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Managing organic pollutant loads in the Lower Cileungsi River, Indonesia

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ABSTRACT

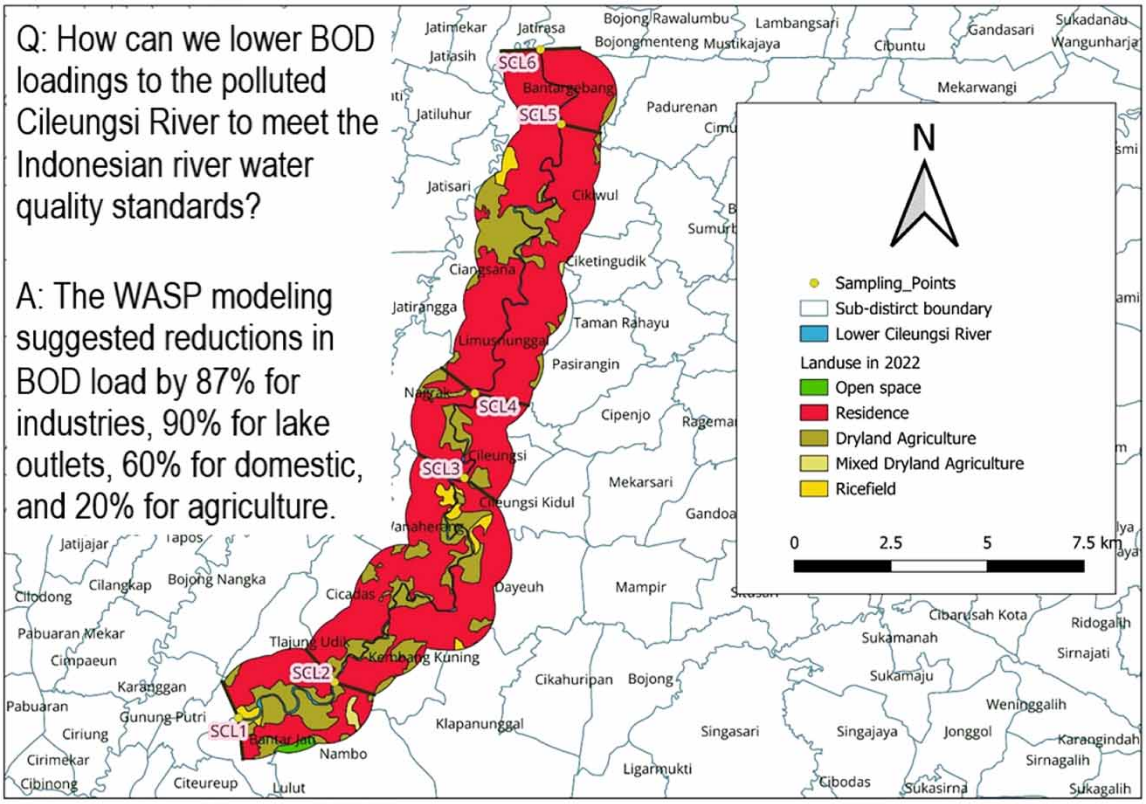
The regency of Bogor has become the regency with the highest population in Indonesia. The regency's 5.4 million population has been driving increased pollutant buildup in areas like those around the Lower Cileungsi watershed, impacting the quality of the river. This study aims to provide input on pollution control strategies in the Lower Cileungsi River based on the load capacity of pollutants from point and non-point sources. This study modeled total potential organic pollutant loads with existing and critical water flows. Organic pollutant load reductions were also simulated to meet the river water quality standard stipulated by Indonesian Government Regulation No. 22 of 2021 for the river. Monitoring data showed that biochemical oxygen demand (BOD) and dissolved oxygen (DO) concentrations in the river did not meet the standard, placing the river water quality status as slightly polluted with an average pollution index value of 2.57. The total potential BOD load from all sectors was 32,851.65 kg/day, exceeding the river's capacity by 21,785.6 kg/day. The modeling suggested reductions in BOD load by 87% for industries, 90% for lake outlets, 60% for domestic, and 20% for agriculture. No BOD reduction is required in the livestock sector.

Key words: Development, Lower Cileungsi River, Pollution load, Population, WASP modeling, Water quality model

HIGHLIGHTS

- The Lower Cileungsi River is a tropical monsoonal river that receives pollutants from a lake and activities in the watershed.
- Biochemical oxygen demand (BOD) and dissolved oxygen (DO) concentrations in the river do not meet the applicable water quality standard.
- This study uses combined approaches of limited monitoring data, total maximum daily load (TMDL), and water quality modeling to provide input in controlling BOD pollution in the river with considerations of low flow.

GRAPHICAL ABSTRACT



Q: How can we lower BOD loadings to the polluted Cileungsi River to meet the Indonesian river water quality standards?

A: The WASP modeling suggested reductions in BOD load by 87% for industries, 90% for lake outlets, 60% for domestic, and 20% for agriculture.

1. INTRODUCTION

Challenges in water resources management commonly coexist with rapid population growth, unplanned urbanization, and changes in land use (Shrestha *et al.*, 2018). Rapid population growth and economic development drive various infrastructure projects and diverse activities to meet growing needs. This exerts significant pressure on water quality due to the increasing potential for waste discharge from these activities. Activities, such as land clearing, farming, agriculture, domestic activities, and industry, can release various organic materials, sediments, nutrients, heavy metals, and pathogens through runoff or irrigation water into rivers, e.g., Sudradjat *et al.* (2024). Additionally, extreme weather events such as droughts and floods can affect the river's ability to dilute pollutants due to differences in river discharge and the quantity of entering pollutants (Anh *et al.*, 2023). Therefore, regular monitoring and control are essential to optimize the self-purification ability of rivers and mitigate potential pollution.

The Lower Cileungsi River is located between Bogor Regency and Bekasi City. Flowing from south to north, it eventually reaches Pantai Utara Jawa. The Lower Cileungsi watershed covers seven districts: Gunung Putri, Klapanunggal, Cileungsi, Bantargebang, Jati Asih, Mustikajaya, and Rawa Lumbu. Bogor Regency is recognized as the regency or city holding the first position for the highest population in West Java and Indonesia, totaling 5,427,068 people, with an annual population growth rate of 1.37% (OpendataJabar, 2020). This population and its growth have spurred various developments, including housing and industrial projects.

In a study by Collen (2021), a comparison of land use maps in the Lower Cileungsi watershed for 2015 and 2019 revealed a decrease in green spaces, including forests (−7.79%), rice fields (−24.02%), open land (−9.79%), and water bodies (−9.56%), shifting to mixed gardens (+20.77%) and built-up areas (+17.39%). Built-up areas encompass the construction of roads, settlements, industries, and other public facilities. The study also highlights the relationship between land use changes and their impact on river water quality. Determining the water quality status using the storage and retrieval (STORET) method based on historical water quality data (2015–2019) showed that the land use transition resulted in a moderately polluted Upper Cileungsi River, while the middle and lower parts were heavily polluted. The water quality status of the Cileungsi River was also assessed using the West Java water quality index, indicating that the river is among the most polluted, along with the Citarum and Cimalaya Rivers in West Java (Sutadian *et al.*, 2018). Based on previous research, the water quality parameter in the Cileungsi River that often exceeds quality standards is the biochemical oxygen demand (BOD) concentration, especially during the dry season (Effendi *et al.*, 2021). Uncontrolled values of BOD, total dissolved solids, total suspended solids, total nitrogen, and total phosphorous in river water can lead to various environmental issues, including eutrophication, algal blooms, aquatic life mortality, and a decline in biodiversity, ultimately affecting human life in the surrounding areas (Wang *et al.*, 2014).

