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Pollution Load Allocation on Water Pollution Control in the Citarum River

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Highlights:

- Maintaining river water quality should be based on the total maximum daily load.
- Wastewater discharge permits should be based on the maximum pollution load of each pollutant source.
- The greatest quantity of pollutants originate from non-point sources, predominantly domestic, should be the focus of water pollution control programs.

Abstract. The Citarum River is a strategic river in Indonesia, but has poor water quality. The existing pollution control program has no impact on the river's water quality, because it uses a regulatory approach and prioritizes industrial sources. To improve the quality of the river, every pollutant source needs to reduce the pollution load discharged into the river based on the ability of the river to receive pollution. The purpose of this study was to measure pollution load allocation based on the total maximum daily load (TMDL) of the river. The results show that non-point sources contribute the highest pollution load (85%) compared with point sources (15%). The results of the measurement of pollution load allocation showed that the highest contribution of pollution load was from domestic waste (83.5%), followed by industrial waste (6.6%). The target of pollution load reduction for domestic sources is 81.8%, and for industries is 79.5%. The improvement of river water quality should be started at tributaries and domestic sources. This study can be used by local governments to develop water pollution control programs, for instance as a basis for determining the wastewater discharge permit of pollutant sources and permit trading.

Keywords: *non-point sources; point sources; pollution load allocation; total maximum daily load; tributaries.*

1 Introduction

The Citarum River, a large and strategic river in West Java, Indonesia is heavily polluted. It has experienced a decline in the quality and quantity of water,

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including constriction, silting, turbidity, and decreased oxygen levels. It receives discharges of waste from industries, residences, agriculture, and animal husbandry. Some studies have shown that the water quality in most locations in the upper Citarum River is poor and that the pollution levels far exceed the maximum allowable levels. The water quality has been deteriorating over the past 20 years, as mentioned by the Asian Development Bank and the International Bank for Reconstruction and Development in [1]. The data show that the Citarum River is in a critical condition because of the poor quality of its water, which cannot be used directly.

The Citarum River can be classified as a river with severe pollution from chemicals and from physical and bacteriological indicators, as given by Sholeh, *et al*. [2]. The pollution in the river not only comes from point sources but also from non-point sources, as indicated by Belinawati, *et al*. [3] and Wu and Chen [4]. The biggest pollutant is household waste, which is 60-70% of the pollutant load (CNN Indonesia [5]) and only 20% of industries have wastewater treatment plant (Republika [6]). The Citarum River has become one of the dirtiest rivers in the world, as indicated by the Blacksmith Institute and the Green Cross Switzerland in [7]. The President of the Republic of Indonesia has expressed concern about this problem, as he issued Presidential Regulation Number 15 of 2018 concerning the Acceleration of Pollution and Damage Control in the Citarum River Basin.

The upper Citarum River flows through 4 regencies/cities: Bandung City, Bandung Regency, Cimahi City, and Sumedang, with populations of approximately 5,200,000 people, or approximately 1,000,000 households, based on the data from the Ministry of Environment and Forestry in [8]. The length of the upper Citarum River is approximately 58.14 km and covers 231 465.71 ha. The river flows through 6 other regencies/cities, and along the river are 3 major dams, Saguling, Cirata, and Jatiluhur. These dams are used for generating hydropower for irrigation of 420,000 hectares of land and for supplying clean water to 80% of Jakarta's population.

The government has established regulations related to river water quality management and water pollution control. However, the Citarum River's water quality is still poor and below the water quality standard. This is because pollution control programs focus only on industrial pollutant sources, while other sources of pollutants are ignored. In addition, wastewater discharge permits for industries are still based on the best available technology, without considering the maximum ability of the river to receive pollution. Several studies (Kannel, *et al*. [9], Kannel, *et al.* [10], Camargo, *et al.* [11], Chang and Hong [12], Serrano, *et al*. [13], Chen, *et al.* [14]) have used modeling to determine the total maximum daily load (TMDL), and other studies (Boyacioglu and Alpaslan [15], Elshorbagy, *et al.*

[16]) have proposed using TMDL as the basis of water quality management strategies.

