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Integrated STORET–System Dynamics Approach for Pollution Control and Assimilation Capacity Management in a Small Urban Lake: A Case Study of Situ Tlajung Hilir, Bogor Regency, Indonesia

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ABSTRACT

Small urban lakes are increasingly threatened by domestic and industrial wastewater inputs that exceed their natural assimilation capacity. This study aimed to evaluate the water quality status and develop a dynamic pollution control model for Situ Tlajung Hilir, Bogor Regency, Indonesia. Water quality was assessed using the STORET method as regulated by Government Regulation No. 22/2021 standards, while pollution dynamics were simulated using a system dynamics model that involves population growth, domestic load, industrial load, and assimilation capacity sub-models. Historical monitoring data (2019–2023) were used for calibration and behavioral validation through trend comparison. The lake was classified as heavily polluted, with BOD, Total Nitrogen, and Total Phosphate exceeding permissible limits and surpassing assimilation capacity. Simulation of management scenarios (2020–2035) showed that business-as-usual conditions lead to continuous degradation, whereas integrated domestic and industrial wastewater treatment can reduce pollutant loads by 60–80% and gradually will approach ecological balance. The proposed integrated STORET system dynamics framework provides a practical decision-support tool for sustainable lake restoration and urban water resource management.

Keywords: *Assimilation capacity, STORET, system dynamics, urban lake management, water pollution control*

INTRODUCTION

Water quality reflects the physical, chemical, and biological characteristics of water that determine its suitability for various uses (Diersing, 2009; Effendi, 2003, Rachmawati et al., 2024). Environmental pollution is a serious issue in Bogor Regency, particularly in small lake ecosystems (locally known as situ). These lakes play a vital ecological role as natural water reservoirs, flood regulators, groundwater recharge areas, and habitats for aquatic organisms, while also providing economic, educational, and aesthetic value. However, the increasing population and industrial activities around these lakes have degraded their ecological functions.

Bogor Regency covers approximately 2,986 km² and comprises 40 districts with 435 villages, accommodating a population of 5.49 million (BPS Kabupaten Bogor, 2022) — the highest in West Java, representing 11.25% of the provincial population. This rapid population growth increases land use pressure, demand for clean water, and reduction of open green spaces, leading to environmental degradation, including lake pollution. According to the Department of Public Works and Spatial Planning (DPUPR, 2021), only 44 out of 95 lakes (46%) remain in good condition, while the rest suffer moderate to severe damage due to sedimentation, land-use conversion, and wastewater inflow from domestic and industrial sources.

In the eastern region of Bogor Regency, the water quality of several lakes, including Situ Cicadas and Situ Tlajung Hilir, has significantly deteriorated. Reports from the Environmental Agency (DLH, 2017) documented repeated pollution incidents involving fish mortality, foul odors, and skin irritation among residents using lake water. These recurring events, recorded in 2014, 2016, and 2017, indicate chronic and persistent pollution problems.

Situ Tlajung Hilir, located in Wanaherang Village, Gunung Putri District, faces one of the most severe pollution pressures. The lake serves as a water source for irrigation, fisheries, and domestic use, but the presence of more than 20 surrounding industries has contributed to declining water quality. Untreated industrial effluents discharge into the lake, resulting in blackened, foamy, and foul-smelling water, as well as massive fish deaths. The rapid growth of aquatic weeds also indicates eutrophication caused by excessive nutrient loading, particularly nitrogen and phosphate.

Previous studies confirm the deteriorating condition of lakes in Bogor Regency. Aristawidya et al. (2019) reported that the pollution status of Situ Gunung Putri ranged from lightly to moderately polluted based on the STORET and Pollution Index methods, while Tusminarti (2019) identified domestic and industrial effluents as the primary pollution sources in Situ Tlajung

Hilir and classified its water quality as Class IV (moderately polluted). The condition of water pollution is worsened by the absence of an integrated drainage and wastewater management system, low community awareness, and weak enforcement of environmental regulations.

Ecologically, Situ Tlajung Hilir plays a crucial role in maintaining the hydrological balance of the surrounding area. Socioeconomically, it supports local livelihoods through fisheries, irrigation, and household water use. Continued pollution threatens not only environmental quality but also public health and economic well-being. Therefore, integrated and sustainable management of the lake ecosystem is essential, balancing ecological, social, and economic aspects.

