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Modeling Reservoir Management Efforts for Water Quality in Malang Suko Village, Indonesia Using a Dynamic System Approach

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ABSTRACT

Water quality is an essential component in effective water management, specifically in the reservoir planning. Therefore, this study aimed to determine the water quality of the Malang Suko Reservoir, Malang Regency, Indonesia, by examining temperature, pH, dissolved oxygen (DO), chemical oxygen demand (COD), and biochemical oxygen demand (BOD_5). To achieve this goal, the dynamic system approach for reservoir management was employed, and the software used for water quality modelling was the System Thinking Educational Learning Laboratory with Animation (Stella). The analysis considered several contributing factors, such as settlements, agriculture, and temperature. The results showed that the water quality status of the Malang Suko Reservoir was moderately polluted. The dynamic subsystem simulation had a high level of accuracy with a mean absolute percentage error of 1.1% and 0% for the settlement and agricultural submodels, respectively. Therefore, several scenarios for managing the inflow of waste into the reservoir were suggested, with the role of the community being the most crucial.

Keywords: Malang Suko Reservoir, water quality, dynamic system.

INTRODUCTION

Water is an indispensable resource for human life, playing an essential role in both domestic and agriculture context (Chowdhary et al., 2020, Noerhayati et al., 2023, Vieira and Ribeiro, 2022, Santa-Cruz et al., 2021). However, its availability in terms of quality and quantity was limited, prompting the need for sustainability (Singh, Haque and Grover, 2015, Rahaman and Solavagounder, 2020, Grigoriev and Frolova, 2018). The use of water in Indonesia is increasing with population growth and economic development. The increase in the demand was accompanied by an high pollution, as its significant portion was used for discharging wastewater (Shi et al., 2021, Elehinafe et al., 2022, Iloms et al., 2020).

The development and management of irrigation systems, which are essential components supporting agricultural development, play a crucial and strategic role (García et al., 2020, Veisi et al., 2022, Carter et al., 2019). Addressing water scarcity can be facilitated by the construction of reservoir, a type of infrastructure built to store rain or river water during the rainy season for subsequent usage during the dry season in terms of irrigation, watering, and fulfilling the water needs of the surrounding community (Sharun et al., 2021, Tang, Wasowski and Juang, 2019, Cheng and Pan, 2020, Noerhayati et al. 2022). Furthermore, the reservoir can be used to control floods and maintain water availability during the dry season (Zhang, Wang and Bai, 2021, Dang, Chowdhury and Galelli, 2020, Makhmudova, Djuraev and Khushvaktov, 2021). It also serves as a means to control floods, reduce soil erosion, and enhance agricultural productivity. However, many are in poor condition as well as require maintenance and rehabilitation. The government continues to build better and modern reservoirs to improve water availability for the community. They also seek to increase the community involvement in reservoir management to ensure optimal and sustainable utilization (Sokolov et al., 2020, Bounif, Rahimi, and Boutafoust 2023, Jawecki and Pawłowska 2021, Radionov et al. 2020). Additionally, good water quality regulations is essential for effective management, in order to meet the expected standards. One active reservoir in Indonesia is the Malang Suko Reservoir in Malang Regency, East Java, Indonesia, which receives inflow from river water, containing domestic wastewater and agricultural runoff. At the Malang Suko reservoir, people have yet to research the condition of the waste entering the reservoir.

System thinking educational learning laboratory with animation (Stella) is the software that facilitates the creation of dynamic system simulations and has intuitive components for assembling dynamic process simulations (Ramos et al. 2023) (Liu et al. 2022). The Stella software is used to determine the suitability of water quality and the status of the Suko Malang Reservoir according to Class III water quality criteria for irrigation. This evaluation used the water quality index/Ipyang application on the Stella system software, applying dynamic modeling principles with an object-oriented approach. The latest research suggests some possibilities for controlling waste entrance into the reservoir. Each scenario was determined by analyzing the following variables: temperature, pH, dissolved oxygen (DO), chemical oxygen demand (COD), and biochemical oxygen demand (BOD_5). It is hoped that the measurement analysis results will determine whether the water condition in the Malang Suko Reservoir meets the criteria for good water quality standards.