The purpose of this study was to measure pollution load allocation based on the TMDL of the river. The results can be used as a basis to determine wastewater discharge permits for each pollution source to improve the water quality of the Citarum River.

2 Methodology

This study used a quantitative approach, focusing on numerical data that were processed by modeling to calculate the total maximum daily load of the river. The data were obtained from the environmental agency of the West-Java provincial government, which regularly takes water quality samples at predetermined sampling points. The data collected consisted of river water quality and wastewater quality from pollutant sources (point sources and non-point sources). In the analysis a total maximum daily load model was used, continued with the measurement of pollution load allocation from pollutant sources.

2.1 Total Maximum Daily Load (TMDL)

TMDL is a measure of the ability of a water body to receive pollution load without causing water pollution, as stated in the Ministry of Environment Decree No. 1, 2010 [17]. This approach aims to control pollutants from various pollutant sources that are discharged into a river by considering the intrinsic conditions of the water source and the specified water quality standards. The formula used to calculate TMDL is as follows:

$$\text{TMDL} = \text{point source} + \text{non-point source} + \text{water quality} + \text{margin of safety} \quad (1)$$

TMDL is calculated using a model, which simplifies a complex system. The model uses a genetic algorithm to maximize the adjustment of the simulated results based on data measured in the field. The model uses Qual2Kw (Pelletier, *et al*. [18]), which is the latest version of the Qual2E model (Brown [19]) and adapted from Qual2K (Chapra [20]). This model is based on the Streets-Phelps theory, which includes the natural purification process in river water. The compatibility is determined as the reciprocal of the weighted average of the normalized root mean square error (RMSE) of the difference between the model predictions and the observed data for water quality constituents (Kannel, *et al*. [9]). The RMSE test is used to show the error rate of this modeling: a smaller RMSE test value indicates that the error rate of the modeling is also small.

The scenario is used to determine the target pollution load reduction needed so that the total pollution load does not exceed the total maximum daily load of a river, according to Kurniawan [21]. Studies to calculate the maximum capacity of a river to receive pollutants have been conducted by Hall, *et al.* [22], Lee, *et al*. [23], Lestari, *et al*. [24], and Osmi, *et al.* [25]. The follow-up implementation of the model has been studied by Ning and Chang [26], Tan [27], Yang, *et al.* [28], Zhang, *et al.* [29], Zhang, *et al.* [30], and Zolfagharipoor [31], who recommended integrating their studies as a basis for policies such as those that govern water pollution control and permits. Komarudin, *et al.* [32] combined numerical and spatial models in a pollution load analysis.

2.2 Pollution Load Allocation

The calculation of pollution load allocation follows the calculation of the TMDL. The results of pollution load allocation are the amount of pollutant load that must be decreased from each pollutant source that discharges wastewater into the river per administrative location.

2.2.1 Point Sources

The method of estimating the amount of load generated from industrial sources is calculated by the following equation from the Ministry of Environment [17]:

$$I,i = Ci \times V \times OpHrs \ / \ 1\,000\,000 \tag{2}$$

I,i = pollution load/emissions, kg/yr
Ci = concentration of pollutant type in wastewater discharge, mg/l (primary data)
V = wastewater discharge flow rate, l/h
OpHrs = number of operating hours per year, h/yr
1 000 000 = conversion factor (mg/kg)

2.2.2 Non-point sources

In this study, non-point sources consist of domestic, livestock, agriculture, fishery, and forestry. The potential pollution load from domestic sources is estimated using the equation from Iskandar [33]:

$$PLP = \alpha \times population \times effluent\ factor \times cer \tag{3}$$

where, PLP = pollution load potential of domestic waste; α = coefficient related to distance from the river. It is a measure of the ease with which waste reaches the river.