River classification and wastewater discharge permits have generally been established for managing river environments. However, water pollution and declining water quality still frequently occur, often due to the ineffective enforcement of established discharge standards. Therefore, one alternative to enhance water quality is through the total maximum daily load (TMDL) control system. In this control system, the maximum allowable amount of a pollutant released into a water body is estimated to meet specified water quality standards for that pollutant. This system also allows for setting pollutant reduction targets and allocating waste load reduction to pollutant sources (Fan *et al.*, 2021). The determination of the TMDL can be facilitated using water quality models. Water quality models are tools used to simulate water quality by simplifying and imitating actual processes, although they do so through various approaches and assumptions. This aids in predicting the TMDL of rivers and assists in decision-making regarding the most feasible management actions (Andesgur *et al.*, 2019). The water quality model in determining the TMDL has the advantage that the process can be faster, easier, and save costs.

Models such as EPD-RIV1 (a one-dimensional riverine hydrodynamic and water quality model), Hydrological Simulation Program-FORTRAN (HSPF) (a hydrological simulation program), QUAL2KW (a one-dimensional steady-state water quality model), and the U.S. Environmental Protection Agency (USEPA) water quality analysis simulation program (WASP) are commonly used for predicting the TMDL (Sharma & Kaushal, 2021). The WASP model has been widely used to analyze various water quality-related issues in diverse water bodies such as rivers, lakes, reservoirs, ponds, estuaries, and coastal waters. This model employs a flexible compartmental modeling approach and simulates spatial and temporal mass conservation by applying finite-difference equations for each compartment or segment. It can be applied in 1D, 2D, and 3D with advective and dispersive transport between discrete segments (Mulla *et al.*, 2019). Identifications of critical water quality conditions in developing watershed management plans, such as determining the TMDL, are crucial. This is because, during critical conditions, the potential for an increase in pollutant concentration becomes more concerning, leading to the violation of water quality standards over an extended period. A simple approach to calculating low flow, a critical condition, uses the 7-day average value with a recurrence interval of 10 years (7Q10). This approach is commonly used in developing steady-state models related to water quality assessments.

This study aims to provide input on pollution control strategies in the Lower Cileungsi River, one of the most polluted rivers in Indonesia, based on BOD load capacities. BOD, originating from point (PS; industry and tributaries) and non-point sources (NPS; domestic, agricultural, and livestock), was simulated in the WASP model with existing and critical water flows (7Q10) under steady-state assumptions. These various BOD sources, including a lake, with their low level of BOD management and predominantly surrounded by densely populated residential areas, make the river unique. As mentioned above, previous studies have helped to understand the variability and the status of water quality in the river, but none have focused on its water quality modeling based on BOD loads. BOD management in the river has been challenging, and results from water quality modeling, such as this study, can help shed light on answering the challenge, including during low flow conditions.

2. MATERIALSAND METHODS

2.1. Study area

The Lower Cileungsi watershed is located between 106° 54′ 33.473″ and 106° 58′ 14.550″ East Longitude and 06° 36′ 50.242″ and 06° 18′ 14.550″ South Latitude. This river flows from south to north, then merges with the Cikeas River to form the Bekasi River, and empties into the Pantai Utara Jawa. The Lower Cileungsi River has a total length of 35.05 km. The Upper Cileungsi watershed is located near the northern slope of Mount Pangrango, Babakan Madang, Bogor Regency, while the river outlet is in Bekasi City. The majority of the Cileungsi watershed is in Bogor Regency, with varying elevations ranging from 15 meters above sea level (masl) to 3,019 masl at the peak of Mount Pangrango. The Middle Cileungsi watershed has elevations between 100 and 200 masl, which is similar to the lower part of the watershed, which has elevations ranging from 100 to 200 masl. The northern slope of the Cileungsi watershed has a slope inclination of 0–15%. Andosols, Acrisols, and Nitisols soil types dominate the geological conditions in this watershed (Nugraha *et al.*, 2022). The land use map of the Cileungsi watershed in 2022 is shown in Figure 1.

Figure 1 shows that the Lower Cileungsi watershed was predominantly covered by built-up/residential areas, accounting for 81.49% of the 5,053.89-ha study area. The remaining land uses included dryland agriculture (15.23%), rice fields (2.38%), open space (0.46%), and mixed dryland agriculture (0.44%).

2.2. Methodology

This study started with the segmentation of the study area, followed by the collection of primary and secondary data, the determination of the river water quality status and its TMDL, and ended with the modeling of BOD loads and river water quality to simulate and identify the best policy scenarios for managing the water quality of the Lower Cileungsi River.

2.2.1. Study area segmentations

For this study, a buffer zone of 1 km from the left and right of the river bank is used to facilitate the identification of BOD loads entering the Lower Cileungsi River. The river length of 35.05 km, with a width varying between 18 and 51 m, was divided into five segments. The starting point for modeling is at upper Segment 5 (Gunung Putri) and ends at lower Segment 1 (Bojong Menteng). The sampling points were divided into six points, SCL 1 to SCL 6. Figure 2 shows the segmentation and location of sampling points, and Tables 1 and 2 provide their details.

2.2.2. Data collection

The data collection carried out in this study included primary data and secondary data. Primary data were obtained from field observations in the dry season (August 2nd, 2023). Primary data, i.e., hydraulic and water quality, was used to calibrate model results with the existing conditions. The primary data collection method in the form of sampling was carried out by referring to the Indonesian Sampling Standard of SNI 6989.57:2008. River discharge data were obtained by measuring river flow speed on-site using a calibrated current meter (universal current meter, type C20 ‘10.005’). The dissolved oxygen (DO), water temperature, and pH measurements were conducted on-site at each sampling point. The DO and water temperature were measured using a DO meter (Amtast, MT-08), and pH

