FORUM GEOGRAFI
ISSN: 0852-0682 | E-ISSN: 2460-3945

HTTPS://JOURNALS.UMS.AC.ID/INDEX.PHP/FG/

Research article

An Evaluation of Phosphorus Control Interventions through a Multi-Scenario Approach to Controlling Eutrophication in Lake Rawapening Indonesia

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Citation:
Rhosadi, I., Mardiatno, D., Setiawan, M. A., Hayat D. M, (2025). An Evaluation of Phosphorus Control Interventions through a Multi-Scenario Approach to Controlling Eutrophication in Lake Rawapening Forum Geografi. 40(2), 213-227.

Article history:
Received: 23 February 2025
Revised: 7 May 2026
Accepted: 20 May 2026
Published: 25 May 2026

Abstract

Eutrophication triggered by excessive nutrient loading has become a major driver of lake degradation in many parts of the world. Lake Rawapening is one of Indonesia's national priority lakes for environmental restoration and has experienced eutrophic conditions progressing toward a hypertrophic state due to high phosphorus loads (P-load) and total phosphorus concentrations (TP-C). Despite the implementation of lake rehabilitation programs, their effectiveness in improving trophic status has not been quantitatively evaluated, limiting stakeholders' understanding of the outcomes. This study evaluates the effectiveness of rehabilitation interventions in controlling the trophic state of Lake Rawapening using a calibrated SWAT hydrological model. Seven scenarios were developed by combining land use changes from seasonal agriculture to agroforestry; fertilizer management in paddy fields; and lake deepening. Model simulations compared TP-C responses across scenarios. The results indicate that conversion of seasonal agricultural land to agroforestry is the most effective intervention, reducing TP-C by 33% (from 0.029 mg/L to 0.020 mg/L) and improving the trophic state from eutrophic to mesotrophic. Conversely, fertilizer management scenarios, even when applied according to recommended dosages, consistently increased TP-C by 14%. Lake deepening scenarios also tended to elevate TP-C by 20.9% due to increased water volume of 90% and phosphorus residence time (P-RS) of 92.4%. The study provides a measurable and replicable approach for simulating spatial dynamics and trophic responses to lake rehabilitation interventions. The findings support the development of multi-scenario management strategies for Lake Rawapening and other lakes in Indonesia.

Keywords: Lake Rawapening; SWAT Tool; Phosphorus Control; Total-Phosphorus; Eutrophication; Trophic State.

1. Introduction

Eutrophication is a significant global environmental issue, affecting approximately 40% of lakes worldwide, driven by excessive nutrient loading, especially phosphorus (P) from both external and internal sources (Wang *et al.,* 2023; Wang *et al.,* 2020; Wu *et al.,* 2025). Lake Rawapening has hydrological and ecological functions that support the socio-economic sustainability of surrounding communities (Darsono *et al.,* 2018). However, it faces various ecological pressures and anthropogenic activities that trigger eutrophication (Pertiwi *et al.,* 2025; Sadewo *et al.,* 2022). In 2020, the lake reached a hypertrophic state, as indicated by a TP-C of 94 µg/L (Prasetyo *et al.,* 2024). Excessive nutrient inputs, particularly phosphorus (P) and household waste, are driving the process (Li & Shen, 2025; Nada *et al.,* 2023; Putra *et al.,* 2025). In response, Lake Rawapening has been targeted for restoration at both national and local levels under Presidential Regulation No. 60 of 2021 and the 2019–2022 Lake Rawapening Management Plan. These policies emphasize integrated restoration through catchment management and in-lake interventions to control eutrophication. Consequently, prioritizing these interconnected sectors is essential to achieve long-term nutrient reduction and sustainable management (Mardiatno *et al.,* 2023). Despite ongoing restoration efforts, assessing outcomes is challenging due to disjointed management and the lack of trophic state indicators (Hirji & Duda, 2025).

Moreover, most previous studies have focused solely on evaluating a single intervention, a single-scenario approach, including i) the conversion of agricultural land use into agroforestry; ii) fertilizer management in paddy fields, or iii) lake deepening (Quinlan *et al.,* 2021; Tay *et al.,* 2022; Tay, *et al.,* 2022). Perennial crops increase nutrient absorption and retention in watersheds, whereas variations in land cover and agricultural practices result in differing nutrient load responses into lakes (Good *et al.,* 2025; Pradoto *et al.,* 2024; Ramachandra *et al.,* 2025; Subedi *et al.,* 2025). The practice of fertilizing paddy fields contributes to nutrient loading in lakes (Jin *et al.,* 2023; Zhang *et al.,* 2025; Zhang *et al.,* 2025), yet remains essential for maintaining crop productivity (Yang *et al.,* 2026; Yang *et al.,* 2024). Additionally, deepening lakes through dredging is often considered a solution for improving lake conditions (Kato *et al.,* 2025; Xiang *et al.,* 2024; Yi *et al.,* 2026). However, compared to a single scenario, the application of multiple scenarios can reduce the failure rate of lake management by providing more relevant alternatives with reasonable trade-offs (Gunacti & Cetinkaya, 2025; Ruiz-Marín *et al.,* 2024).

To assess the performance of ecosystem intervention scenarios, it is necessary to apply spatial-based models that represent conceptual parameters that are difficult to measure in the real world (Luján *et al.,* 2025; Mai, 2023). However, environmental modeling must maintain simplicity to reduce overfitting, and model bias should be quantifiable (Lopez *et al.,* 2025). The Soil & Water Assessment Tool (SWAT) is a hydrological model that translates conceptual parameters into hydrologic response units (HRUs) to simulate hydrological processes and pollutant dynamics (Mirdarsoltany *et al.,* 2024; Murumkar *et al.,* 2025; Neitsch *et al.,* 2011). SWAT is beneficial in multi-scenario testing of lake rehabilitation taking place in catchment areas and/or within water bodies. Various studies have been conducted to support the eutrophication control program in Lake Rawapening (Hirji & Duda, 2025; Prasetyo *et al.,* 2024), but they have not explicitly demonstrated their effectiveness in reducing the lake's trophic status. This study provides a multi-scenario approach to evaluating phosphorus control interventions in the lake. This approach not only models current conditions, but also projects the effectiveness of various policy scenarios before they are implemented.

2. Methods

This research was conducted in the Lake Rawapening catchment area located in Semarang Regency and Salatiga City, Central Java Province, Indonesia (Figure 1). The area covers 17,307.2 ha, with the lake itself covering 2,313.1 ha, comprising 14 inlets and one outlet. The SWAT model was utilized within this study area to simulate both spatial dynamics and the resulting lake trophic states. Table 1 shows the data used in the SWAT model. The watershed delineation in the model was generated from a combination of the DEMNas downloaded from https://tanahair.indonesia.go.id/portal-web/unduh, sub-catchment boundaries, and the stream network. In addition, the HRUs were generated from a combination of land use, soil maps and slope data. The weather data, obtained from the NASA database, included daily data for the period 2000 to 2024. The SWAT model is a GIS-based hydrological model that can simulate the spatial dynamics of P loads in catchments and nutrient concentration in lake water bodies (Li *et al.,* 2025; Pyo *et al.,* 2025).