α = 1 (0-100 m), 0 .85 (100-500 m), 0 .3 (above 500 m)

Effluent factor = 0.04 kg/day (BOD), 0.55 kg/day (COD), 0.038 kg/day (TSS) cer = city equivalent ratio , cer = 1 (urban areas), 0.8125 (suburbs)

The pollution load potential from livestock was calculated using emission factors. The data needed were the type and number of livestock, while the BOD emission factors were developed by Iskandar and used in Juwana and Nugroho [34] and Komarudin, *et al.* [32]. The factors were: buffalo 207 g/day, cattle 292 g/day, horse 226 g/day, pig 128 g/day, sheep 55 .7 g/day, goat 34 .1 g/day, chicken 2 .36 g/day, and duck 0 .88 g/day. The formula is:

$$PLP_{livestock} = number\ of\ livestock\ \times\ emission\ factor\ \times\ 20\ \% \quad (4)$$

Pollution loads from agricultural activities were obtained based on agricultural land area data. Emission factors for BOD pollution parameters for agriculture were obtained from Iskandar in Komarudin, *et al.* [32]: 18 kg/(ha·season) for rice fields, 9 kg/(ha·season) for palawija (crops planted in the dry season that require less water), and other plantations at 9 kg/(ha·season).

The formula is:

$$PLP_{ricefield} = land\ area \times\ emission\ factor\ \times 10\ \% \quad (5)$$

$$PLP_{palawija} per\ season = land\ area\ \times emission\ factor \times 1\ \% \quad (6)$$

$$PLP = \frac{PLP_{rice\ fielsd/palawija}}{days\ of\ season} \quad (7)$$

The fishery emission factor was obtained from the development of the BOD parameter emission factors for goldfish aquaculture from Iskandar [34], i.e. 0.0966 per kg of production.

The level of urgency to control the pollution load can be counted by the ratio of pollution load reduction compared with the existing pollution load. This ratio can be overlaid with the spatial data.

$$Ratio = \frac{BOD_{existing}}{BOD_{TMDL}} \quad (8)$$

3 Result and Discussion

The river water quality model used in this study was a computerized numerical model that was built using QUAL2Kw. The data used were monitoring data obtained during the month of July 2018 with a minimum flow rate. Water quality monitoring in the upstream segment is routinely carried out by the Bandung Regency Environmental Agency at four sampling points (Figure 1).

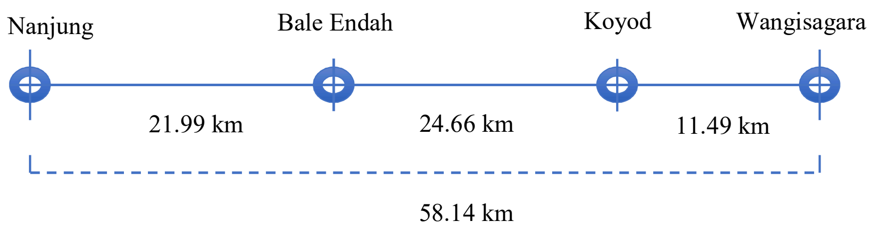

Figure 1 Sampling points in the Upper Citarum River.

The result of river water quality sampling in July 2018 shows that the water samples from all sampling points exceeded the water quality standard (WQS) for the BOD parameters compared with the Water Quality Standard Class 2 (Figure 2). The Water Quality Standards (WQS) are 2 mg/l (Class 1), 3 mg/l (Class 2), 6 mg/l (Class 3), and 12 mg/l (Class 4).

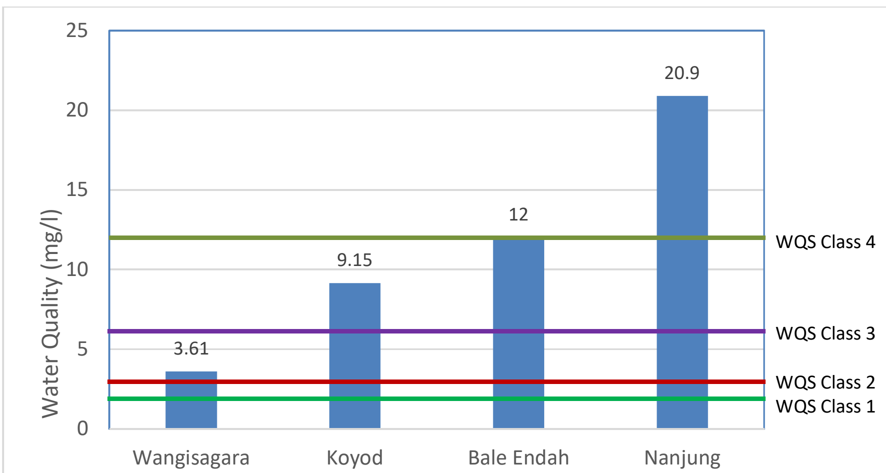

Figure 2 BOD concentration in the Upper Citarum River. Source: Environmental Agency of Bandung Regency (2018).