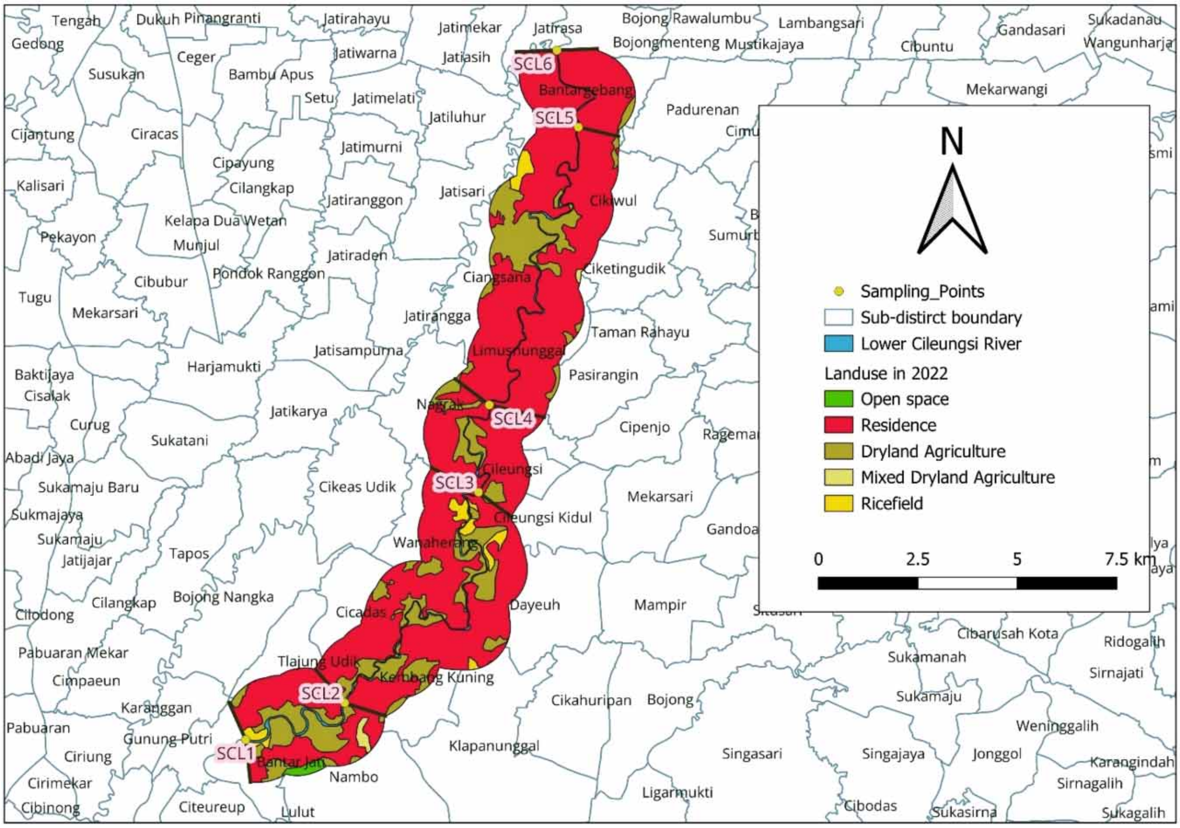


Fig. 1 | Land use map of the Lower Cileungsi Watershed.

was measured using a pH meter (PH-108 ATC). BOD measurement was carried out at Adhikarilab, located in Bogor Regency, which is accredited by the Indonesian National Accreditation Committee (Komite Akreditasi Nasional; KAN) under the accreditation code LP-720-IDN. The procedure followed the standard specified in the Indonesian National Standard (Standard National Indonesia; SNI) 6989.72:2009 using the 5-day BOD measurement method (BOD_5). This method measures the amount of oxygen required by microorganisms to decompose organic matter in water over 5 days at a temperature of 20 °C. Secondary data were obtained from the relevant institutions. All the secondary data required for this study, as well as their sources, are summarized in Table 3.

2.2.3. Calculation of the river water quality status

This study used the pollutant index (PI) method for calculating the river water quality status based on the Indonesian Minister of Environment Decree No. 115 of 2003. The PI value was calculated from several water quality parameters, including pH, DO, and BOD, as shown in the following equation:

$$\mathrm{PI}_j = \frac{\sqrt{(C_i/L_{ij})_{\mathrm{M}}^2 - (C_i/L_{ij})_{\mathrm{R}}^2}}{2} \tag{1}$$

where PI_j is the pollution index for designation (j); L_{ij} is the parameter concentration according to the quality standard used (j); C_i is the concentration of water parameters measured; $(C_i/L_{ij})_{\mathrm{M}}$ is the maximum C_i/L_{ij}

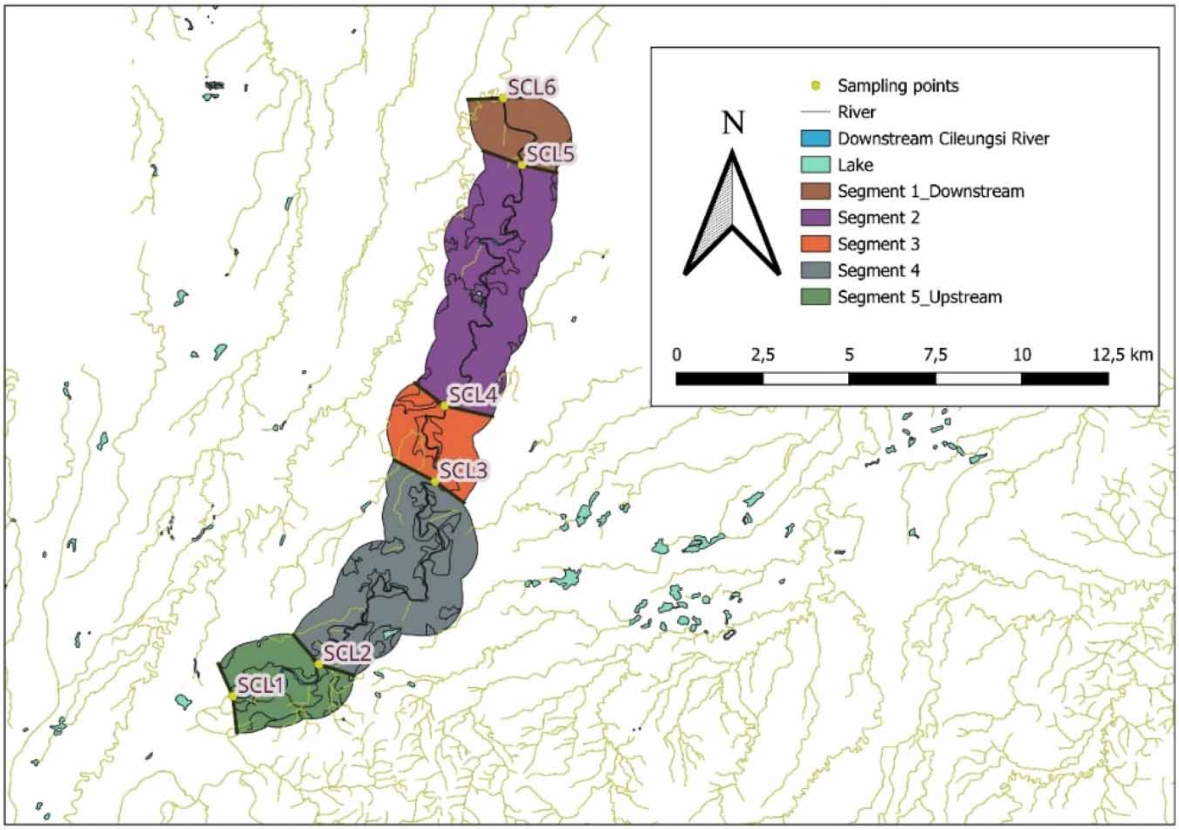


Fig. 2 | The segmentations and sampling points of the Lower Cileungsi Watershed.

Table 1 | Sampling points.