Current lake management efforts in Bogor Regency remain fragmented and sectoral, making them ineffective in addressing long-term pollution issues. The complex interactions among stakeholders—including communities, industries, and government institutions—require a systemic and integrative approach to identify key pollution drivers and formulate effective control strategies. Complex environmental systems are best analyzed using a systems approach due to feedback interactions among variables (Eriyatno, 1999; Dewata & Iswandi, 2017).

A system dynamics approach offers a powerful analytical framework to simulate relationships among variables in complex environmental systems. Through dynamic modeling, alternative management scenarios can be tested to determine optimal and sustainable pollution control strategies. Sustainable lake management requires integration of ecological, social, and institutional aspects (Hasim, 2017; Syafei, 2018; Yuswandi et al., 2024).

This study aims to analyze the water quality status, estimate pollution loads, and develop a dynamic system model for sustainable water pollution control in Situ Tlajung Hilir, Bogor Regency. The results are expected to contribute both scientifically and practically to local government and stakeholders in preserving the ecological function of the lake as part of the region's vital environmental assets. Unlike previous studies that focused solely on pollution status assessment (Babagana-Kyari et al., 2024; Rachmawati et al., 2024; Setiawati et al., 2025), this research integrates STORET-based water quality evaluation with dynamic assimilation capacity modeling to develop adaptive pollution control scenarios specifically for small urban lakes. This integration allows the estimation of realistic management interventions based on the carrying capacity of the water body rather than static regulatory compliance.

METHODS

Research Location

The study was conducted in Situ Tlajung Hilir, located in Wanaherang Village, Gunung Putri District, Bogor Regency, West Java, Indonesia, geographically positioned at 106°56'06.6" E and 06°24'51.4" S (Figure 1). Sampling was carried out at three representative points: inlet, middle, and outlet of the lake, each reflecting different flow and pollution characteristics.

Figure 1. The research location in a small lake of Situ Tlajung Hilir, Bogor Regency, West Java, Indonesia.

The research was carried out in between May 2023 and January 2024 and consisted of three main stages: (1) Planning, including the design of the study, determination of methods, and collection of secondary data; (2) Fieldwork and laboratory testing, involving water sampling on December 28, 2023, and laboratory analysis completed on January 12, 2024; and (3) Data analysis and system modeling, carried out after all laboratory results were obtained.

Tools and Materials

Field equipment included sampling bottles, portable pH and DO meters, thermometer, GPS, and digital camera for documentation. Laboratory instruments comprised a Spectrophotometer, Atomic Absorption Spectrophotometer (AAS), BOD incubator, COD reactor, analytical balance, oven, and other standard glassware. For modeling, Powersim Studio 10 Academic (Version 10.13.5538.6, 64-bit, Release 5) was used for system dynamics simulation and data analysis.

Data Collection

Data collection was divided into primary and secondary data. Primary data were obtained from field measurements and laboratory analyses following SNI

6989.57:2008 (Surface Water Sampling Method) and SNI 8995:2021 (Water Sampling Method for Physical and Chemical Testing). Sampling was performed at three points (inlet, middle, outlet) using composite samples to represent the lake's overall condition.

Laboratory analyses were conducted at PT Adhikarilab Indonesia, an accredited environmental laboratory (KAN No. LP-720-IDN) recognized by the Ministry of Environment and Forestry (MoEF). Tested parameters included pH, temperature, DO, BOD, COD, Total Nitrogen (TN), and Total Phosphate (TP).

Secondary data were collected from the Bogor Regency Environmental Agency (DLH) and other relevant institutions, as well as from previous studies and literature. These included historical water quality data (2019–2023) and information on pollution sources and land use.

Research Design and Analysis Procedure

Sampling followed the national standards (SNI 6989.57:2008 and SNI 8995:2021) and adhered to ISO/IEC 17025:2017 laboratory requirements. Collected water samples were stored in pre-cleaned containers, labeled, and transported under cold conditions to prevent degradation. Analyses were performed for physical, chemical, and biological parameters. Water quality results were compared to the Indonesian Government Regulation (PP) No. 22 of 2021, Annex VI, Table 2, which specifies the quality criteria for lake and reservoir waters. The STORET method was used to assess pollution status based on deviations from standard limits.

Data Analysis

Data were analyzed descriptively and quantitatively. The STORET method determined the pollution index by assigning weighted scores to parameters exceeding the standard limits. The scores classified the lake's status into unpolluted, lightly polluted, moderately polluted, or heavily polluted. For predictive analysis, a system dynamics model was developed using Powersim Studio 10 Academic.