The pollutant sources in the Citarum River watershed can be divided into point and non-point sources. Point sources consist of industries and tributaries, while non-point sources consist of residences, animal husbandry, fisheries, land and forest, and agriculture. Water quality modeling was carried out based on two scenarios, as shown in Table 1. In the first scenario, modeling was based on existing conditions where the pollution load from point sources (PS) was based on primary data, while the non-point source load (NPS) was based on trial and error until the modeling results were close to the monitoring data. In the second scenario, the water met the Water Quality Standard Class 2 in Government Regulation No. 82, 2001. The pollution load from industries was based on the Wastewater Quality Standards, while the result for tributaries was obtained by trial and error until the water quality of the rivers in all segments met the Water Quality Standard Class 2.

Table 1 Model scenario of Total Maximum Daily Load (TMDL) of Citarum River.

Scenario	Flow Rate	Upstream		Output
		Water Quality	Pollution Load	
1 Existing load	Minimal result	Measurement result	Input model PS: Data field NPS: trial and error	Existing Pollution Load Model
2 TMDL	Minimal result	Class 2	PS: effluent standard Tributaries: Class 2 NPS: trial and error	TMDL Model Class 2

The results (Table 2) show that the highest proportion of the pollution load (85%) came from non-point sources (NPS), while the pollution loads from point sources accounted for 15% of the total. Quantitatively, the total pollution load of the existing BOD was 187,048.01 kg/day, while the pollution load based on TMDL was 34,580.00 kg/day, so that the reduction of the pollution load was 152,468.01 kg/day (82%).

The results of the BOD parameter model with pollutant loads from point sources and non-point sources in segment 1 of the Citarum River are stated by the RMSE test as 0.001. From the point sources, the highest pollution load came from tributaries that enter the upstream segment of the Citarum River. The highest target of reduction came from non-point sources. This shows that management of pollution from non-point sources needs to be prioritized.

Table 2 Pollution load reduction in the upper citarum watershed.

No	Pollution Sources	Existing BOD Pollution Load (kg/day)	BOD Pollution Load TMDL (kg/day)	Target of Pollution Load Reduction (%)
1	Point sources	27 806.98	11 457.43	58.80
a	Industries	295.49	137 .95	53.31
b	Tributaries	27 511.49	11 319.48	58.86
2	Non-point sources	159 240.91	23 122.58	85.48
	TOTAL	187 047.89	34 580.02	81.51

The upper Citarum River is influenced by several tributaries, including Cirasea, Citarik, Cikeruh, Cikapundung, Cisangkuy, and Ciwidey. The highest pollution load of the Citarum River tributaries comes from the Cikapundung River (6609.86 kg/day), followed by the Cipalasari River (5388.77 kg/day) and Citarik River (4492.90 kg/day) (Table 3). However, based on the TMDL, the most important target of pollution reduction is the Cipalasari River (98%), followed by the Cikeruh River (88%) and Cikapundung River (80%).

Table 3 Target of pollution load reduction in Citarum tributaries.

Pollution source	Flow rate (m^3/s)	Existing BOD pollution load (kg/day)	BOD pollution load TMDL (kg/day)	Target of pollution load reduction (%)
Cirasea	2.42	3398.98	717.98	79
Citarik	6.50	4492.90	1684.80	62
Cikeruh	1.15	2484.00	298.08	88
Cipalasari	0.33	5388.77	85.54	98
Cikapundung	5.10	6609.60	1321.92	80
Cisangkuy	6.23	3229.63	1614.82	50
Ciwidey	2.76	1907.71	715.39	62
TOTAL		**27 511.49**	**6438.53**	**77**

The pollution load in each tributary is contributed by all pollutant sources, including non-point sources. The value of the pollution load in each tributary indicates that improving the water quality of the tributaries would also improve the water quality of the Citarum River. However, it is difficult to determine the target of pollution load reduction of each pollutant source in each tributary due to a lack of data. Therefore, it was calculated using the potential load of the pollutants, and overlaid with spatial data (Tables 4 and 5).