MATERIAL AND METHODS

Primary data

The collection of primary data begins with the experiment aimed at assessing the environmental conditions and important aspects related to the study area. The experiment also aid in identifying points or locations for the collection of sample, which is to be tested based on point and non-point sources to obtain optimal results. Primary data obtained were the information regarding the existing water quality of the Malang Suko Reservoir. Sample collection was accomplished at the study location, specifically at the inlet of the reservoir, which was located at the core. Furthermore, water quality parameters, such as temperature, was analyzed directly (in situ), while BOD_5, COD, DO, and pH were examined in the laboratory.

Secondary data

Secondary data were obtained from records, previous results, and information from relevant agencies. They includes water quality, population in the study area, agricultural, and flow data. Furthermore, this information was used to determine relevant emission factors (specific estimates) according to each polluting source activity. In this study, secondary data was needed to complement incomplete primary data.

METHODS

Study area description

This study was conducted at the Malang Suko Village Reservoir, Tumpang Subdistrict, Malang Regency, East Java (Fig. 1). This reservoir had technical data plans, covering approximately 0.9 hectares, and a water storage capacity of 24,000 m^3 to irrigate an agricultural area of 614,000 hectares.

Data collection

The required data includes primary, secondary, and literature data. Primary data includes the water flow rate of Malang Suko Reservoir, as well as existing conditions, such as COD, DO, BOD, pH, and temperature (Fig. 2). Secondary data comprises laboratory test results for reservoir water and reservoir water supply.

RESULTS AND DISCUSSION

Temperature

The Class III water quality standard for temperature has a standard deviation of ± 3. This can be interpreted as ± 3°C from the natural water temperature. Therefore, when the normal water temperature in Class III is 29°C, the criteria exhibit limitation of 26–32°C. This result was presented in Figure 3:

The temperature of the Malang Suko Reservoir in this study ranged from 26–30°C, which was within the water quality standard of 26–32°C.