		Coordinate	
Point	**Location**	**S**	**E**
SCL 1	Behind of Hutama Prima (Gunungputri)	06° 27′ 42″	106° 54′ 07″
SCL 2	WIKA Bridge (Klapanunggal)	06° 27′ 11″	106° 55′ 28″
SCL 3	Cikuda Bridge (Wanaherang)	06° 24′ 19″	106° 57′ 16″
SCL 4	Eka Hospital	06° 23′ 07″	106° 57′ 26″
SCL 5	Bojong Kulur Bridge (Pangkalan I)	06° 19′ 19″	106° 58′ 37″
SCL 6	Saropati I, Bekasi	06° 18′ 15″	106° 58′ 19″

value; and $(C_i/L_{ij})_R$ is the average C_i/L_{ij} value. Rivers with a PI value of 0–0.1 are declared to be in good condition, a PI value of 1.1–5.0 in a lightly polluted condition, a PI value of 5–10 in a moderately polluted condition, and a PI value of more than 10 in a heavily polluted condition. Rivers with a PI value in the range of $0 \leq \mathrm{PI}_j \leq 1.0$ are declared to be in good condition; a PI value in the range of $1.0 < \mathrm{PI}_j \leq 5.0$ in lightly polluted

Table 2 | River segmentations.

Point	Segment name	River mile	Average width (m)	Slope	Q (m^3/s)
SCL 5–6	Segment 1_Lower	0.00	51.14	0.0004	13.87
SCL 4–5	Segment 2	2.80	36.83	0.0019	11.75
SCL 3–4	Segment 3	15.33	17.62	0.0025	7.84
SCL 2–3	Segment 4	18.94	20.48	0.0009	5.12
SCL 1–2	Segment 5_Upper	30.51	26.17	0.0024	3.27

Table 3 | Source of secondary data.

Type of data	Source
Cileungsi River profile	Bogor Regency Environmental Department
Historical water quality of Cileungsi River	
PS (industry, tributary and lake)	
Regional profile of Bogor Regency and Bekasi City	Statistics Indonesia
Landuse of West Java	Regional Development Planning Agency (West Java)
Environmental (solar radiation, air temperature, wind speed and dew point)	NASA Power
Historical flow data	River Basin Management Agency of Ciliwung-Cisadane

conditions; $5.0 < \mathrm{PI}_j \leq 10$ in moderately polluted conditions; and PI value grater than 10 in heavily polluted conditions.

2.2.4. Calculation of potential pollutant loads

BOD loads from several sources, including industrial, domestic, agricultural, and livestock sectors and the lake outlet, were calculated based on the Indonesian Minister of Environment Regulation Number 1 of 2010 on Water Pollution Control Procedures. The potential pollutant sources were calculated using two approaches. First, when data are available, the pollutant load is directly calculated using the pollutant concentration values and the pollutant flow rate from the source. In the lack of data, the pollutant load is estimated using an emission factor approach based on the type of source activity, as referenced in the 'Pollutant Load Calculation Study for the Citarum River' conducted by the Directorate General of Pollution and Environmental Damage Control, Ministry of Environment and Forestry in 2014. The limits for each sector of pollutant sources included in the calculations applied to each pollutant source located within a distance of 1,000 m from both the left and right sides of the river in each segment.

2.2.4.1. Industrial pollutant loads and lake outlets. Pollutant loads from PS were divided into two categories (industrial and lake outlet). The industrial wastewater quality data and the quality data from the lake outlets were obtained from historical records spanning the past 10 years, provided by the Environmental Agency of Bogor Regency. The pollutant load for PS tends to be concentrated in river segments within Bogor Regency.

The pollutant loads from these sources were determined based on the following equation (BLK PSDA, 2014):

$$\mathrm{PL(Industry)} = Q_{\mathrm{eff}} \times C_{\mathrm{eff}} \times 86.4 \tag{2}$$

where PL(Industry) is the pollutant load from the industrial sector (kg/day); Q_{eff} is the waste effluent discharge from each industry (m^3/s); and C_{eff} is the waste effluent concentration (mg/L).

2.2.4.2. Domestic pollutant loads. The pollutant load from the domestic sector was calculated using an indirect method determined by creating buffers at distances of 0–100, 100–500, and 500–1,000 m from the left and right sides of the river based on the following equation (BLK PSDA, 2014):

$$\mathrm{PL(Domestic)} = P \times \mathrm{EF} \times R \times \alpha \tag{3}$$

where PL(Domestic) is the pollution load from the domestic sector (kg/day); P is the population or number of residents (people); EF is the emission factor (kg/person/day); R is the city equivalent ratio (discharge load); and α is the load transfer coefficient (delivery load).

2.2.4.3. Agricultural pollutant loads. The equation for calculating agricultural pollutant loads is shown as follows (BLK PSDA, 2014):

$$\mathrm{PL(Agriculture)} = \frac{A \times \mathrm{EF} \times \%\mathrm{Waste}}{t} \tag{4}$$

where PL(Agriculture) is the pollutant load from the agricultural sector (kg/day); A is the agricultural land area (ha); EF is the agricultural emission factor (kg/ha/season); %Waste is the percentage of waste entering the river (%); t is the length of growing season (days).

2.2.4.4. Livestock pollutant loads. The equation for calculating livestock pollutant loads is shown as follows (Yusuf, 2014):

$$\mathrm{PL(Livestock)} = n \ \times \mathrm{EF} \times \alpha \tag{5}$$

where PL(Livestock) is the pollutant load from the agricultural sector (kg/day); n is the number of livestock (head); EF is the livestock emission factor (kg/head/day); and $\alpha$is the seasonal influence coefficient (%).

2.2.5. Model running

Water quality modeling of the Lower Cileungsi River was conducted using WASP 8.32. The required input data include river segmentation data, hydrometric data, climatology, daily discharge, discharge, and waste quality, as well as the quality of the Lower Cileungsi River. The modeling was conducted under the assumption of a steady-state condition. Water quality parameter calculations in the WASP are based on the mass balance principle, as shown in Equation (6) (Iqbal *et al.*, 2018). The mass balance equation is discretized using the finite-difference method. In the modeling conducted in this study, the Euler technique was chosen to solve the following equation:

$$\frac{dC}{dt} = -A\frac{dUC}{dx} + \frac{d}{dx}\left(EA\frac{dC}{dx}\right) \pm \ \mathrm{SC} \tag{6}$$

where C represents the concentration of different parameters of water quality factors, U represents the average water velocity, A represents the cross-sectional area, and x represents the distance in one dimension. SC stands for exterior and internal sinks and sources, whereas E stands for longitudinal dispersion coefficient.

For simulations in WASP, the eutrophication module was selected, and the 1D kinematic wave approach was utilized. The maximum time step was set to 0.041 (days) in the simulations with the simulation period from August 1 to 30 2023. Result visualization from the WASP modeling needs the integration of additional software, i.e., the Water Resource Database (WRDB). In this study, WRDB version 6.1 was selected.

2.2.6. Sensitivity analysis and calibration of parameters

2.2.6.1. Sensitivity analysis. In this study, to test the sensitivity of the analytical method, a local sensitivity analysis method was employed based on the sensitivity analysis approach proposed by Lenhart *et al.* (2002). The advantage of this method lies in its simplicity, practicality, and wide applicability. To assess the sensitivity of parameters within the WASP model in this research, the initial values for each parameter were first established for analysis. These initial values were derived from previous research. The initial value of each parameter was then varied by ±50%. To effectively compare the sensitivity of each parameter, only one parameter was altered at a time while keeping the others constant. The sensitivity index for each parameter modification was then calculated. The equation for calculating the sensitivity index is shown in the following equation (Obin *et al.*, 2021):

$$\mathrm{SI} = \frac{(\Delta Y/Y)}{(\Delta X/X)} \tag{7}$$

where SI represents the sensitivity index, X represents the parameter value, Y represents the simulation value, ΔX represents the relative change of the parameter value, and ΔY represents the relative change in the pollution caused by the change in the parameter (focused on changes in the lower section).