Based on the TMDL and the potential BOD pollution load in each tributary, the existing pollution load for each source of pollutants can be seen in Table 4. The highest contributions were from domestic sources at 158,016.38 kg/day (83.5%) and from industrial sources at 12,296.75 kg/day (6.6 %).

Compared with other tributaries, the Cikapundung River had the highest existing pollution load of all sources, i.e. 66,732.22 kg/day, followed by Cipalasari (24,243.62 kg/day) and Citarik (23,779.84 kg/day). This result is reasonable because along those rivers there are highly populated residential areas and also textile industries.

This is in agreement with Komarudin *et al.* [32] who state that water quality should be improved by improving the water quality of tributaries and by focusing on domestic waste, as described in Belinawati *et al.* [3], Lestari *et al.* [24], and Munfarida *et al.* [35].

Table 4 Existing BOD pollution load allocation in tributaries.

Tributary	City/ Regency	Pollution Load of BOD (kg/day)						TOTAL (kg/day)
		Domestic	Animal husbandry	Fishery	Land & forest	Agriculture	Industry	
Cirasea	Bandung	16 955.89	1673.85	716.72	565.97	1046.05	1853.24	22 811.73
Citarik	Bandung	15 168.64	634.08	149.34	497.15	725.30	1089.82	18 264.34
	Sumedang	2730.55	151.78	73.12	116.25	99.78	2344.01	5515.50
Cikeruh	Sumedang	3540.00	226.06	84.24	240.03	78.52	-	4168.85
	Bandung	4501.76	444.89	17.74	237.04	174.80	-	5376.23
	Bandung City	9208.31	234.20	-	314.05	87.02	-	9843.58
Cikapundung	Bandung City	50 237.21	471.74	-	955.29	37.11	3307.12	55 008.46
	Bandung	10 218.18	981.80	13.86	225.12	182.70	102.11	11 723.76
Cisangkuy	Bandung	13 646.78	1032.96	132.21	550.62	788,92	2354.55	18 506.04
Cipalasari	Cimahi	10.558,19	158.10	71.29	243.60	14.58	1245.90	12 291.65
	Bandung City	7370.77	126.09	-	140.16	4.50	-	7641.52
	Bandung	4144.03	16.84	1.98	83.71	63.90	-	4310.45
Ciwidey	Bandung	9736.10	488.82	80.39	502.32	778.16	-	11 585.79
TOTAL		158 016.38	6641.21	1340.89	4671.31	4081.35	12 296.75	187 047.89

Table 5 BOD pollution load based on total maximum daily load.

Tributary	City/ Regency	BOD Pollution Load (kg/day)						TOTAL (kg/day)
		Domestic	Animal Husbandry	Fishery	Land & Forest	Agriculture	Industry	
Cirasea	Bandung Regency	3093.41	305.38	130.76	103.25	190.84	338.10	4161.75
Citarik	Bandung Regency	3667.14	153.29	36.11	120.19	175.35	263.47	4415.56
	Sumedang Regency	660.13	36.70	17.68	28.11	24.12	566.68	1333.42
Cikeruh	Sumedang Regency	543.41	34.70	12.93	36.85	12.05	-	639.42
	Bandung Regency	691.05	68.29	2.72	36.39	26.83	-	825.28
	Bandung City	1413.53	35.95	-	48.21	13.36	-	1511.05
Cikapundung	Bandung City	7837.39	73.59	-	149.03	5.79	515.94	8581.74
	Bandung Regency	1594.12	153.17	2.16	35.12	28.50	15.93	1829.00
Cisangkuy	Bandung Regency	3719.66	281 .55	36.04	150.08	215.03	641.77	5044.14
Cipalasari	Cimahi City	1533.10	22.96	10.35	35.37	2.12	180.91	1784.81
	Bandung City	1060.27	-	-	-	-	-	1109.59
	Bandung Regency	601.73	2.44	0.29	12.16	9.28	-	625.90
Ciwidey	Bandung Regency	2283.10	114.63	18.85	117.79	182.48	-	2716.86
TOTAL		28 698.06	1282.66	267.88	872.55	885.76	2522.81	34 578.52