The model comprised four sub-systems such as: (1) Population growth; (2) Residential pollution load; (3) Total pollution load; and (4) Pollutant assimilation capacity. The simulation covered the period 2020–2035, evaluating various policy and management scenarios for sustainable pollution control.

RESULTS AND DISCUSSION

Water Quality Condition of Situ Tlajung Hilir

The results of physical, chemical, and microbiological analyses of water samples from Situ Tlajung Hilir are presented in Table 1. Measurements were taken at three locations: inlet, middle, and outlet of the lake. The data are compared with the Indonesian water quality standards for Classes I–IV (Government of Indonesia, 2021).

Table 1. Water quality characteristics of Situ Tlajung Hilir compared with Class II standards.

No	Parameter	Unit	Inlet	Middle	Outlet	Class II Standard	Evaluation
			Physical Parameters				
1	Temperature	°C	25.7	25.7	25.7	±3°C deviation	Within limit
2	TDS	mg/L	217	212	221	1000	Within limit
3	TSS	mg/L	8	14	54	50	Slightly exceeds
4	Colour	Pt-Co	7	6.4	6.7	50	Within limit
			Chemical Parameters				
1	pH	-	7.68	7.84	7.81	6.0-9.0	Within limit
2	DO	mg/L	4.8	7.1	5.4	≥ 4	Slight fluctuation
3	BOD	mg/L	5.8	10	18	3	Exceeds limit
4	COD	mg/L	21.5	34.9	61.1	25	Exceeds limit
5	Total Nitrogen	mg/L	3.2	3.5	3.6	0.75	Exceeds limit
6	Total Phospate	mg/L	3.4	0.21	0.88	0.03	Exceeds limit
7	Phenol	mg/L	0.055	0.063	0.05	0.005	Exceeds limit
			Micro-biological Parameters				
1	Faecal Coliform	MPN/100 mL	0	17	79	1000	Within limit
2	Total Coliform	MPN/100 mL	47	797	599	5000	Within limit

Source: Government of Indonesia, 2021.

Interpretation of Water Quality Status

The results show that BOD, COD, Total Nitrogen, Total Phosphate, and Phenol concentrations exceeded Class II water quality standards, indicating organic and nutrient enrichment as the dominant pollution types. Elevated BOD and COD levels suggest a high concentration of biodegradable and non-biodegradable organic materials originating from domestic wastewater and industrial effluents.

The high Total Nitrogen (3.6 mg/L) and Phosphate (0.88 mg/L) levels reflect nutrient loading that can trigger eutrophication, evidenced by the abundant growth of aquatic weeds observed during field surveys. The DO concentration (ranging from 4.8–7.1 mg/L) fluctuates spatially; lower values at the outlet indicate oxygen depletion due to organic decomposition.

Physically, water temperature and color remained within acceptable limits, while TSS levels slightly exceeded the threshold at the outlet, possibly due to sediment resuspension and inflow carrying solid waste.

Pollution Classification Using STORET Method

The STORET method is widely used to evaluate water pollution status in tropical aquatic ecosystems (Kadim et al., 2017). The water quality status of Situ Tlajung Hilir was assessed using the STORET method, referring to the Decree of the State Minister for the Environment No. 115 of 2003 on Water Quality Status Determination Guidelines. The STORET index was calculated by assigning weighted scores to parameters exceeding water quality standards using the following general equation:

STORET score = Σ (weight × deviation from standard)

Classification criteria were applied as follows:
score 0 = good condition;
score -1 to -10 = lightly polluted;
score -11 to -30 = moderately polluted;
score < -31 = heavily polluted.

The assessment was conducted for Classes II, III, and IV based on cumulative scores calculated from deviations of measured parameters from the standard limits. As shown in Table 2, the cumulative STORET score indicates a heavily polluted condition.

Table 2. Water quality status of Situ Tlajung Hilir based on the STORET method (2018–2023).

No	Class	STORET Score			Status		
		2018	2019	2023	2018	2019	2023
1	Class II	-44	-126	-24	Heavily Polluted	Heavily Polluted	Heavily Polluted
2	Class III	-26	-106	-100	Moderately Polluted	Heavily Polluted	Heavily Polluted
3	Class IV	-2	-24	-28	Slightly Polluted	Moderately Polluted	Moderately Polluted

Source: Decree of the State Minister for the Environment No. 115 of 2003.