The sensitivity test results were categorized as follows: If $0.00 \leq \mathrm{SI} \leq 0.05$, it is classified as sensitivity level 1 (small to negligible); if $0.05 \leq \mathrm{SI} \leq 0.20$, it is classified as sensitivity level 2 (medium); if $0.20 \leq \mathrm{SI} \leq 1.00$, it is classified as sensitivity level 3 (high); and if $\mathrm{SI} \geq 1.00$, it is classified as sensitivity level 4 (very high).

2.2.6.2. Calibration of parameter. After the local sensitivity method, we conducted the trial-and-error method to calibrate the model parameters. The trial-and-error method for calibrating parameter constants was conducted by referring to the parameter range values from prior research and the reference study of Yusuf (2016) until the simulation results closely matched the field observation data.

2.2.7. Model verification and validation

The performance of the WASP 8.32 model needed to be evaluated by assessing the suitability of the observation data and simulation data. Model verification aims to adjust incoming parameters so that there will be a closer match between simulated and observed values. Flow, DO, and BOD concentrations were verified before being used for simulation. The statistical estimators that can be used to evaluate the accuracy of verified results are the root mean square error (RMSE) and the coefficient of determination (R^2) (Iqbal *et al.*, 2018). RMSE and R^2 were commonly used for water quality modeling calibration (Yusuf, 2014). The R^2 measured the fit between observed and predicted data. The R^2 value ranged from 0 to 1. If the R^2 value was close to 1, the model predictions matched the measured data more closely. The method used for data validation is the same as for verification, involving error analysis using RMSE and R^2 parameters. However, validation is performed using data from a different time. Verification was conducted using observation data from August 2, 2023, while validation utilized data from observations made in March 2022 (secondary data from the Bogor Regency Environmental Department and the Ciliwung-Cisadane River Basin Authority).

2.2.8. Determination of the pollutant load capacity

The pollutant load capacity, i.e., TMDL, of the Lower Cileungsi River was used to determine the standard assessment of water quality and quantity from the maximum amount of BOD. The pollutant load capacity was calculated with the mass balance equation; this involves calculating the difference between the pollutant load according to the quality standard and the pollutant load measured (Saily *et al.*, 2019).

2.2.9. Model scenarios

Simulations using the WASP model were carried out with various scenarios. The following six model simulation scenarios used in this study are shown in Table 4.

Scenario 1 was the business as usual scenario, which represented the current water quality conditions of the Lower Cileungsi River without any control measures, using data from the existing conditions. Scenario 2 was simulated to assess the river's condition at its most critical state, where pollutant loads were assumed to be the same as the current conditions, but the river discharge was at its minimum (discharge calculated using the 7Q10 method). By understanding the pollutant load-carrying capacity of the Lower Cileungsi River under critical conditions (Scenario 2), if it exceeds the carrying capacity, Scenario 3 was simulated as a proactive or control measure for this condition. Scenario 3 simulated the changes in river water quality when control measures were implemented by tightening wastewater discharge from all industrial sectors to comply with the industrial wastewater quality standards set by the Minister of Environment Decree in 2019. This scenario was feasible since controlling PS pollution was easier than controlling NPS. Scenario 4 simulated a combination of pollutant load reductions from PS and NPS, with 50, 70, and 80% reductions. These reduction percentages were considered based on observations of the existing water quality of the Lower Cileungsi River, particularly since the BOD parameter had significantly exceeded the water quality standards for Class II rivers as per Government Regulation No. 22 of 2021, necessitating significant reductions, so we started with the reduction combination of PS and NPS by 50, 70, and up to 80%. Scenario 5 simulated a reduction combination solely from PS, as the analysis of the industrial wastewater quality data and lake water quality data obtained from the Environmental Agency over the past 10 years showed that the BOD concentration in both sources remained significantly above the limits specified by the applicable quality standards at that time. Scenario 6 was conducted by optimizing reductions from all pollutant sources until the Lower Cileungsi River water quality met the standard of river water quality class II of Government Regulation No. 22 of 2021.

Table 4 | Model scenarios.

Scenario	Flow	Pollutant sources	Water quality
1	Existing	Existing	Existing
2	Q_{min}	Existing	Model
3	Q_{min}	Wastewater Quality Standard	Model
4	Q_{min}	Reduce PS and NPS 50, 70, and 80%	Model
5	Q_{min}	Reduce industry and lake 50, 70, and 80%	Model
6	Q_{min}	Optimize reduction simulation	Class 2

3. RESULTS AND DISCUSSION

3.1. Existing conditions

Table 5 shows BOD and DO concentrations from samplings taken on August 2, 2023, at SCL 1 through SCL 6. Organic matter in water can originate from pollution sources such as domestic waste, industrial activities, livestock, and agriculture. BOD in water represents the total oxygen needed to break down organic matter biochemically. The more organic matter is in the water, the lower the DO will be (Daroini & Arisandi, 2020). As for the Cileungsi River on August 2, 2023, the BOD values exceeded water quality standards at all points, ranging from 3.30 to 27 mg/L, with the highest BOD value measured at points SCL 3 and SCL 4. These results indicated that organic pollution has occurred at all monitoring points, leading to high BOD concentrations.

DO in water can originate from the atmosphere through diffusion and from aquatic plants through photosynthesis. A river body with a high DO indicates a healthy water body. Conversely, a DO deficit may indicate the presence of organic pollution from untreated waste in the surrounding areas (Kozaki *et al.*, 2016). Other factors influencing DO concentration in water include turbulence, temperature, salinity, and depth (Mainali & Chang, 2021). Table 5 shows opposite patterns of DO and BOD concentrations. High DO concentrations at SCL 1 were due to fewer BOD-contributing activities upstream. A sudden decrease in DO occurred at SCL 3 and SCL 4, where SCL 4 has the lowest DO among the points. This indicated an influx of organic waste from activities around these points, leading to a high BOD (Astono *et al.*, 2008). A black color and a foul smell from the water accompanied the low DO at SCL 4. This aligns with field observations where segments 4 (SCL 2–SCL 3) and 3 (SCL 3–SCL 4) are predominantly influenced by industrial and domestic activities compared to other segments and receive input from the lake outlets. The recovery zone of DO started at SCL 5, supported by aeration processes at the Curug Parigi waterfall.

3.2. Determination of the water quality index

The water quality status of the Lower Cileungsi River was calculated following the Minister of Environment and Forestry Regulation Number 27 of 2021 (Chrisnawati *et al.*, 2023). PI values for the Lower Cileungsi River on August 2, 2023, based on pH, DO, and BOD, at each monitoring location point are shown in Figure 3.

Figure 3 shows that the river water quality status for the six sampling points was lightly polluted, with an average PI value of 2.57. The highest PI value was at point 4, with a PI value of 4.34. This shows that SCL 4 was the

Table 5 | Water quality monitoring (August 2, 2023).

	Measurement location			
	On-site			**Adhikari Lab**
Sampling point	**Temperature (°C)**	**pH**	**DO (mg/L)**	**BOD (mg/L)**
SCL 1	27.50	8.22	6.10	4.90
SCL 2	28.40	8.10	5.20	7.40
SCL 3	30.20	7.68	2.60	17.00
SCL 4	30.50	7.42	2.40	27.00
SCL 5	30.00	7.90	4.70	3.30
SCL 6	29.00	7.82	3.85	9.30
Class II Standard[a]	Dev 3	6–9	4.00	3.00

[a] Class II Standard based on Indonesian Government Regulation No. 22 of 2021.