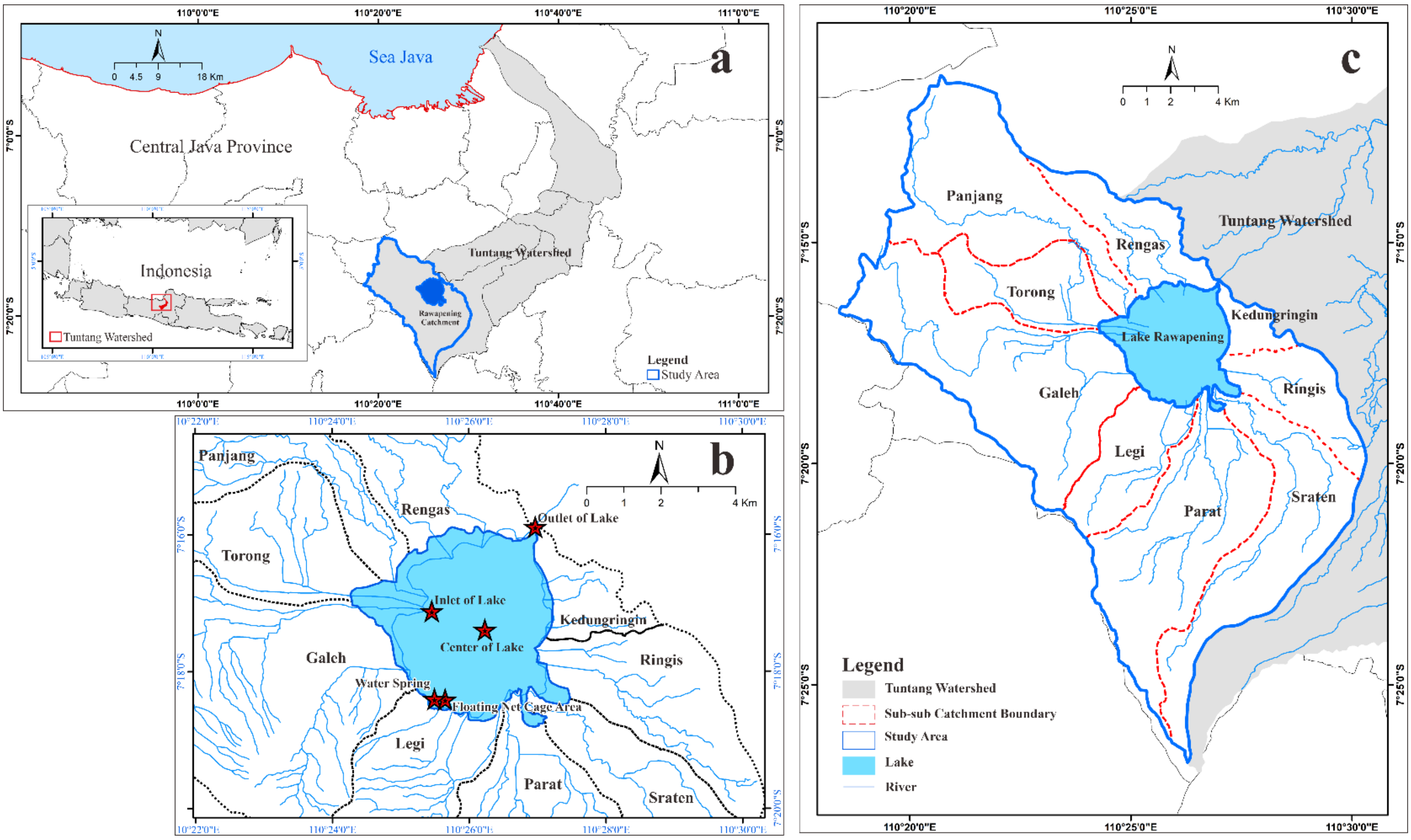

Figure 1. Lake Rawapening Catchment Area.

Table 1. SWAT Tool Data.

No	Data	Source
1	National DEM (DEMNas) Resolution 8 meter	Geospatial Information Agency https://tanahair.indonesia.go.id/portal-web/unduh
2	Stream Network	Geospatial Information Agency
3	Sub-catchment Boundary	Ministry of Environment and Forestry
4	Water Body Boundary	Ministry of Environment and Forestry
5	Modified Land Use 2024	Ministry of Environment and Forestry
6	Slope	Generated from DEMNas
7	Soil Map	Generated from Landform Map and BPDAS Pemali Jratun.
8	Lake Morfometry	Lake Rawapening Monitoring and Evaluation Document
9	Lake Water Quality	Agency of Environmental and Forestry, Central Java Province
10	Weather Data (Precipitation, Temperature, Relative Humidity, Solar Radiation, Wind Speed)	Downloaded from https://power.larc.nasa.gov/data-access-viewer/ – Nasa

Phosphorus (P) analysis requires the input of lake data into a .RES file and water quality data into a .LWQ file. The Agency of Environment and Forestry, Central Java Province (AoEF), is the operational-level authority responsible for collecting and analyzing water quality data in Lake Rawapening, collecting lake water samples every six months. The sampling follows the Indonesian National Standard (SNI 6989.57-2008), which outlines methods for collecting surface water samples. Meanwhile, the method for analyzing total phosphorus concentration (TP-C) follows SNI 06-6989.31-2005 using spectrophotometry. Figure 1b shows the TP-C water sampling locations in Lake Rawapening, positioned at lake inlets, outlets, springs, the main water body, and areas adjacent to floating net cages. These datasets were used as the primary reference for model calibration and validation, as they represent official, standardized measurements for the lake.

Model calibration was conducted using in situ TP-C observations obtained from AoEF for the period 2015–2019, with an average TP-C of 0.023 mg/L. Calibration was performed by adjusting the PSETLR (phosphorus settling rate) parameter within the range of 70–269 in the *.LWQ file using a stepwise approach. Due to data availability constraints, calibration focused on the most sensitive parameter affecting TP-C, resulting in a simplified in situ approach that demonstrates sufficient performance for comparative scenario analysis and decision support. Model performance was evaluated using PBIAS, RMSE and SMAPE. Validation was conducted utilizing TP-C data issued by AoEF from 2020 to 2024, with an average TP-C of 0.029 mg/L. The sampling method used by AoEF complies with SNI 8995:2021 on Sampling Methods for Water Testing for Physical and Chemical Analysis. The TP analysis method complies with SNI 6989-31:2021 and utilizes UV/Vis spectrophotometry. A calibrated and validated model scenario serves as a baseline for developing alternative scenarios. The model outputs include trophic state classification under different intervention scenarios and corresponding recommendations for lake rehabilitation.

Figure 2 shows the framework for P load and trophic state in Lake Rawapening, while Table 2 shows the scenario development for trophic state control in the lake. The second scenario is fertilizer management in paddy fields in the lake. The management is adjusted to the nutrient needs of paddy varieties in Central Java Province, namely Inpari 32 and Inpari Nutrizinc. These varieties have nutrient needs of 150-160 kg N/ha and 10-20 kg P/ha with a planting cycle of 115-120 days (Dewi *et al.,* 2021; Sembiring *et al.,* 2025; Sitaresmi *et al.,* 2023). They have the following optimal cultivation cycle comprising transplanting at 15 days after sowing (DAS); initial fertilization of 7-10 days after planting (DAP); second fertilization of 20-30 DAP; third fertilization of 40-45 DAP; a maturation period: of 45-100 DAP; and harvesting at 100-115 DAP (Purbiati *et al.,* 2024). The fertilizers used are those officially commercialized in Indonesia, specifically urea fertilizer (46% N), ZA (ammonium sulphate – 21% N) and SP-36 (36% P_2O_5, corresponding to 15.7% P).

Table 2. Scenario development in Lake Rawapening.

Scenario	Land use	Lake Depth (m)	Fertilization	Nutrient Rate (kg/ha)
RWP 0 – baseline	Existing	2.6	Applied	N = ~138; P = ~16
RWP 1	Existing	2.6	None	-
RWP 2	Existing	4.6	None	-
RWP 3	Existing	4.6	Applied	N = ~138; P = ~16
RWP 4	Modified	2.6	None	-
RWP 5	Modified	2.6	Applied	N = ~138; P = ~16
RWP 6	Modified	4.6	None	-
RWP 7	Modified	4.6	Applied	N = ~138; P = ~16