Pollution Sources

The dominant sources of pollution in Situ Tlajung Hilir are domestic wastewater and industrial effluents from surrounding residential and manufacturing areas. More than 20 industries are located within the watershed, including chemical, food processing, and textile sectors, which potentially discharge untreated wastewater into drainage channels leading to the lake.

The presence of high nutrient and organic concentrations accelerates eutrophication, reduces water clarity, and disrupts the aquatic ecosystem. Similar eutrophication patterns have been reported in tropical urban lakes where domestic wastewater dominates nutrient loading and exceeds natural assimilation capacity (Kadim et al., 2017; Paitaha, 2020). These findings support that population-driven nutrient enrichment is a primary driver of lake degradation in rapidly urbanizing regions.

Similar modeling approaches have been applied in environmental management and watershed planning (Johnson et al., 1997; Kusuma & Djamaluddin, 2020; Suryanta, 2016).

Constructed wetland treatment can also significantly reduce nutrient concentrations in small lakes (Puspita et al., 2005).

Implications for Lake Pollution Management

The observed pollution trend highlights the urgent need for integrated pollution control strategies. Priority actions include as follows: (1) Establishing domestic wastewater treatment facilities for nearby settlements; (2) Enforcing stricter industrial effluent standards; (3) Implementing aquatic plant management to control eutrophication; and (4) Promoting community-based environmental awareness programs.

Applying a system dynamics model enables stakeholders to evaluate policy scenarios and simulate long-term pollution control outcomes. The model results support that interventions combining industrial treatment and domestic wastewater management could reduce BOD and nutrient loads by up to 60–80% by 2035.

Dynamic System Modeling for Pollution Control

Model development

A system dynamics approach was used to model the interaction between population growth, domestic and industrial wastewater generation, pollutant load, and lake assimilation capacity. The model was developed using Powersim Studio 10 Academic and consists of four main sub-models:

1. Population Growth Submodel – simulates the increase in residents around the watershed and its effect on wastewater generation.
2. Domestic Waste Load Submodel – quantifies the organic and nutrient pollutants from household activities.
3. Industrial Waste Load Submodel – estimates effluent contributions from nearby industries.
4. Assimilation Capacity Submodel – represents the natural purification ability of the lake through sedimentation, dilution, and biological processes.

The relationships among these submodels are illustrated in Figure 2, presented in the form of a causal loop diagram (CLD).

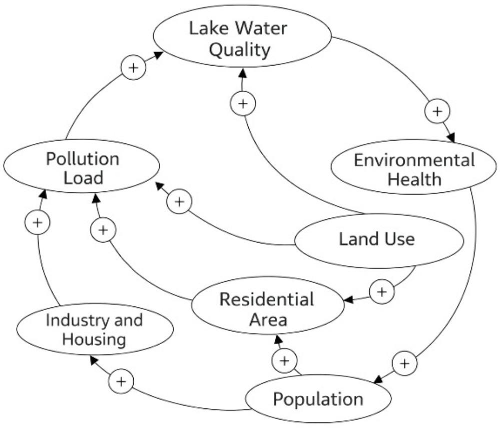

Figure 2. Causal Loop Diagram of the Dynamic System Model for Water Pollution in Situ Tlajung Hilir.

The CLD describes how population growth and industrial activity increase wastewater loads, leading to higher pollution levels and lower water quality. Reduced water quality, in turn, affects community well-being and triggers management interventions, creating balancing and reinforcing feedback loops.

Model validation

Model validation was conducted using behavioral validation by comparing simulated trends with historical monitoring data from 2019–2023. The simulated patterns of BOD, Total Nitrogen, and Total Phosphate showed consistent dynamic behavior with observed trends, particularly in the increasing pollution tendency caused by population growth and wastewater discharge.

The model is therefore considered structurally and behaviorally valid and suitable for policy scenario analysis rather than numerical prediction.

Stock and flow representation

To quantitatively simulate the system, a stock and flow diagram was constructed as shown in Figure 3.

This structure allows tracking of pollutant accumulation (stock) and inflow–outflow rates (flows), enabling scenario testing and sensitivity analysis.