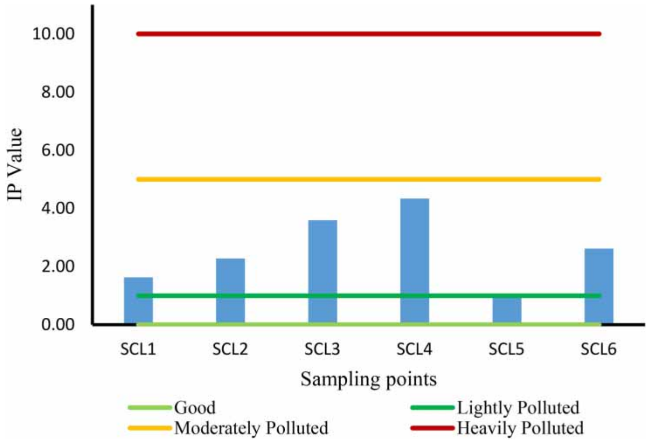


Fig. 3 | Water quality status of the Lower Cileungsi River.

most polluted compared to other points. Although the BOD concentration values at the six sampling points have significantly exceeded the Class II water quality standards in Government Regulation No. 22 of 2021, the overall water quality status indicates that the river is slightly polluted. This may be because the water quality status is determined using the PI method, which combines various water quality parameters into a composite index rather than evaluating individual parameter violations. In the index method, even though one parameter (BOD) significantly exceeds the limit, other parameters such as pH and DO may still fall within the acceptable range, thereby balancing the final index result. Furthermore, if the deterioration in BOD occurs only at certain points rather than consistently throughout the river, the index may result in lower pollution levels.

3.3. Calculation of potential pollutant loads

To calculate the potential BOD load, it was necessary to identify organic pollutant sources from tributaries and industrial, domestic, agricultural, and livestock activities. The effluent data for PS calculations were obtained from the Bogor Regency Department of Environment. Potential pollutant load from NPS was obtained by calculating potential pollutant loads included in the buffer zone using Equations (3)–(5). Table 6 shows BOD pollutant loads from all sources in the Lower Cileungsi River. It is shown that the highest BOD load was from the lake outlet reaching 68.91% of the total load. Segment 3 received the highest total BOD loads from all sources.

Table 6 | Pollutant loads in the Lower Cileungsi River.

Segment	**Domestic**	**Industry**	**Agriculture**	**Lake outlet**	**Livestock**	**Amount (kg/day)**
1_Lower	905.15	71.68	0.00	0.00	0.36	977.19
2	978.83	0.00	35.39	0	0.97	1,015.19
3	754.51	602.77	5.28	15,552.00	0.27	16,914.83
4	2,030.94	2,496.34	63.08	7,084.80	0.63	11,675.79
5_Upper	1,033.42	1,203.08	31.93	0.00	0.24	2,268.67
Amount	5,702.85	4,373.86	135.68	22,636.80	2.45	32,851.65
(%)	17.36%	13.31%	0.41%	68.91%	0.01%	100%

3.4. Sensitivity analysis and calibration of parameter results

3.4.1. Sensitivity analysis results

The parameters selected for the sensitivity test in this study are the primary parameters for each water quality index. The parameter values obtained from previous research were adjusted by ±50% from their initial values. The results of the sensitivity test in this study are presented in Table 7.

Based on the sensitivity testing results for BOD, DO, and water temperature parameters, it was found that the CBOD decay rate constant and temperature correction coefficient in segments 3 and 4 exhibit relatively high sensitivity to the BOD and DO parameters. For the DO parameter specifically, the Global Reaeration Rate Constant at 20 °C demonstrated the highest sensitivity. In contrast, the water temperature parameter exhibited low sensitivity across all constants.

3.4.2. Parameter calibration results

After the sensitivity test, the influential parameters were calibrated using a trial-and-error approach, referencing parameter ranges from previous studies that closely correspond to the study area. The parameter values were adjusted to achieve the simulation results that most closely matched the observed data. Table 8 shows kinetic constants in the model.

3.5. Calculation of load balance

Based on the 2007–2022 discharge data from the Ciliwung-Cisadane River Basin Center (BBWS), the 7Q10 flow of the Cileungsi River was 3.12 m^3/s. This flow was used to simulate Scenario 2 (representing the critical condition). Table 9 shows the load balance from the TMDL, under critical conditions, at each segment. Under Scenario 2, simulations showed that excess loads exceeding the Class 2 River TMDL were observed in all

Table 7 | Parameter sensitivity analysis.

	BOD				**DO**				***W***			
Parameters	**−50%**	**+50%**	**SI**	**Class**	**−50%**	**+50%**	**SI**	**Class**	**−50%**	**+50%**	**SI**	**Class**
Water temperature												
WT2	0.0	0.0	0.0	1	0.0	0.0	0.0	1	0.0004	0.0000	0.0002	1
WT3	0.0	0.0	0.0	1	0.0	0.0	0.0	1	0.0031	0.0032	0.0032	1
CBOD												
CBD1	0.0186	0.0199	0.0193	1	0.0	0.0	0.0	1	0.0	0.0	0.0	1
CBD2	0.0151	0.0232	0.0192	1	0.0	0.0	0.0	1	0.0	0.0	0.0	1
CBD3	0.0503	0.0819	0.0661	2*	0.0573	0.0495	0.0534	2*	0.0	0.0	0.0	1
CBD4	0.0419	0.0717	0.0568	2*	0.0322	0.0248	0.0285	1	0.0	0.0	0.0	1
CBD5	0.0034	0.0340	0.0187	1	0.0	0.0	0.0	1	0.0	0.0	0.0	1
CBT1	0.3019	1.2908	0.7964	3*	0.2186	0.8644	0.5415	3*	0.0	0.0	0.0	1
CBS1	0.0492	0.0361	0.0426	1	0.0285	0.0237	0.0261	1	0.0	0.0	0.0	1
DO												
DO1	0.0	0.0382	0.019	1	0.4942	0.2441	0.3692	3*	0.0	0.0	0.0	1
DO2	0.0	0.0	0.0	1	0.0007	0.0007	0.0007	1	0.0	0.0	0.0	1

* The key parameter affecting the simulated output concentration.

Table 8 | Kinetic constants for the WASP model.

Parameters	Symbol	Value
Global constant		
Fresh water = 0; Marine water = 1	GC1	0
Water temperature		
Heat exchange option (0 = full heat balance, 1 = equilibrium temperature)	WT1	0
Coefficient of bottom heat exchange (Watts m^{-2} °C^{-1})	WT2	0.3
Sediment (ground) temperature (°C)	WT3	25
Ice switch (0 = no ice solution, 1 = ice solution, 2 = detailed ice)	WT4	0
CBOD		
CBOD Decay Rate Constant @20°C (1/day) – BOD Segment 1_Lower	CBD1	0.35
CBOD Decay Rate Constant @20°C (1/day) – BOD Segment 2	CBD2	0.35
CBOD Decay Rate Constant @20°C (1/day) – BOD Segment 3	CBD3	0.62
CBOD Decay Rate Constant @20°C (1/day) – BOD Segment 4	CBD4	0.62
CBOD Decay Rate Constant @20°C (1/day) – BOD Segment 5_Upper	CBD5	0.35
CBOD Decay Rate Temperature Correction Coefficient	CBT1	1.047
CBOD Half Saturation Oxygen Limit (mg O_2/L)	CBS1	2
DO		
Global reaeration rate constant at 20°C (1/day)	DO1	2.5
Theta – SOD temperature correction	DO2	1.047
Light		
Background light extinction coefficient (1/m)	L1	0.1
Detritus and solids light extinction multiplier 1/m (mg/L)	L2	0.3

Table 9 | Load balances in the Lower Cileungsi River under Scenario 2.