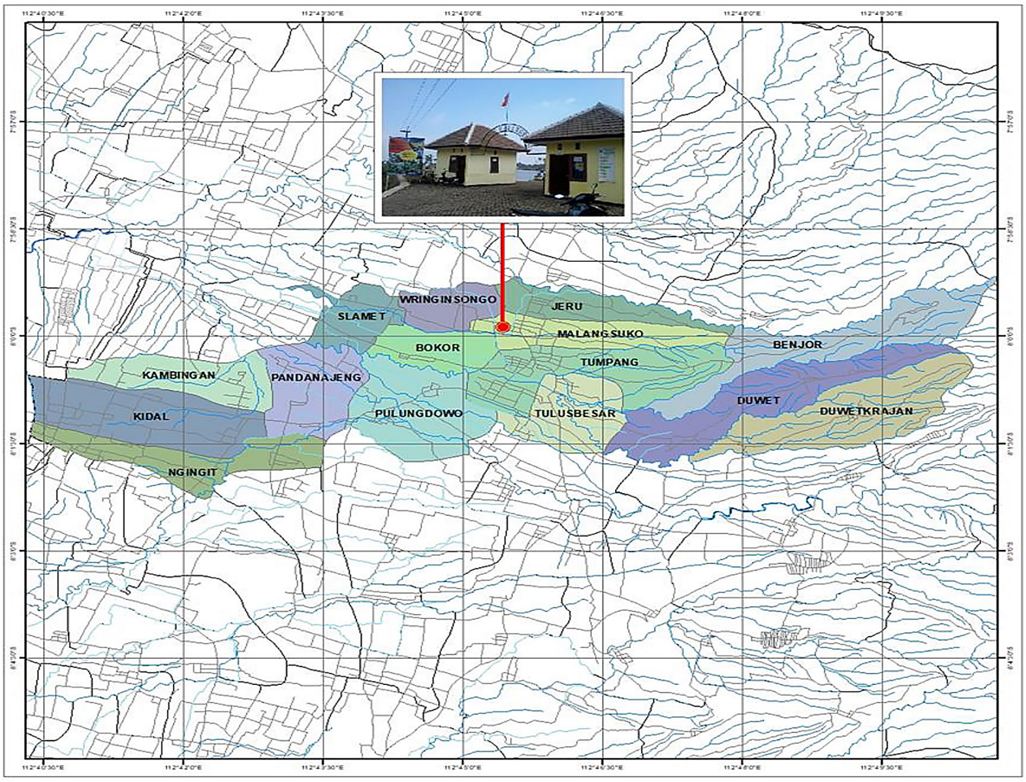

Fig. 1. Study location

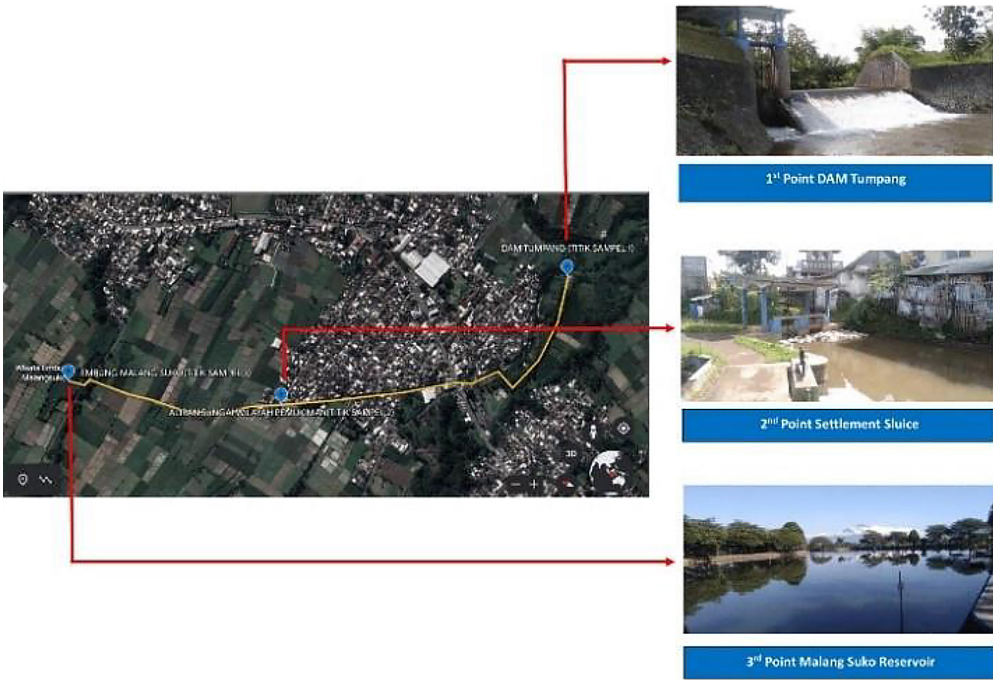

Fig. 2. Water sample collection locations

Calculation of the pollution index:
- Water quality standard (L_i) = deviation 3.
- Water temperature (C_i) = 29°C.
- Ambient air temperature = 28°C.

$$L_{i\ average} = \frac{26+32}{2} = 29.$$

$$(C_i / L_i)_{new.} = \frac{c}{L} = \frac{29-28}{32-28} = 0.25$$

Acidity (pH)

The pH parameter was analyzed in the laboratory, and the pH levels in the Malang Suko