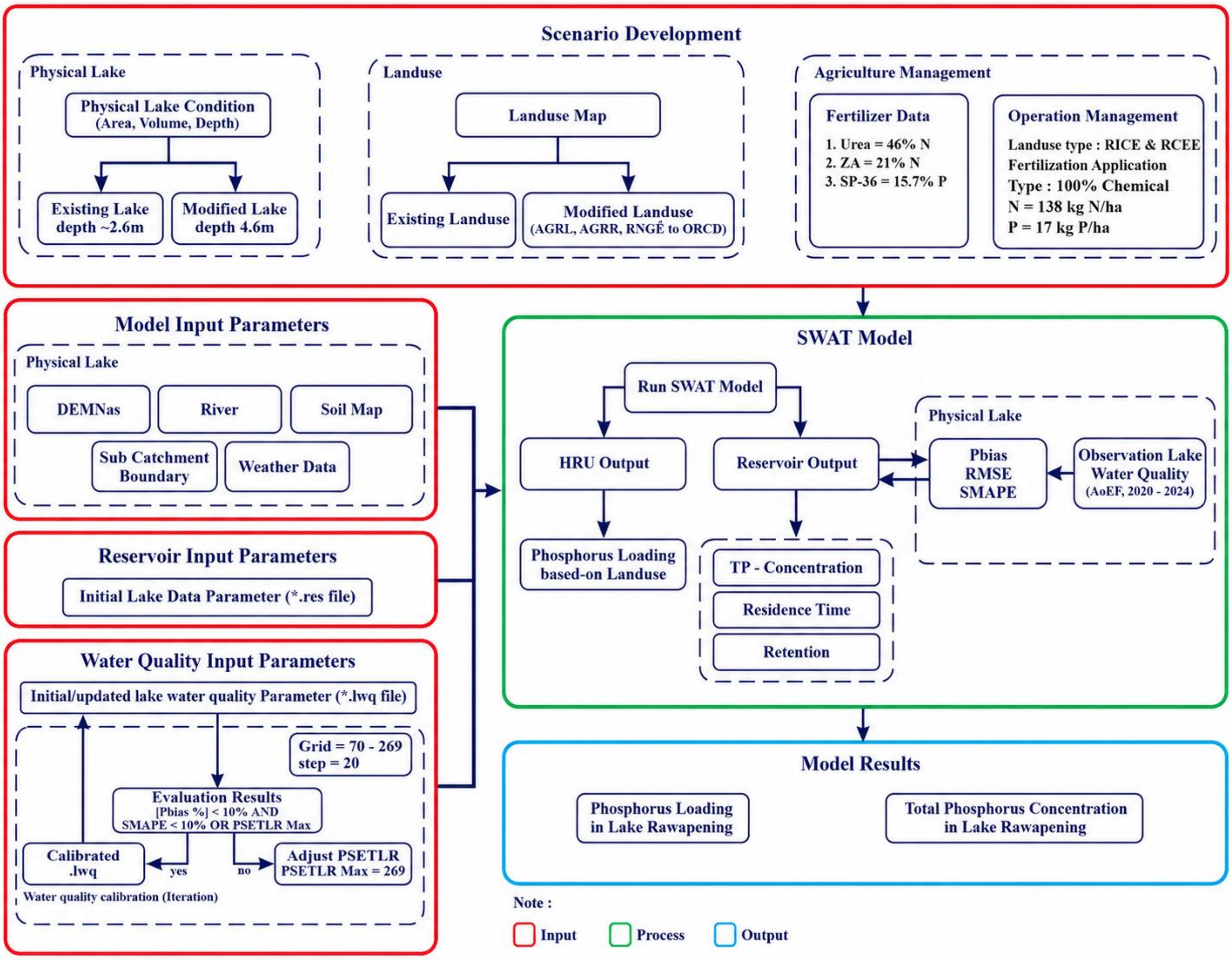

Figure 2. Multi-Scenario ArcSWAT workflow for P Load and TP assessment in Lake Rawapening.

For the study, paddy fields are categorized into two types: rainfed paddy fields (RCEE) and irrigated paddy fields (RICE), due to their distinct operational management practices. Moderate fertilizer doses of 138 kg N/ha and 16 kg P/ha were used to determine nutrient requirements. Table 3 shows the operational management of rainfed paddy fields (RCEE), while Table 4 shows that of irrigated fields (RICE). The operational management tables serve as the foundation for management in the SWAT model.

Table 3. Operation management schedule in rainfed paddy fields (RCEE).

Year	Month	Date	Operation Management	Fertilizer Applied (kg/ha)	Day after planting
1	Dec	1	Plant/begin, growing season		
1	Dec	11	Fertilization 1st	SP-36=100, Urea=60, ZA=60	10
1	Dec	31	Fertilization 2nd	Urea=90, ZA=40	30
1	Jan	15	Fertilization 3rd	Urea=90, ZA=30	45
1	Mar	10	Harvest and Kill Operation		100
1	May	1	Plant/begin, growing season		
1	May	11	Fertilization 1st	SP-36=100, Urea=60, ZA=60	10
1	May	31	Fertilization 2nd	Urea=90, ZA=40	30
1	Jun	15	Fertilization 3rd	Urea=90, ZA=30	45
1	Aug	9	Harvest and Kill Operation		100

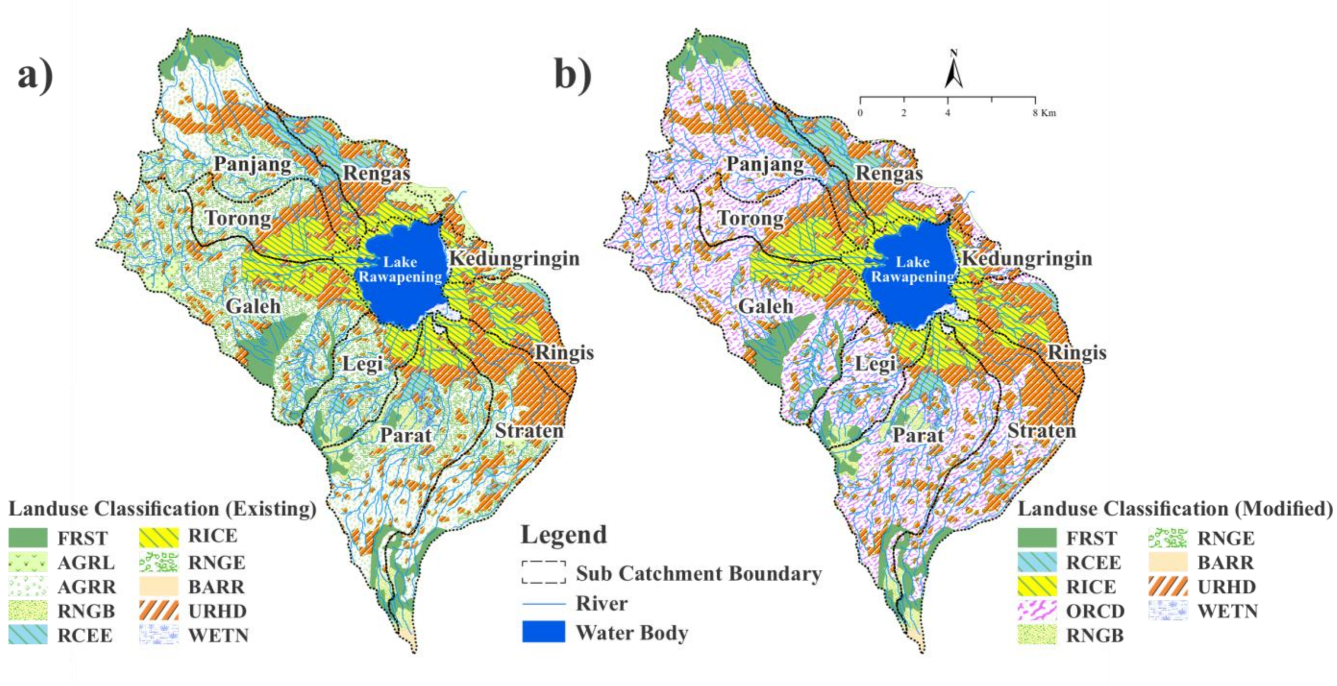

Figure 3. a) Existing Land Use 2024 Map; b) Modified Land Use 2024 Map.
Source : GIS Analysis, 2025.

Land use classification needs to be adjusted to approximate the classification recognized by the SWAT model. The classification in this study was secondary forest (FRST), plantation forest (FRST), agriculture (AGRL), dryland agriculture (AGRR), dryland agriculture mixed with shrub (RNGE), rainfed paddy fields (RCEE), irrigated paddy fields (RICE), shrubland (RNGB), swamp shrubland (WETN), bare land (BARR), settlement (URHD), and water bodies (WATR) (Figure 3a). In the first scenario, the agricultural land group (AGRL, AGRR and RNGE) was modified to agroforestry (ORCD) (Figure 3b). The ORCD land use type is assumed to demand the least maintenance and nutrient input.