Segment	Pollution load (kg/day)	Difference from standard
1_Lower	977.20	2,697.70
2	1,015.20	2,219.60
3	1,6914.80	−14,911.50
4	1,1675.20	−10,389.90
5_Upper	2,268.70	−14,01.60
Total difference (kg/day)		− 21,785.60

segments except Segments 1 and 2. This warrants the compulsory reduction of pollutant loads to meet the Class 2 river water quality standard.

3.6. Model verification and validation

Before proceeding to model simulation, the first step in river water quality modeling is model calibration. Model calibration should start with calibrating the discharge and then the other key parameters (Hindriani, 2013). The calibration is done against field monitoring data. The flow rate is a key parameter in water quality modeling as it can influence dilution and the concentration of pollutants in the river. The larger the river flow rate is, the more pollutants are diluted. The concentration of DO is also important in model calibration. DO in water is crucial to demonstrate the model's capability in the water system, and its concentration in water can be influenced by various factors in the water system, such as water flow rate and the amount of pollutant content. BOD serves as an indicator of pollution from industrial, domestic, agricultural, and livestock sectors. Before conducting the model simulation, the model BOD is also calibrated. The calibration results for flow rate, DO, and BOD are shown in Figure 4.

This study used RMSE and R^2 to evaluate the calibrated model. The results from calibration showed that for discharge, RMSE was 0.42 and R^2 was 0.99; for DO, RMSE was 1.40 and R^2 was 0.84; and for BOD, RMSE was 5.02 and R^2 was 0.89. The results were considered acceptable as the R^2 and RMSE approached 1.

3.7. Model simulation

In this study, model simulations were carried out following the scenarios in Table 4. Based on the six scenarios, Scenarios 1 and 2 used the same pollutant load but different discharges; Scenario 1 used the existing discharge, and Scenario 2 used the minimum discharge (7Q10). Scenarios 3–6 simulated the reductions in pollutant inputs

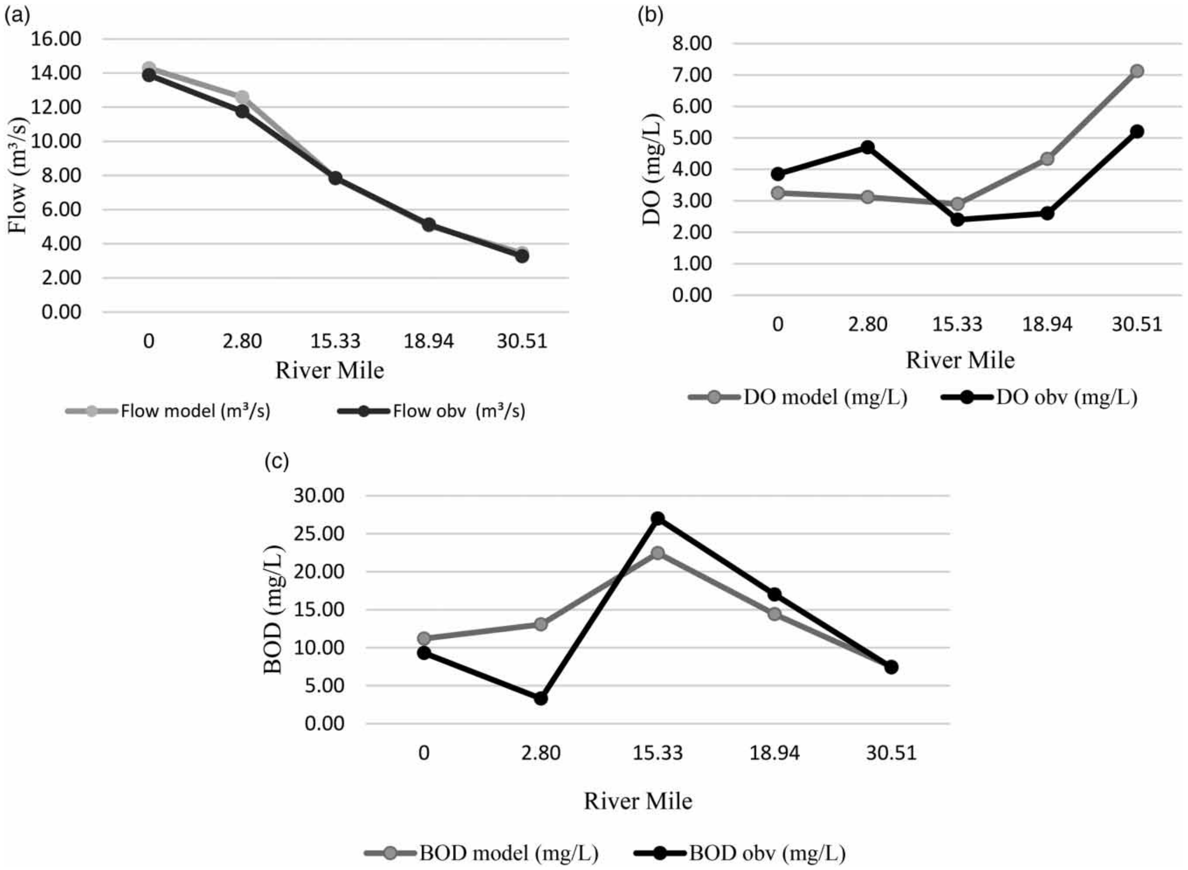


Fig. 4 | Model calibration: (a) flow rate, (b) DO, and (c) BOD.

under the critical water condition. All scenarios were simulated to achieve the Class 2 river water quality standard stipulated in Indonesian Government Regulation No. 22 of 2021. The results for all model simulation scenarios that are shown in Figure 5(a) and 5(b) show similar results from model simulations under Scenarios 1 and 2, respectively. Field sampling was carried out in the dry season when the river discharge was low; consequently, the river discharge in Scenario 1 was close to that in Scenario 2. Scenarios 3–6 were simulated to lower the excessive pollution loads during the critical river conditions. In Scenario 3, the simulation was done, assuming that wastewater from the industrial sector met its effluent standards. Results from Scenario 3 in Figure 5(c) showed a decrease in BOD concentration. Yet, these results did not meet the Class 2 water quality standard.

The simulations under Scenario 4 were done with the assumption that various sectors in the Cileungsi watershed reduced their pollutant loads, both from PS and NPS, by 50, 70, or 80%. The 50% reduction combines a 25% reduction from PS and a 25% reduction from NPS; the 70% reduction combines a 35% reduction from PS and a 35% reduction from NPS; and the 80% reduction combines a 50% reduction from PS and a 30% reduction from NPS. Figure 5(d) shows that the maximum reductions under Scenario 4 only reached compliance with the Class 3 river water quality standard, with an 80% mixed reduction of a 50% reduction from PS and a 30% reduction from NPS.

