 5.

4 CONCLUSION

In conclusion, the graphical method for estimating deoxygenation rate produced more suitable results than the flow depth method. In general, using Thomas method for deoxygenation rate calculation produced the best results, with RMSE, MAPE, and R^2 values of 0.542, 0.035, and 0.981 in rainy season and 0.117, 0.009, and 0.999 in dry season, respectively.

Water quality modeling, incorporating the obtained k_d value, yielded accurate results compared to field measurements in both rainy and dry seasons. For BOD concentration, RMSE, MAPE, and R^2 values were 3.551, 0.162, and 0.331 in rainy season and 1.071, 0.100, and 0.812 in dry season. Meanwhile, for DO, the respective values were 0.138, 0.204, and 0.999 in rainy season and 0.220, 0.081, and 0.841 in dry season.

Based on the modeling results, Cikakembang River did not meet the Class 2 Water Quality Standard. Although DO concentration during rainy season met the required minimum level in the upper reaches, it decreased below the standard downstream. Regarding BOD, the concentration exceeded the permissible limit and during dry season, both DO and BOD concentrations failed to satisfy the quality standard. The results showed the importance of implementing strategies to address increased BOD concentration and declining DO levels, crucial indicators of water quality.

The application of the obtained k_d value in water quality modeling proved effective in simulating BOD and DO variations in both rainy and dry seasons. The result served as a foundation for future river modeling, using suitable values for a more comprehensive understanding of water quality dynamics. Also, the insight obtained from the entire process was important for improving the accuracy of water quality models, particularly in locations with pronounced seasonal fluctuations. The result showed relevance for Cikakembang River and also provided valuable perspectives for broader water quality management, extending to diverse aquatic ecosystems.

DISCLAIMER

The authors declare no competing pecuniary interests or personal connections that could be perceived as having influenced the work described in this paper.

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