Table 4. Operation management schedule in irrigated paddy fields (RICE).

Year	Month	Date	Operation Management	Fertilizer Applied (kg/ha)	Day after planting
1	Jan	1	Plant/begin, growing season		
1	Jan	11	Fertilizer 1st	SP-36 =70, Urea=75	10
1	Jan	31	Fertilizer 2nd	Sp-36=30, Urea=150	30
1	Feb	15	Fertilizer 3rd	Urea=75	45
1	Apr	26	Harvest and Kill Operation		115
1	Jun	1	Plant/begin. growing season		
1	Jun	11	Fertilizer 1st	SP-36 =70, Urea=75	10
1	Jul	1	Fertilizer 2nd	Sp-36=30, Urea=150	30
1	Jul	16	Fertilizer 3rd	Urea=75	45
1	Sept	24	Harvest and Kill Operation		115

The third scenario involved deepening the lake morphologically from 2.6m to 4.6m, in the form of dredging activities performed in Lake Rawapening by the lake management authority. The scenario was conducted by adjusting the RES_ESA, RES_EVOL, RES_PSA and RES_PVOL parameters in the .RES file. However, the SWAT model lacks a sediment removal mechanism and is limited to simulating alteration in lake morphometry (Murumkar *et al.*, 2025). The model can provide results that can be used to assess nutrient conditions in catchment through HRU output tables and in lake water bodies through reservoir output tables (Mirdarsoltany *et al.*, 2024). The model can also calculate nutrient loads in catchments for each type of land use to identity sources of P loads. To calculate the P loads for each land use, the Equation 1 is used:

$$P\_load_{(LU)} = \sum_{hru \in LU} [(\overline{ORGP}_{hru} + \overline{SOLP}_{hru} + \overline{SEDP}_{hru}) \times A_{hru} \times 1000] \quad (1)$$

Where: P_load(LU) is the total P load on land use (ton P/year); ORGP is organic P (kg P/year); SOLP is soluble P (kg P/year); SEDPkg_ha is organic P in sediment particles (kg P/year); Ahru is the HRU area; and 1,000 is the conversion factor from kilograms to metric tons. The TP-C in the lake water body can be calculated using the Equation 2:

$$Res\_TP_{concentration} = RES\_ORGP + RES\_MINP \tag{2}$$

Where: RES_TPconcentration is the TP-C in the lake water (mg P/L); RES_ORGP is the concentration of P in the lake water (mg P/L); and RES_MINP is the mineral P in the lake water (mg P/L). Residence time (RS) is the average time spent by water in the lake before exiting through outlets (Ouyang *et al.,* 2025). RS can be calculated using the Equation 3:

$$RS_{(days)} = \frac{\overline{Volume}}{\overline{Q_{out}} \times 86{,}400} \tag{3}$$

Where: RS(day) is the hydraulic residence time in days; $\bar{V}$ is the lake volume (m^3), $\overline{Q_{out}}$ is the outflow discharge (m^3/s); and 86,400 number of seconds in a day. Lake retention is the ratio of P leaving the reservoir body to that entering it. Lake retention can be calculated using the Equation 4:

$$P\_Retention_{(Lake)} = 1 - \frac{(ORGP_{out} + MINP_{out})}{(ORGP_{in} + MINP_{in})} \times 100\% \tag{4}$$

Where: P_Retention(lake) is the retention value of P (%); ORGPout MINPout is the value of organic P and mineral P leaving the lake water body (kg/year); and ORGPin MINPin is the value of organic P and mineral P entering the lake water body (kg/year).

The determination of the lake trophic state refers to Minister of Environment Regulation No. 28/2009, with the final decision based on the worst-of parameter. Table 5 present the categories of lake trophic state, as defined by the Ministry of Environment and Forestry (MoEF), the designated authority responsible for lake management.

Table 5. Trophic State of Lake.

Trophic State	TN Concentration (mg/L)	TP Concentration (mg/L)	Chl-*a* Concentration (mg/L)	SD (m)
Oligotrophic	≤ 0.6	≤ 0.01	≤ 0.004	≥ 10
Mesotrophic	0.6–0.75	0.01–0.03	0.004–0.010	10–4
Eutrophic	0.75–1.9	0.03–0.1	0.01–0.020	4–2.5
Hypertrophic	> 1.9	> 0.1	> 0.020	< 2.5

Source: (Escober & Espino, 2023); Ministry of Environment and Forestry, 2009, Modified.

3. Results

3.1. Impact of Multi-Scenario Interventions on TP Concentration in Lake Rawapening

Environmental models for ecosystem management must be calibrated before they are applied in the development of alternative scenarios. The initial stage of this study focused on calibrating the PSETLR parameter, which affects TP-C in lake water. The RWP 0 scenario was used as the baseline model for developing alternative scenarios. The RWP 0 calibration results show that at PSETLR = 269, Pbias was found to be 45.7%, RMSE was 0.0005 mg/L, and SMAPE was 18.6%. The calibrated PSETLR value serves as the baseline setting for developing all scenarios in the study. The validation results using the RWP 0 scenario show Pbias of 4.7%, RMSE of 0.0042 mg/L, and SMAPE of 6.8%.

RWP 1–3 represent scenarios with existing land use in a mesotrophic–eutrophic state, whereas RWP 4–7 represent modified land use in a mesotrophic state. Reduced fertilizer use on rice fields resulted in an annual decrease in TP-C in the lake under the RWP 1 scenario to 0.029 mg/L, or 0.003 mg/L (12.1%) less than the baseline. RWP 3 had the highest TP-C value of 0.040 mg/L, which was 33.3% above the baseline (Figure 4). An agroforestry scenario (RWP 4) reduced TP-C in lakes to 0.020 mg/L (-39.4%) relative to the baseline, or 33.3% below the eutrophic threshold. The deepening of the lake under the same catchment management conditions increased the TP-C in the RWP 2 scenario to 0.035 mg/L or 6.1% relative to the baseline. The RWP 7 scenario showed a TP concentration value of 0.028 mg/L with a 15.2% decrease in TP concentration relative to the baseline.

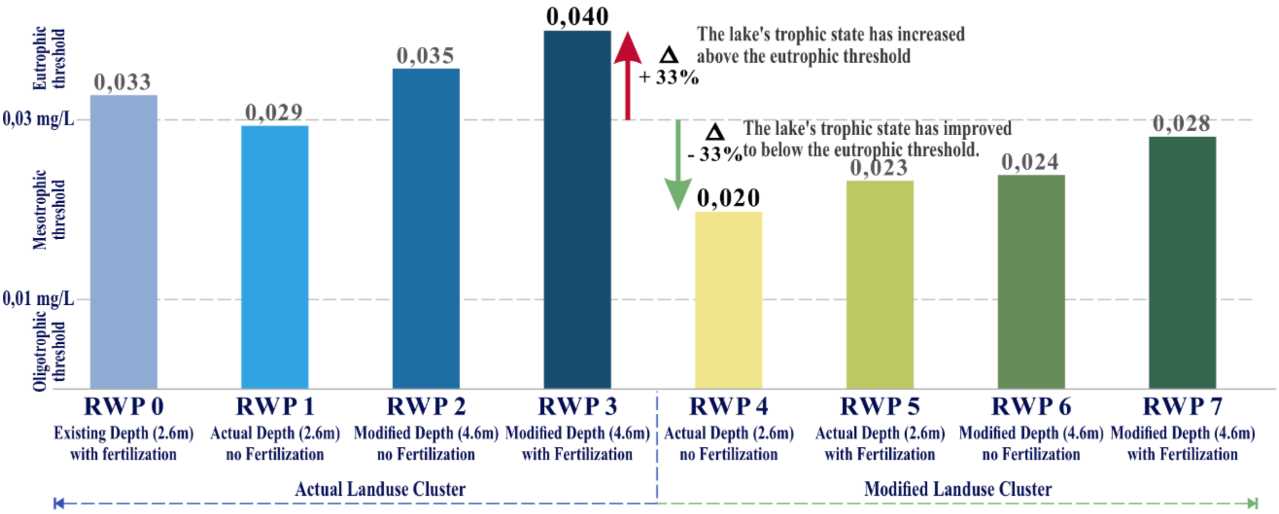

Figure 4. Comparison of annual TP-C across intervention scenarios in Lake Rawapening
Source: SWAT model, 2025