To improve water quality and meet the TMDL, these tributaries have to reduce their pollution load from 187,047.89 kg/day to 34,578.52 kg/day. The]most important pollution load reduction target is the Cikapundung River, which must reduce its pollutant load by 56,321.48 kg/day (84.40%), from 66,732.22 kg/day to 10,410.74 kg/day. This is followed by the Cipalasari River, which must reduce its pollutant load by 20,723.32 kg/day (85.48%), from 24,243.62 kg/day to 3520.3

kg/day. Meanwhile, for the pollutant sources the highest targets of pollution reduction are residential, i.e. from 15,267.31 kg/day to 28 382.43 kg/day (81.84%), and industrial, i.e. from 12,296.75 kg/day to 2,522.81 kg/day (79.48%) (Table 5).

The results can also be used as a basis for local governments to develop pollution control programs based on the highest contribution of tributaries and pollutant sources. Table 6 shows that Bandung Regency, where all tributaries flow through, has the highest pollution load, and so the local government must reduce the pollution load by 78.81%, focusing on domestic and industrial pollution sources. The local government of Cimahi city has the most important target of reduction of pollution load, i.e. 85.48%. This is because the Cipalasari River has the lowest flow rate compared to the other tributaries (0.33 m^3/s).

Programs should focus on domestic and industrial sources in the Cirasea and Citarik Rivers. Bandung city's local government must reduce the pollutant load by 84.55% and focus on the highest pollution load from domestic waste in the Cikapundung River and the Cikeruh River. Sumedang Regency's local government must reduce the pollutant load by 79.63%, and should focus on domestic and industrial waste in the Citarik River and on domestic waste in the Cikeruh River. The majority of local governments have to focus on domestic and industrial waste. This is in line with the data indicating that the upper Citarum River area has a high population density and many textile industries.

Table 6 Target of pollution load reduction in city/regency.

City/Regency	BOD Pollution Load		Target of Pollution Load Reduction (%)
	Existing (kg/day)	TMDL (kg/day)	
Bandung Regency	92 578.34	19 618.49	78.81
Bandung City	72 493.56	11 202.38	84.55
Cimahi City	12 291.65	1784.81	85.48
Sumedang Regency	9684.35	1972.84	79.63
Total	**187 047.89**	**34 578.52**	

Figure 3 shows the ratio of the existing BOD pollution load compared with the pollution load in terms of TMDL. A high ratio (6-7) was found in Cikapundung River, Cipalasari River, and Cikeruh River, which shows that those rivers are already highly polluted, while the lowest ratio was found in Cisangkuy (3-4), where the pollution is relatively low.

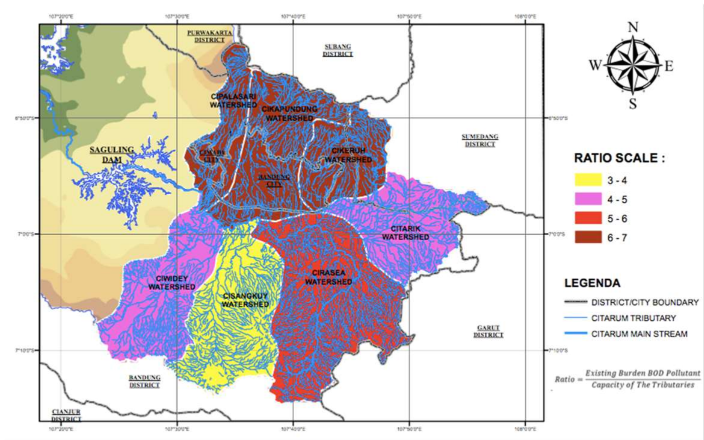

Figure 3 Ratio of existing BOD pollution load and TMDL.