Under Scenario 5, pollutant load reductions specifically for PS, i.e., industries and lake outlets, were simulated. The simulation results under Scenario 5, as shown in Figure 5(e), showed drastic reductions in pollutant loads at a distance of 15.33 miles. In other segments, the load remained relatively close, because the pollutant loads from lake outlets did not influence them. None of the simulations done under Scenario 5 met the Class 2 river water quality standard. The most favorable outcome was achieving compliance with the Class 3 water quality standard with a simulation of 80 and 90% reductions in pollutant loads from the lake.

Simulations done under Scenario 6 were carried out by trial-and-error so that the water quality of the Cileungsi River met the Class 2 quality standard. As shown in Figure 5(f), results showed that to achieve the Class 2 water quality standard, it was necessary to reduce pollutant loads by 87% from industry, 90% from lake outlets, 60% from domestic, and 20% from agriculture sectors. No reduction from the livestock sector was necessary, as its contribution is low.

Domestic BOD load reductions can be achieved through the implementation or use of off-site and on-site (communal) wastewater management systems (Wardhani & Salsabila, 2022). Decreasing BOD loads from the industrial sector can be accomplished by using aerobic–anaerobic wastewater treatment plants (WWTPs) or by applying granular activated carbon in operational WWTPs (Zahmatkesh *et al.*, 2023). To reduce BOD loads originating from lakes, lake restoration can be carried out through the application of aeration and macrophytes (Lokhande & Dixit, 2017). BOD load reductions in the agricultural sector can be achieved by minimizing fertilizer use. It is necessary to apply the principles of Integrated Water Resources Management (IWRM) covering social equity, economic efficiency, and ecological sustainability that are supported by supporting regulations, stakeholder participation, efficient water use, and an environmental sustainability perspective (SIWI, 2020).

4. CONCLUSIONS

This study has shown that the Lower Cileungsi River has been polluted with BOD loads exceeding the Class 2 river water quality standard, and its DO levels were lower than the standard. The river water quality status was classified as slightly polluted, with an average PI value of 2.57. The total potential pollutant load from all sectors was 32,851.65 kg/day, exceeding the TMDL under critical conditions by 21,785.6 kg/day. As the Lower Cileungsi River watershed is within the region with wet and dry seasons, the TMDL under low flow conditions should be of primary concern in BOD management, as BOD loadings from industries, lake outlets, and domestic will not decrease.

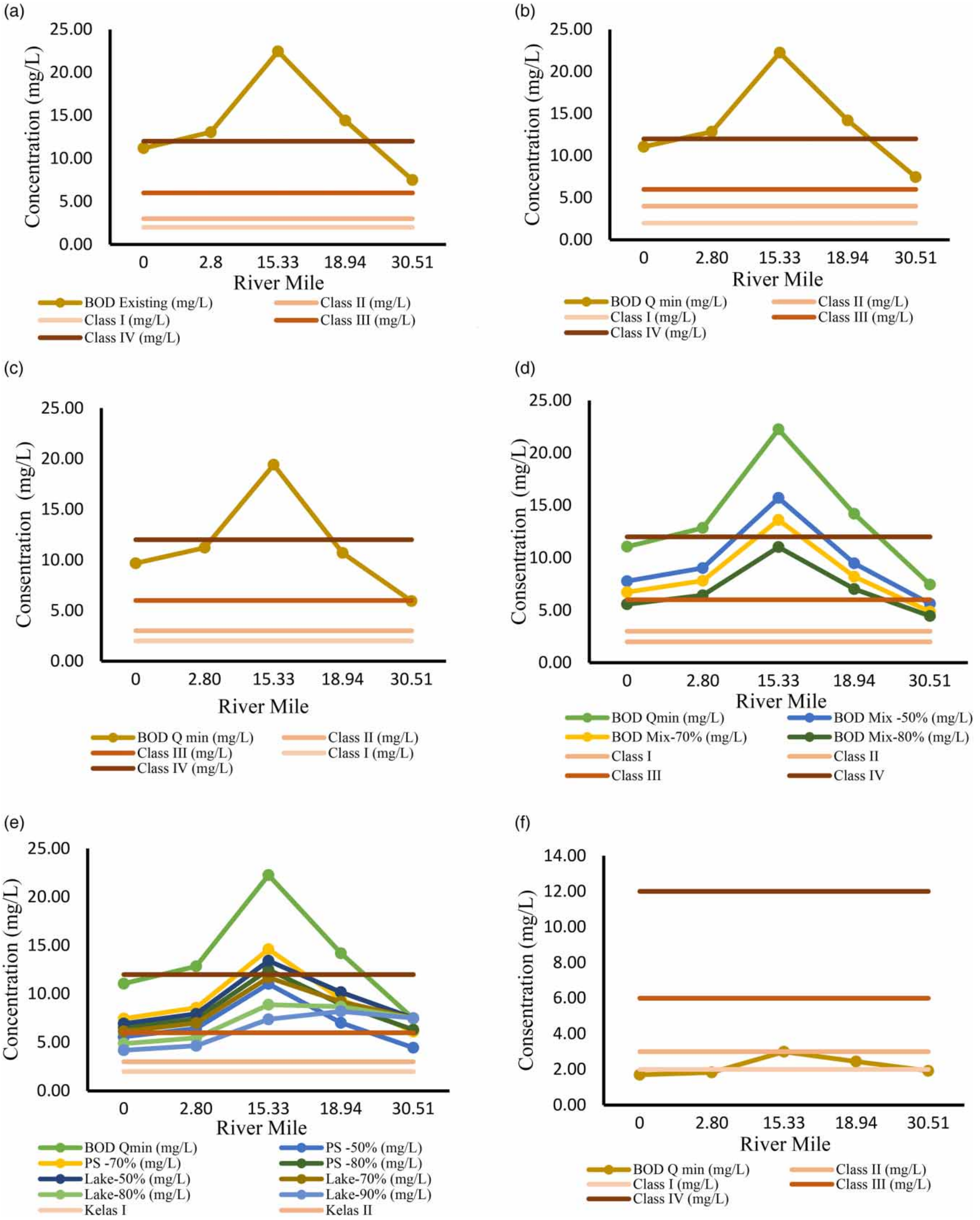


Fig. 5 | Model simulation results from (a) Scenario 1, (b) Scenario 2, (c) Scenario 3, (d) Scenario 4, (e) Scenario 5, and (f) Scenario 6.

Results from the model simulation warranted the need to reduce 87% of industrial, 90% of lake outlets, 60% of domestic, and 20% of agriculture BOD loads to meet the Class 2 river water quality standard. No reduction was required from the livestock sector as it did not contribute significantly; however, waste management is still compulsory. IWRM implementation through various aspects, such as improving regulations, support, and participation of all stakeholders, regulating water allocation for efficient water use, and improving environmental management practices to achieve sustainability, is highly recommended.

Based on the results of this study, further development would be beneficial, particularly to test additional water quality parameters. Additionally, it would be advantageous to incorporate climatological data monitoring closer to the study area location for improved accuracy. In addition, integrating the WASP model with SWAT, HSPF, or other models is recommended to improve the accuracy of pollution load calculations, particularly from NPS. This combined approach will enhance the precision of predictions by accounting for the complexities of diffuse pollution and hydrological processes, leading to more reliable water quality assessments.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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