3.2. Effect of Agroforestry Land Use Scenarios

The TP-C in the water body was quantified and the sources of P-load in the Lake Rawapening catchment area were mapped. Table 6 presents the annual P-load entering the lake resulting from land use change interventions and fertilization activities. In RWP Scenario 1, the P-load under conditions without fertilization was 275 tons P/year. The most significant contributors to P loading into the lake in this scenario included RNGE 92.5 tons P/year (33.6%), URHD 58.1 tons P/year (21.1%), and AGRR 46.6 tons P/year (16.9%). In the scenario, agricultural groups contributed a P-load value of 148.5 tons P/year (54%). The paddy field groups (RCEE and RICE) produced a P-load of 56.4 tons P/year (20.5%). Interventions to transform agricultural land to agroforestry (ORCD) reduced the total P-load entering the lake (RWP4) to 182.9 tons P/year (-33.5%). In the agricultural group, the shift to agroforestry resulted in a 62% decrease in the P-load, from 148.5 tons P/year to 56.5 tons P/year.

Table 6. Annually P-load According Agriculture Land Use Change.

Land Use Group	Land Use Classification	Existing Land Use		Modified Land Use	
		Area (ha)	P-Load – RWP 1 (ton P/year)	Area (ha)	P-Load – RWP 4 (ton P/year)
Agriculture	AGRL	757.1	9.4	-	
	AGRR	3,301.0	46.6	-	
	RNGE	8,815.7	92.5	-	
	ORCD	-	-	12,873.7	56.4
Paddy Field	RCEE	1,198.2	17.9	1,198.2	17.9
	RICE	3,023.4	38.6	3,023.4	38.6
Generic	BARR	57.7	0.4	57.7	0.4
	FRST	1,571.4	4.8	1,571.4	4.7
	RNGB	535.5	5.7	535.5	5.7
	URHD	6,734.8	58.1	6,734.8	58.1
	WATR	266.5	-	266.5	-
	WETN	161.7	1.1	161.7	1.1
Total :		26,422.8	275.0	26,422.8	182.9

Source: SWAT model, 2025.

In the RWP 4 scenario, the most significant P-load came from settlement (URHD) land use at 58.1 tons P/year (31.8%), and ORCD at 56.3 tons P/year (30.8%). Figure 5 shows the effect of agricultural land use and fertilizer management interventions on paddy fields. Agricultural land is predominantly located in the Panjang, Torong, Galeh, Legi, Parat and Sraten sub-catchments (Figure 5a). The majority of agricultural land is in the P-load class of 6.8–13.5 kg P/ha/year and the class of 13.5–20.3 kg P/ha/year in parts of the Panjang, Parat and Sraten areas. In addition to reducing TP concentrations in lakes, changes in agricultural land use also affected the P load entering lakes. Figures 5b and 5c show changes in phosphorus load classes in agricultural areas from 13.5–20.3 tons P/year to 6.8–13.5 tons P/year. The paddy fields are located around the lake, and some areas extend into Lake Rawapening in the Torong, Panjang and Rengas sub-catchments (Figure 5d). Residential areas are also scattered around the paddy field areas, with the highest concentration in Sraten and Ringis sub-catchment areas.

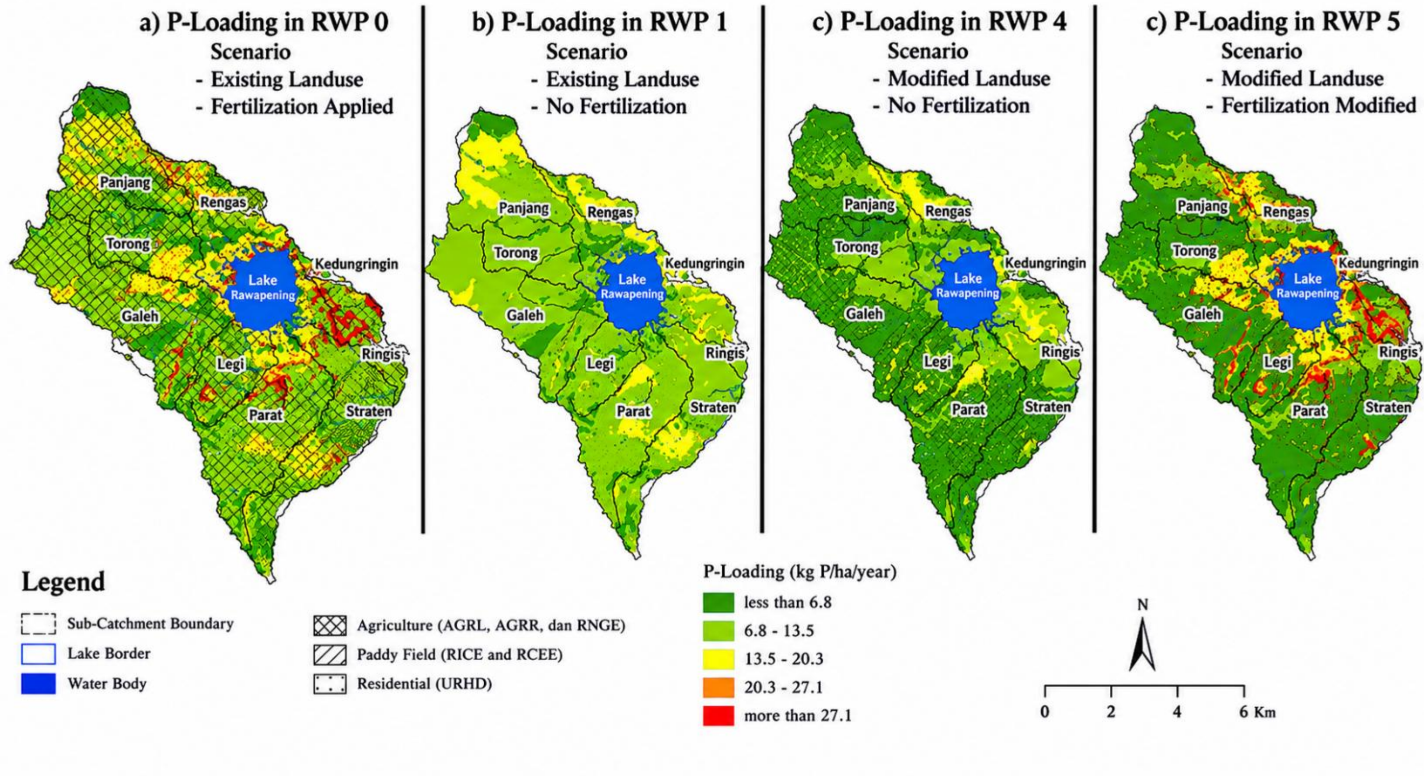

Figure 5. Spatial distribution of TP in Lake Rawapening catchment: a) Scenario RWP 0; b) Scenario RWP 1; c) Scenario RWP 4; d) Scenario RWP 5

Source: SWAT model, 2025.

3.3. Effect of Fertilization in Paddy Fields

The application of fertilizers in paddy fields influences the influx of phosphorus into lakes. Fertilization of irrigated paddy fields (RICE) increased the annual P-load from 38.6 tons P/year to 60.3 tons P/year, or 56.2% (Figure 8). On the other hand, in rainfed paddy fields (RCEE), there was an increase in annual P load from 17.9 tons P/year to 27.9 tons P/year (55.9%). The total area of paddy fields (RICE + RCEE) without fertilization contributed 56.5 tons of P/year (20.5%) to the total P load in the RWP 0 scenario and 30.9% in the RWP 4 scenario. Meanwhile, when fertilization was applied to the paddy fields, the P load became 88.2 tons P/year (28.7%) of the total P load in scenario RWP 1 and 41.1% in RWP 5 (Table 7).