Pollution load allocation can be used as a basis for wastewater discharge permits. Table 7 shows the contribution of the BOD pollution load (discharge wastewater) from 12 companies along the Citarum River. The wastewater quality of these companies has to meet BOD concentrations based on Ministerial Regulation No. 16 Year 2019, where companies with a wastewater discharge < 100 m^3/day have a wastewater quality standard of 60 mg/L, and companies with a wastewater discharge of 100 to 1000 m^3/day have a wastewater quality standard of 45 mg/L.

Table 7 Target of pollution load reduction in industry.

Industry	Waste-water discharge (m^3/day)	BOD Existing		BOD based on TMDL		Target of pollution load reduction (kg/day)
		Concen-tration (mg/l)	Pollution load (kg/day)	Concen-tration (mg/l)	Pollution load (kg/day)	
PT. UBK	319.68	58.00	18.54	45.00	14.39	4.15
PT. ST	457.92	22.15	10.14	45.00	20.61	
PT. DS	460.29	307.00	110.61	45.00	16.21	94.40
PT. PM	199.58	42.00	8.38	45.00	8.98	
PT. BCP	129.60	40.00	5.16	45.00	5.83	
PT. NM	265.25	55.00	14.59	45.00	11.94	2.65
PT. SDT	150.34	66.69	10.03	45.00	6.77	3.26
PT. AM	599.62	172.00	103.13	45.00	26.98	76.15
CV. DM	4.32	381.00	1.65	60.00	0.26	1.39
PT. MAS	199.58	10.73	2.14	45.00	8.98	
PT. PN	224.64	49.00	11.01	45.00	10.11	0.9
PT. FJ	1.73	49.00	0.08	60.00	0.10	
			295.49		**131.16**	

Based on the data in Table 7, it can be seen that seven industries have to reduce their pollution load: PT. UBK (4.15 kg/day), PT. DS (94.40 kg/day), PT. NM (2.65 kg/day), PT. SDT (3.26 kg/day), PT. AM. (76.15 kg/day), CV.DM (1.39 kg/day), and PT. PN (0.9 kg/day). The results of this study can be used as a basis for determining the wastewater discharge limits for each industry that can be tolerated by the river.

4 Conclusion

The upper Citarum river watershed is heavily polluted, with the highest proportion of pollutants coming from non-point sources (85%), while that from point sources is 15%. Point sources consist of industries and tributaries, with the highest pollutant contributors being tributaries. Based on the potential pollution load, the highest contribution to the total pollution load comes from domestic waste (83.5%), followed by industrial waste (6.6%). The target of pollution load reduction for domestic sources is 81.8% and 79.5% for industries. The target pollution load reductions for tributaries are Cikapundung River (84.40%), Cipalasari River (85.48%), Citarik River (75.82%), and Cikeruh River (84.65%). The results show that to improve the Citarum River, local governments should start by improving the water quality of it tributaries.

The result of the measurement of pollution load allocation can also be used as a basis for determining wastewater discharge permits for industrial pollutant sources. To achieve a BOD pollution load based on the TMDL, local governments should set the wastewater quality standard and pollution load allocation of each industry in their wastewater discharge permit. In this study, PT. UBK, PT. DS, PT. NM, PT. SDT, PT. AM, CV.DM, and PT. PN have to reduce their pollution load 4.15 kg/day, 94.40 kg/day, 2.65 kg/day, 3.26 kg/day, 76.15 kg/day, 1.39 kg/day, and 0.9 kg/day respectively.

To improve the water quality of the Citarum River, local governments can develop a water pollution control program by measuring pollution load allocations based on TMDL. In this study, all local governments have to reduce pollution loads by approximately 78 to 85%, and most of them need to focus on domestic and industrial waste. These load allocations can be used as a basis to develop a pollution control program for the Citarum River. To cope with the pollution from domestic sources, the local governments have to develop communal wastewater treatment plants, while in order to handle the pollution from industrial sources they can apply strict law enforcement (all industries have to have a wastewater treatment plant and have to comply with the requirements in their permits) or apply other approaches such as permit trading.

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