Key equations (conceptual form)

Pollutant Load = Population × Emission Factor
Lake Concentration = (Total Load − Removal) / Lake Volume

$\text{Pollution Load}\,(t) = \int (L_{d,domestic} + L_{i,industrial} - R_{out,assimilation})\, dt$

where:
Ld = domestic wastewater load (kg/day)
Li = industrial wastewater load (kg/day)
R = pollutant removal rate through natural processes (kg/day)

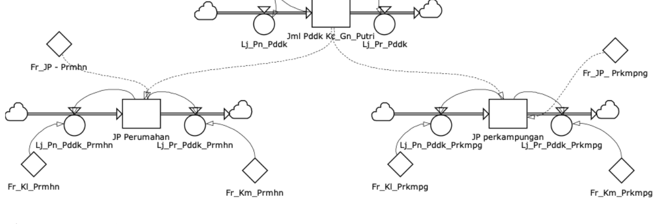

Figure 3. Stock and flow diagram of the dynamic system model for water pollution control in Situ Tlajung Hilir.

The stock and flow diagram shown in Figure 3 illustrates the overall structure of the dynamic system model developed using *Powersim Studio 10 Academic*. This model represents the interactions between pollutant generation, transport, and natural assimilation processes within the Situ Tlajung Hilir lake ecosystem.

Simulation and Scenario Analysis

Simulation was conducted for the period 2020–2035, testing three scenarios:

1. Scenario 1 (Business as Usual) – no new intervention; pollution continues at current rate.
2. Scenario 2 (Domestic Control) – 50% reduction in domestic waste load.
3. Scenario 3 (Integrated Control) – domestic and industrial wastewater treated according to Class II standards.

Tables 3–5 present the simulated BOD, Total Nitrogen, and Total Phosphate loads under the three scenarios.

Table 3. Simulated BOD load reduction scenarios (2020–2035).

Year	Reduction Intervention 10%	Reduction Intervention 20%	Reduction Intervention 40%	Reduction Intervention 60%	Reduction Intervention 80%
2020	-34.84	-26.85	-10.86	5.12	21.11
2021	-35.97	-27.98	-11.99	3.99	19.98
2022	-37.1	-29.11	-13.12	2.86	18.85
2023	-38.23	-30.24	-14.25	1.73	17.72
2024	-39.36	-31.37	-15.38	0.6	16.59
2025	-40-49	-32.5	-16.51	-0.53	15.46
2026	-41.62	-33.63	-17.64	-1.66	14.33
2027	-42.75	-34.76	-18.77	-2.79	13.2
2028	-43.88	-35.89	-19.9	-3.92	12.07
2029	-45.01	-37.02	-21.03	-5.05	10.94
2030	-46.14	-38.15	-22.16	-6.18	9.81
2031	-47.27	-39.28	-23.29	-7.31	8.68
2032	-48.4	-40.41	-24.42	-8.44	7.55
2033	-49.53	-41.54	-25.55	-9.57	6.42
2034	-50.66	-42.67	-26.68	-10.7	5.29
2035	-51.79	-43.8	-27.81	-11.83	4.16

Table 4. Simulated Total Nitrogen (TN) load reduction scenarios (2020–2035).

Year	Reduction Intervention 10%	Reduction Intervention 20%	Reduction Intervention 40%	Reduction Intervention 60%	Reduction Intervention 80%
2020	18.47	-77.48	-48.84	-20.2	18.47
2021	17.34	-78.61	-49.97	-21.33	17.34
2022	16.21	-79.74	-51.1	-22.46	16.21
2023	15.08	-80.87	-52.23	-23.59	15.08
2024	13.95	-82	-53.36	-24.72	13.95
2025	12.82	-83.13	-54.49	-25.85	12.82
2026	11.69	-84.26	-55.62	-26.98	11.69
2027	10.56	-85.39	-56.75	-28.11	10.56
2028	9.43	-86.52	-57.88	-29.24	9.43
2029	8.3	-87.65	-59.01	-30.37	8.3
2030	7.17	-88.78	-60.14	-31.5	7.17
2031	6.04	-89.91	-61.27	-32.63	6.04
2032	4.91	-91.04	-62.4	-33.76	4.91
2033	3.78	-92.17	-63.53	-34.89	3.78
2034	2.65	-93.3	-64.66	-36.02	2.65
2035	1.52	-94.43	65.79	-37.15	1.52

Table 5. Simulated Total Phosphate (TP) load reduction scenarios (2020–2035).