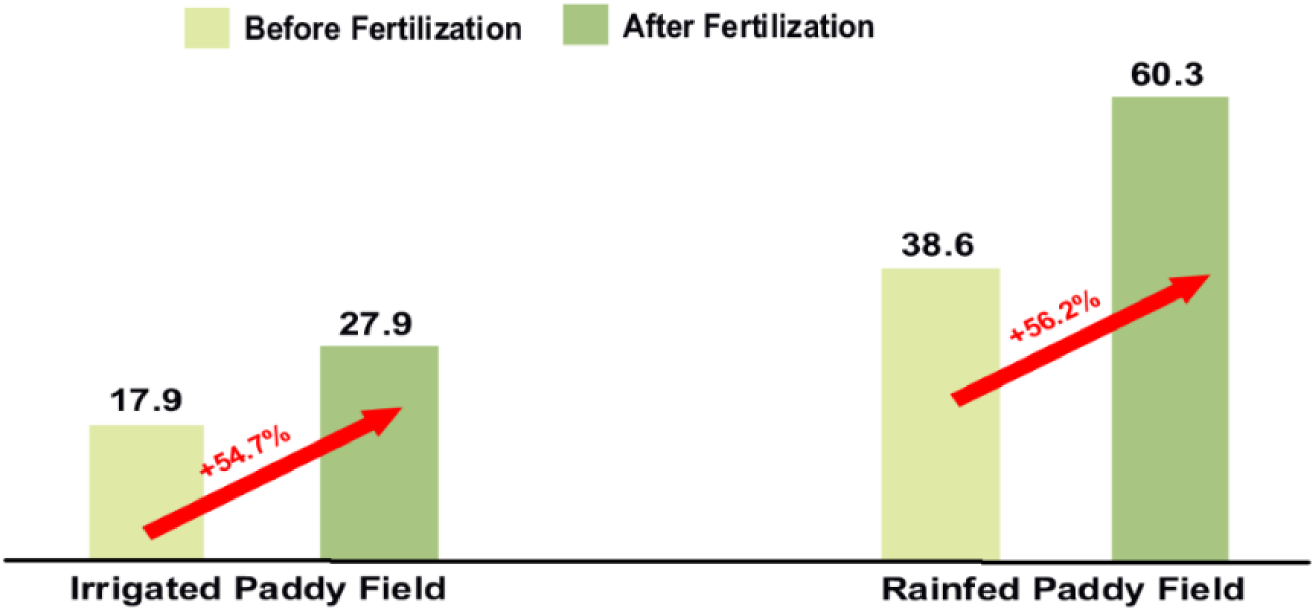

Figure 6. Annual phosphorus loading from paddy field land use classification
Source: SWAT model, 2025.

Table 7. Impact of fertilization management in the Rawapening catchment area
Source: SWAT model, 2025.

Land use classification	**P-load in existing land use (ton P/year)**			**P-load in modified land use (ton P/year)**		
	Area (ha)	**With Fertilizer (Baseline)**	**Without Fertilizer (RWP 1)**	**Area (ha)**	**With Fertilizer (RWP 5)**	**Without Fertilizer (RWP 4)**
AGRL	757.1	9.4	9.4	-	-	-
AGRR	3,301.0	46.6	46.6	-	-	-
RNGE	8,815.7	92.5	92.5	-	-	-
ORCD	-	-	-	12,873.7	56.4	56.4
BARR	57.7	0.4	0.4	57.7	0.4	0.4
FRST	1,571.4	4.8	4.8	1,571.4	4.7	4.7
RCEE	1,198.2	27.9	17.9	1,198.2	27.9	17.9
RICE	3,023.4	60.3	38.6	3,023.4	60.3	38.6
RNGB	535.5	5.7	5.7	535.5	5.7	5.7
URHD	6,734.8	58.1	58.1	6,734.8	58.1	58.1
WATR	266.5	-	-	266.5	-	-
WETN	161.7	1.1	1.1	161.7	1.1	1.1
Total :	26,422.8	306.7	275.0	26,422.8	214.6	182.9

3.4. Effect of Lake Deepening

Lake deepening intervention increased the depth from 2.6m to 4.6m. In a single-intervention scenario focusing solely on lake deepening, changing from baseline to RWP 3 increased the TP-C of the lake from 0.033 mg/L to 0.040 mg/L (21.2%). The impact of deepening on other scenarios was as follows: RWP 1 to RWP 2 increased from 0.029 mg/L to 0.035 mg/L (20.7%); RWP 4 to RWP 6 increased from 0.020 mg/L to 0.024 mg/L (20%); and RWP 5 to RWP 7 increased from 0.023 mg/L to 0.028 mg/L (21.7%). The simulation results show an increase in volume from 50.5 × 106 m^3 to 95.9 × 106 m^3, or a 90% increase, while the discharge remained stable at between 13.0 and 13.7 m^3/s (Table 8). Phosphorus residence time due to lake deepening increased from 43 days to 81–85 days (88–98%), while the lake retention values ranged from 88.7 to 89.2%.

Table 8. Impact of Lake Deepening in the Rawapening Water Body
Source: SWAT model, 2025

Parameters	**Depth 2.6 m**				**Depth 4.6 m**			
	Base-line	**RWP 1**	**RWP 4**	**RWP 5**	**RWP 2**	**RWP 3**	**RWP 6**	**RWP 7**
Volume ($\times 10^6$ m^3)	50.5	50.5	50.5	50.5	95.9	95.9	95.9	96.0
Q (m^3/s)	13.7	13.7	13.7	13.7	13.7	13.7	13.6	13.0
Residence Time (day)	43	43	43	43	81	81	81	85
Reservoir P loading in (ton P/year)	304.9	273.2	182.1	213.6	273.2	304.9	182.1	213.6
Reservoir P loading out (ton P/year)	33.6	30.7	20.2	23.0	30.7	33.5	20.3	23.2
Lake Retention (%)	89.0	88.7	88.9	89.2	88.8	89.0	88.8	89.2
Concentration TP in Lake (mg/L)	0.033	0.029	0.020	0.023	0.035	0.040	0.024	0.028

4. Discussion

4.1. Model Calibration and Validation

The SWAT model used for the study needed to be calibrated with comparative AoEF observation data. Luján *et al.,* (2025) and Mai, (2023) state that many parameters in environmental models are conceptual in nature and cannot be directly measured in the field, thereby introducing uncertainty. However, such uncertainty can still be used to determine the relative change in TP-C for each scenario in our study. Han *et al.,* (2025) and Yu *et al.,* (2022) argue that the calibration process should focus on parameters that are most relevant to the research objectives so that the model is not overly complex, while Lopez *et al.,* (2025) emphasize that models should remain simple and model limitations should be recognized in order to reduce overfitting. Therefore, this study focuses on the PSETLR (Phosphorus Settling Rate) parameter in the .LWQ file that affects the TP-C results in the lake. Calibration of the RWP 0 scenario yielded a PSETLR value of 269 m/day, which is the maximum limit specified in the SWAT manual for reservoirs. The results show a relatively high deviation from the calibration dataset, but with an absolute deviation of TP-C of 0.005 mg/L. Validation of TP-C in RWP 0 using the AoEF dataset for 2020–2024 yielded a PBIAS of 14.7% and an RMSE of 0.0042 mg/L, indicating that the relative and absolute deviations are acceptable compared to the validation dataset. The SMAPE of 6.8% indicated relatively low model error in following the validation dataset pattern. Based on the validation results, the RWP 0 scenario was considered feasible for use as a baseline for developing other scenarios.