Year	R+D54eduction Intervention 10%	Reduction Intervention 20%	Reduction Intervention 40%	Reduction Intervention 60%	Reduction Intervention 80%
2020	-32.41	-24.68	-9.24	6.2	21.65
2021	-33.54	-25.81	-10.37	5.07	20.52
2022	-34.67	-26.94	-11.5	3.94	19.39
2023	-35.8	-28.07	-12.63	2.81	18.26
2024	-36.93	-29.2	-13.76	1.68	17.13
2025	-38.06	-30.33	-14.89	0.55	16
2026	-39.19	-31.46	-16.02	-0.58	14.87
2027	-40.32	-32.59	-17.15	-1.71	13.74
2028	-41.45	-33.72	-18.28	-2.84	12.61
2029	-42.58	-34.85	-19.41	-3.97	11.48
2030	-43.71	-35.98	-20.54	-5.1	10.35
2031	-44.84	-37.11	-21.67	-6.23	9.22
2032	-45.97	-38.24	-22.8	-7.36	8.09
2033	-47.1	-39.37	-23.93	-8.49	6.96
2034	-48.23	-40.5	-25.06	-9.62	5.83
2035	-49.36	-41.63	-26.19	-10.75	4.7

Therefore, the 60–80% reduction scenario can be considered the most realistic policy recommendation for sustainable water quality.

Simulation Results

Simulation analysis for the period 2020–2035 was carried out to evaluate the effectiveness of various pollution control strategies at Situ Tlajung Hilir. Three main scenarios were tested to represent different levels of intervention:

1. Scenario 1 (Business as Usual): No new intervention implemented, and pollution continues at the current growth rate of population and domestic waste generation.
2. Scenario 2 (Domestic Control): Implementation of household waste management with an estimated 50% reduction in domestic pollutant load through the improvement of septic tank systems and community-based wastewater treatment.
3. Scenario 3 (Integrated Control): A comprehensive approach combining domestic and industrial wastewater treatment according to Class II water quality standards (Government of Indonesia, 2021).

The simulation results indicate that water pollution control in Situ Tlajung Hilir is most effective under combined intervention scenarios, specifically when the rate of population growth and pollutant concentrations (BOD, Total Nitrogen, and Total Phosphate) are reduced by 60–80%. This integrated scenario shows a consistent downward trend in pollutant load throughout the simulation period, approaching the lake's natural assimilation capacity by 2035.

In contrast, the *business as usual* scenario exhibits a continuous increase in pollutant load, which would further deteriorate water quality and intensify eutrophication risks. The domestic-only intervention yields moderate improvement but remains insufficient to restore water quality to Class III standards. The scenario also highlights the importance of population control measures, integrated wastewater infrastructure, and active community participation in maintaining the ecological balance of the lake ecosystem.

The reduction range of 60–80% represents achievable removal efficiency of combined communal wastewater treatment plants and industrial pre-treatment systems commonly reported in domestic wastewater management practices. Therefore, the selected intervention scenario represents a technically feasible environmental management policy rather than a theoretical reduction.

CONCLUSION

The results of this study indicate that Situ Tlajung Hilir is heavily polluted, particularly under Class II and III water quality classifications, based on the STORET analysis, referring to the Decree of the State Minister for the Environment No. 115 of 2003. The pollution level has worsened between 2018 and 2023, with STORET scores decreasing from -44 to -122 (classified as Class II), which indicates a persistent and chronic water quality degradation. The main pollutants identified include biochemical oxygen demand (BOD), chemical oxygen demand (COD), total nitrogen (TN), total phosphate (TP), and phenolic compounds, all of which exceed the limits set in water quality standards for Class II. These findings confirm that organic matter and nutrient enrichment from domestic and industrial wastewater discharges are the dominant contributors to water quality decline.

The system dynamics model demonstrates that integrated pollution control combining domestic wastewater treatment, industrial effluent management, and community-based lake restoration can significantly reduce BOD and nutrient loads by up to 60–80% by 2035. Hence, this approach provides a practical decision-support tool for local governments and stakeholders to plan effective, sustainable, and adaptive pollution control strategies for the long-term recovery of Situ Tlajung Hilir. Future studies should incorporate hydrodynamic processes and seasonal variability to improve model robustness.

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to contribute to the sustainable management of Situ Tlajung Hilir as an important freshwater ecosystem in Bogor Regency, West Java.

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