4.2. Multi-Scenario Lake Ecosystem Rehabilitation

This study developed seven scenarios (RWP 1 – RWP 7) for the rehabilitation of the Lake Rawapening ecosystem. Such rehabilitation requires an integrated approach and demands solutions tailored to specific ecological and socioeconomic contexts (Gunacti & Cetinkaya, 2025; Ruiz-Marín *et al.,* 2024; Zhan *et al.,* 2023). These scenarios integrate both catchment-level and in-lake interventions, referring to the pillar-based and object-based management concepts proposed by Mardiatno *et al.,* (2022). The proposed concept encompasses management scenarios and actions, good governance, and science-based information as its main management pillars. In addition, water bodies, watersheds and fertilization (N and P) are the main study objects. The development of various scenarios was designed to connect the concept of management with the operational management of the Lake Rawapening ecosystem. The SWAT model used for scenario simulation can be utilized as a science-based tool for providing information related to impact estimates and trade-offs between the scenarios developed. Figure 4 illustrates the impact of intervention on TP-C dynamics in Lake Rawapening. The results of RWP scenarios 1–7, with a TP-C value range of 0.020–0.040 mg/L, illustrate the dynamics of changes in the lake's trophic state resulting from the implemented interventions. Results from several scenarios can be classified into three categories: ideal scenarios, compromise scenarios with trade-offs, and scenarios to be avoided. The ideal scenario is the RWP 4 scenario, with a 33.3% decrease in TP-C below the eutrophic state threshold. This condition was reached by converting agricultural land to agroforestry, excluding fertilizing and lake deepening actions. This scenario was shown to effectively reduce the trophic status of the lake from eutrophic to mesotrophic. However, it is challenging to implement this approach, due to the established practice of fertilizing paddy fields in Lake Rawapening. A study of Lake Rotorua, in New Zealand revealed that less intensive farming can yield long-term economic benefits by enhancing ecosystem services (Mueller *et al.,* 2019). In the context of Lake Rawapening management, RWP 4 represents the best solution ecologically; however, socioeconomically, achieving short-term agricultural yields is challenging.

Therefore, a scenario is needed that can provide a reasonable trade-off between ecological and socioeconomic recovery for the community around Lake Rawapening. The scenarios classified as acceptable compromises include RWP 5, which has a more realistic equilibrium between ecological and socioeconomic trade-offs, although the results are not as significant as RWP 4. The RWP 5 scenario effectively reduced TP-C to 0.023 mg/L, which is 22.7% beneath the eutrophic threshold. This condition suggests that agroforestry within the lake catchment can reduce TP-C without compromising crop productivity, provided that fertilizer application is restricted in paddy fields. The RWP 3 scenario, which focuses only on lake deepening, represents a scenario that should be avoided. The related findings resulted in an elevation of TP-C to 0.040 mg/L, representing a 33.3% increase above the eutrophic threshold, alongside expensive lake dredging. Further discussion on the impact of interventions in agricultural land use change, fertilization management in paddy fields, and deepening will be discussed in the following sub-sections.

4.3. Effects of Agroforestry Scenarios

Scenarios were developed for converting the agricultural land use group (AGRL, AGRR and RNGE) to agroforestry (ORCD). Table 6 shows that moving from seasonal agriculture (RWP 1) to agroforestry (RWP 4) resulted in a 33.5% reduction in the P-load in the catchment, from 275.0 tons P/year to 182.9 tons P/year. In scenario RWP 1, the most significant contributors are RNGE at 92.5 tons P/year (33.6%), URHD at 58.1 tons P/year (21.1%), and AGRR at 46.6 tons P/year (16.9%). The primary contributor to the P-load by land use classification area is RCEE, with a value of 0.015 tons P/ha/year, followed by RICE at 0.013 tons P/ha/year. The transition of seasonal agricultural groups to agroforestry (RWP 4) resulted in a 62% decrease in P-load, from 148.5 tons P/year to 56.4 tons P/year. The P-load contribution of ORCD was 0.004 tons P/ha/year, which was inferior to that of the agricultural groups AGRR, AGRL and RNGE, which reached 0.014, 0.012 and 0.010 tons P/ha/year respectively. Nayanarangani *et al.,* (2025) state that actively- managed perennial agricultural land has eleven times lower P availability than seasonal agriculture with the same cultivation practices. Furthermore, Good *et al.,* (2025) confirm that agriculture using deep root systems and minimal intervention is more effective in P retention. These findings suggests that converting seasonal agricultural to agroforestry effectively reduces the P-load from the catchment area.

Alongside agricultural land, settlement areas (URHD) emerged as major contributors across all scenarios. The phosphorus load in the URHD class was 58.1 tons P/year (21.1%), rendering it the second-largest contributor in the RWP 1 scenario. In the RWP 4 scenario, it was the predominant contributor, accounting for 31.8%. The condition relates to the ratio of residential zones, encompassing 6,734.8 hectares or 25.5% of the overall catchment area. However, settlement areas have a comparatively low specific P load (0.009 tons P/ha/year); their extensive area leads to a continual significant accumulation of P loads. The development of residential areas puts pressure on the balance of the ecosystem. Research at Phewa Lake, Nepal, reveals that settlement expansion has altered the lake's status from oligotrophic to eutrophic over 20 years (Subedi *et al.,* 2025). while research at Poyang Lake, China, indicates that agricultural and urbanization activities exert pressure on the phosphorus influx into the lake (Li & Zhenyao, 2025). Figure 5a shows that agricultural land use is concentrated in the Panjang, Torong, Galeh, Legi, Parat and Sraten sub-catchments.

The P load in these regions typically ranges from 6.8 to 13.5 kg P/ha/year, whereas in certain sections of the Parat, Panjang and Sraten sub-catchments, it varies from 13.5 to 20.3 kg P/ha/year. The conversion of agricultural land to agroforestry reduced the P load from 6.8–13.5 kg P/ha/year and 13.5–20.3 kg P/ha/year to less than 6.8 kg P/ha/year (Figure 5c). In scenario RWP 4, paddy fields are situated around the lake, with specific fields positioned within the lake itself, as observed in the Panjang, Torong and Rengas sub-catchment areas. This situation highlights that the management of paddy fields is a crucial issue. The distribution of residential areas throughout all the sub-catchments requires regulation, particularly in highly populated regions such as the Sraten and Ringis areas. The transition from seasonal agricultural patterns (RWP 1) to agroforestry (RWP 4) consistently reduced the lake's trophic state, as discussed in subsection 4.2. These scenario results have the potential to inform the design of long-term intervention priorities for the rehabilitation of Lake Rawapening.

4.4. Effects of Paddy Field Fertilization

The study assesses the impact of fertilizer application on paddy fields in the Lake Rawapening catchments. The development of this scenario is grounded in established paddy cultivating procedures. Table 7 shows that the total area of rice fields is 4,221.6 ha, or 16.0% of the total catchment area. Irrigated paddy fields before fertilization have a P load of 38.6 tons P/year, with a specific P load of 0.013 tons P/ha/year. On the other hand, rainfed paddy fields exhibit a P load of 17.9 tons P/year, with a specific P load of 0.015 tons P/ha/year. Yang *et al.* (2026) argue that, mathematically, an increase in nutrients from a level of 0.4 to 0.65 (63%) results in a reduction of tipping time from 9 to 3 (67%) units of time. An elevated nutrient load from fertilization influences the rate at which lakes transition to a more adverse trophic state. The findings of this study indicate that the elimination of fertilization treatments resulted in a reduction of TP-C from 0.033 mg/L to 0.029 mg/L, consequently altering the lake's trophic status from eutrophic to mesotrophic.

After fertilization, Irrigated paddy fields experienced a 56.4% increase in P-load, and rainfed paddy fields experienced a 55.8% increase in P-load. These conditions suggest that applying fertilizer to paddy fields results in a substantial overall increase in P loads in the lake catchments by 31.7 tons P/year (10 – 15%). Tables 3 and 4 show the fertilizer dosages and schedules for Irrigated paddy fields and rainfed paddy fields. The SP-36 fertilizer application was 100 kg/ha, equivalent to 15.7 kg P/ha, while the phosphorus requirement for the Inpari 32 and Inpari Nutrizinc rice varieties is around 10–30 kg P/ha (Sembiring *et al.,* 2025; Sitaresmi *et al.,* 2023). Even though the fertilizer dose was 52% below the recommendation, there was still an increase in P-load and TP-C. A meta-analysis indicated that crop yield can be sustained with a 30% reduction in fertilizer usage (Jin *et al.,* 2023). In addition, Zhang *et al.* (2025) found that 20.2–25.8% of P-load was lost during the high-risk period of 0–20 days after fertilization. This intervention scenario demonstrates that, although a fertilizer dose is below the recommended level, it does not necessarily ensure complete safety for the ecological rehabilitation process of a lake. Zhang *et al.,* (2025) indicated that a mixture of organic fertilizer (40%) and chemical fertilizer (60%) applied to paddy plants could decrease phosphorus loss by 13%.

The Irrigated paddy fields are situated directly along the lake's border, with some areas extending into the water body of Lake Rawapening, particularly in the Torong, Panjang and Rengas sub-catchments. This situation makes Lake Rawapening highly vulnerable to an influx of phosphorus that instantly enters the lake. Based on spatial distribution, Irrigated paddy fields are located around the lake bodies in the Galeh, Legi, Parat, Ringis and Kedungringin sub-catchments. In contrast, rainfed paddy fields are located in the upstream areas of the Rengas, Ringis, Parat and Legi sub-catchments. These differences in position present distinct challenges and necessitate different management strategies for paddy fields. Generally, Irrigated paddy fields are situated in the downstream area, whereas the wet zone of Lake Rawapening receives fertilizer runoff from upstream, posing a direct risk of water pollution. Meanwhile, the rainfed paddy fields area located upstream requires adjustments to the dosage and fertilization schedule. Based on the conditions at Lake Rawapening, a best management practice strategy needs to be developed, it should 1) gradually reduce fertilizer doses on rainfed paddy fields by 20% of the recommended dose; 2) reduce fertilizer doses for Irrigated paddy fields around the lake border by 30% of the recommended dose; 3) reduce the use of fertilizer on Irrigated paddy fields within the lake's water body more aggressively or even eliminate it; and 4) make improvements to the timing of P fertilizer application to prevent accumulation at a specific time. Alongside fertilizer management approaches, engineering interventions such as the establishment of ecological ditches and temporary storage ponds have demonstrated a 37.9% reduction in TP (Yang *et al.,* 2024). Nada *et al.,* (2023) found that managing riparian and buffer zones in Lake Rawapening to a distance of 30 meters could diminish the P-load by 45.5%. In the context of the lake, this strategy could be implemented in the form of technical civil engineering in areas with high P load, such as in the Galeh, Parat, Ringis and Kedungringin sub-catchments. Ecological ditches could be constructed in proximity to the banks of the rivers that discharge into the lake to reduce phosphorus loads. Irrigated paddy fields land could function similarly to the wetland concept, so that rice nutrient requirements can be met from nutrients carried by the flow. With an adaptive management strategy, the trade-off between ecological rehabilitation and agricultural productivity could be more balanced and feasible.

4.5. Impacts of Deepening

In many studies, lake deepening through dredging is considered to be an effective alternative for controlling lake degradation, such as Lake Taihu and Lake Dianchi. However, the results of the deepening scenario show that lake deepening cannot stand alone. Without consistent control of phosphorus loading, an increase in TP-C is shown. Table 8 indicates that deepening under the same management conditions actually increased TP concentrations by 20.0–21.7%. Dredging increased the lake volume from 50.5 × 106 m^3 to 95.9 × 106 m^3 (89.1%), but the outflow remained almost unchanged, ranging between 13.0 m^3/s and 13.7 m^3/s. This situation resulted in an increase in P residence time from 43 days to 81 days (88.4%). Lake Rawapening consistently has a high P retention value, ranging between 88.7% and 89.2%. The RWP 1 scenario involves conditions closest to reality in Lake Rawapening. Deepening interventions directly increase TP-C by 21.2% in RWP 1 from 0.033 mg/L (eutrophic), to 0.040 mg/L (eutrophic) in RWP 3. This implies that deepening alone is counterproductive to the goal of rehabilitating lake ecosystem conditions. In lakes with high retention, an increase in residence time leads to a corresponding increase in P concentration in the water column (Liu *et al.,* 2024). Riza et al., (2023) found that the results of dredging for lake eutrophication control are limited by time and the external P loads entering the lake. Xiang et al., (2024) report that dredging has a positive impact on water quality within 2–5 years after dredging, depending on the lake depth, initial water quality, and the dredging method. Kato *et al.,* (2025) also argue that dredging increases nutrient concentrations and disrupts the balance of the aquatic ecosystem that existed prior to dredging, a disruption that persists for several months. Lake deepening is optimal when performed in deep lakes with relatively calm hydrodynamics (Wu *et al.,* 2025; Yang *et al.,* 2023).

The study presents alternatives that can be implemented to optimize lake deepening. In the RWP 6 scenario, a deepening scenario is combined with a change in land use from agriculture to agroforestry. The related results show a 27.3% decrease in TP concentration from 0.033 mg/L (RWP 1 - eutrophic) to 0.024 mg/L (RWP 6 - mesotrophic). Although the model results show improvement, the scenario has the potential to reduce rice field productivity due to the loss of fertilization. Trade-offs in deepening must consider short-term and long-term recovery as well as ecological improvement and socioeconomic sustainability. Scenario RWP 7 shows a more moderate trade-off, with a 15.2% improvement in TP concentration from 0.033 mg/L (RWP 1 – eutrophic) to 0.028 mg/L (RWP 7 – mesotrophic). Although not as good as RWP 6, RWP 7 is the most feasible intervention for Lake Rawapening. In various scenarios developed for the lake, combining land use changes could be the most significant factor for improvement. Agroforestry land use changes can reduce the impact of fertilization on rice fields and lake deepening. This implies that lake management policies involving deepening through dredging need to consider controlling the phosphorus load entering the lake from upstream.

The study is limited by the scarcity of continuous field monitoring data required to calibrate and validate Total Nitrogen (TN) and Chlorophyll-a (Chl-a) parameters. The SWAT model also has limitations in simulating sediment export in scenarios involving deepening. This implies that adjustments need to be made to the assumptions of morphological deepening and sediment dredging in the water body. The limited data on the types of agriculture in the Lake Rawapening catchment also pose a challenge to the accuracy of phosphorus loads entering the lake. Furthermore, measured discharge and sedimentation data at each of the 14 inlets and the single outlet are unavailable, introducing potential bias into the calculated P load balance. Further research should focus on collecting and analyzing observations of the TN, Chl-a and P content in sediments, accompanied by measurements of discharge and sedimentation, to provide more comprehensive simulation results.

5. Conclusion

The research shows that all three interventions simulated using the SWAT tools resulted in both increased and decreased TP levels in Lake Rawapening. The conversion of agricultural land to agroforestry significantly reduced the amount of P entering the lake. Fertilization practices, even under moderate conditions in accordance with technical recommendations for rice varieties, resulted in a significant increase in P load and TP-C. There need to be restrictions or even a ban on the use of fertilizers, adjusted to the relative distance of the rice fields from Lake Rawapening. The practice of deepening the lake without consistent intervention to reduce the P load entering it would worsen TP-C due to increased volume and P residence time.

RWP 5 is a combination of interventions with feasible and realistic trade-offs in the context of Lake Rawapening. The conversion of agricultural land to agroforestry without deepening the lake can effectively compensate for the surge in P load and TP-C resulting from fertilization practices in rice fields. These results serve as a basis for developing a management strategy for the lake, enabling the achievement of the goal of ecosystem improvement. Further research is needed to consider the parameters of TN, Chl-a, discharge and plant types in the lake catchment area to obtain more precise results.

Acknowledgements

This research was funded by RTA Program Universitas Gadjah Mada with Grand Number 5075/UNI/P/II/Dit-Lit/PT.0101/2023.

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Conceptualization: Rhosadi, I., Mardiatno, D., Setiawan, M. A.; **methodology**: Rhosadi, I, Mardiatno, D, Setiawan, M. A.; **investigation**: Rhosadi, I, Mardiatno, D, Setiawan, M. A.; **writing—original draft preparation**: Rhosadi, I, Mardiatno, D, Setiawan, M. A, Hayat D. M.; **writing—review and editing**: Rhosadi, I, Mardiatno, D, Setiawan, M. A.; **visualization**: Rhosadi, I. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

All authors declare that they have no conflicts of interest.

Data availability

Data is available upon request.

Funding

This research was funded by RTA Program Universitas Gadjah Mada with Grand Number 5075/UNI/P/II/Dit-Lit/PT.0101/2023.

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