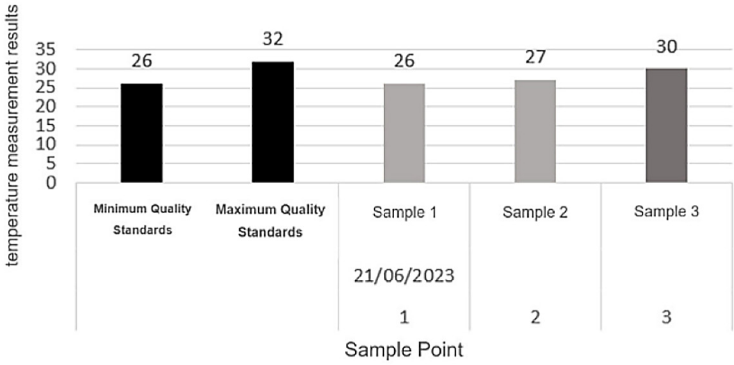

Fig. 3. Temperature concentration in Malang Suko Reservoir

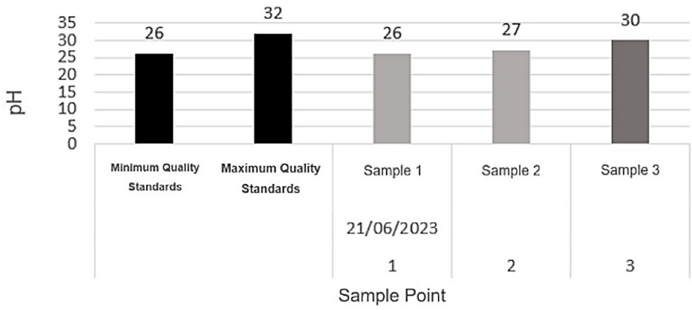

Fig. 4. pH concentration in Malang Suko Reservoir

Reservoir are presented in the Figure 4. On the basis of this results, it was concluded that the pH of the Malang Suko Reservoir waters met the standard for Class III waters, falling within the acceptable range of 7–8.

The calculation of the pollution index is as follows:

Class III pH standard (L_i) = 6–9

pH (C_i) = average pH = 7.5

Since the pH parameter has a range of values, Equation was employed for the calculation:

$$L_{i\ average} = \frac{6+9}{2} = 7$$

$$(C_i/L_{ij})_{new} = \frac{(\text{pH average})-(\text{ci}-\text{Lij})}{\text{Lij (maximum)}-\text{Lij(average)}} = \frac{7.5+0.5}{9-7.5} = 4.6$$

Because $C_i/L_i > 1$, hence:

$$C_i/L_i = 1 + P\log(C_i/L_i) = 1 + 5\log(4.6) = 4.3$$

Dissolved oxygen

The results of the dissolved oxygen test are shown in Figure 5. On the basis of this figure, the concentration of DO in the Malang Suko Reservoir waters did not meet the Class III water quality standard and was relatively high in comparison. The quality standard in the reservoir was in the range of 4.1–4.5 mg/L, while for Class III standard, it was 3 mg/L. Finally, the high DO levels were attributed to the discharge of wastewater (Slamet, 2016).

Calculation of the pollution index is as follows:

- Water quality standard (L_i) = 3 mg/L
- DO concentration (C_i) = 4.3 mg/L (average DO)
- DO saturation (29°C) = 12.9 (total DO)

$$(C_i/L_{ij}) = \frac{Cim - C\ I\ (measurement\ result)}{Cim - C\ I} = \frac{12.9-4.3}{12.9-3} = 0.86$$

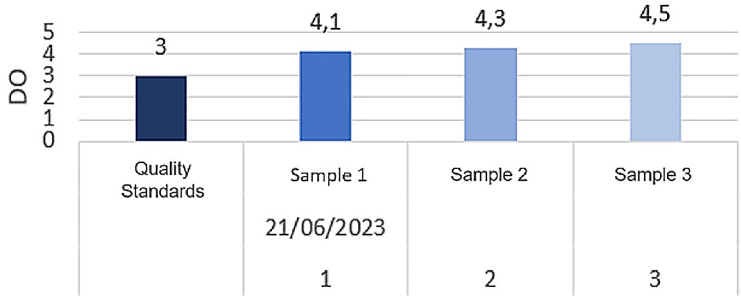

Fig. 5. DO concentration in Malang Suko Reservoir

Chemical oxygen demand

The concentration level of COD in the Malang Suko Reservoir are shown in Figure 6. On the basis of Government Regulation on Environmental Management No. 82 of 2001, the water quality standard for COD in Class III and IV were 50 and 100 mg/L, respectively. The COD analysis results for the Malang Suko Reservoir water, was in the range of 147–150 mg/L, indicating relatively high pollution. Calculation of the pollution index:

- Water quality standard (L_i) = 50 mg/L
- COD concentration (C_i) = 149 mg/L (average COD)

$$C_i/L_i = 149/50 = 2.98$$

Because $C_i/L_i > 1$, hence:

$$C_i/L_i = 1 + P \log(C_i/L_i) = 1 + 5 \log(2.98) = 3.37$$

Biochemical oxygen demand (BOD_5)

The concentrations of BOD_5 are shown in Figure 7. The BOD_5 concentration ranges from 40 mg/L to 44.13 mg/L, and when compared to the Class III water quality standard of 6 mg/L, it showed a substandard level. The following is the calculation on the pollution index:

- Water quality standard for BOD_5 (L_i) = 6 mg/L
- BOD_5 concentration (C_i) = 42.6 mg/L (average COD)

$$C_i/L_i = 42.6/6 = 7.1$$

Because $C_i/L_i > 1$, hence:

$$C_i/L_i = 1 + p \log(C_i/L_i) = 1 + 5 \log(7.1) = 5.2.$$

Determination of water quality status with PI method

Water quality status was determined based on the data obtained from laboratory or field analysis and calculations (Table 1). This was achieved using the PI method. On the basis of the data, all C_i/L_i values are known, hence, the calculation of the pollution index was conducted using:

- Ci/Li average = 2.7
- Ci/Li maximum = 5.2

$$P_{ij} = \sqrt{\frac{\left(\frac{ci}{Lij}\right)m2+\left(\frac{ci}{Lij}\right)R2}{2}} = \sqrt{\frac{(5.2)2+(2.7)2}{2}} = 4.1$$

Slightly polluted

Table 1. Overall PI calculation results

No.	Concentration	(C_i/L_i) results
1	Temperature	0.25
2	Ph	3.7
3	COD	3.37
4	BOD	5.2
5	DO	0.86
Total		13.38
Average		2.7

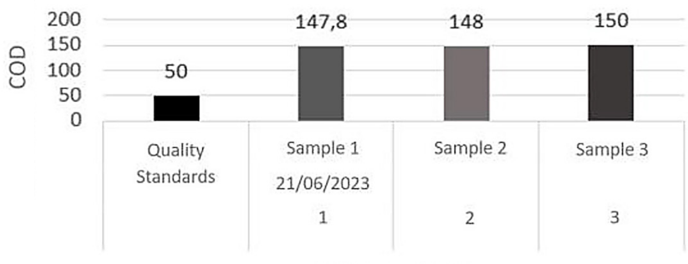

Fig. 6. COD concentration of Malang Suko Reservoir

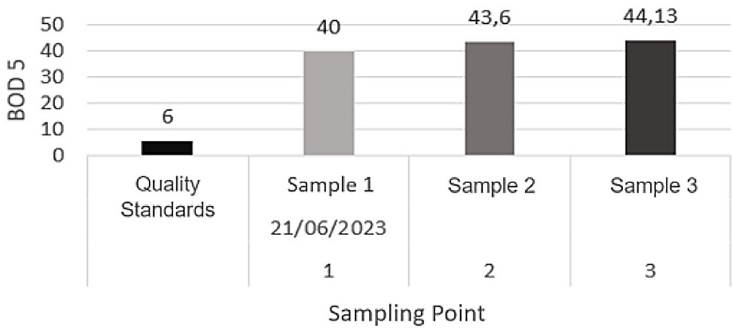

Fig. 7. BOD_5 concentration in Malang Suko Reservoir

The highest C_i/L_i calculation result was observed for the BOD_5 concentration at 5.2, while the lowest corresponded to the temperature of 0.25.

Dynamic subsystem for Malang Suko Reservoir Water Quality

The dynamic subsystem was constructed based on pollutant sources from the water quality data obtained from laboratory or field analysis. Furthermore, it aimed to determine the potential pollution load (PPL) that enters the Malang Suko Reservoir water. The following are factors influencing changes in reservoir water quality (Table 2).

Table 2. Emission factors for domestic waste pollution load

Pollution	Emission factor (gr/day)	Emission factor (kg/month)
BOD	27	0.81
COD	55	1.65
DO	40	0.90

Submodel for settlements toward Malang Suko Reservoir water quality

The pollution load submodel for settlements was constructed based on the population as the source of wastewater. In the study location, settlement areas were the largest contributors to pollution due to high population density, with an initial simulation of 76,892 people (Statistics Center Agency of Tumpang Subdistrict) in 2021. Among them, 5,126 people directly discharge wastewater into the drainage channels (Technical Implementation Unit of Water Division in Tumpang Subdistrict) (Table 3).

To determine the wastewater load calculation results for settlements, the following equation is used:

$$\text{PPL Domestic} = \text{Population} \times \text{FE} \times \text{REK} \times \text{load transfer/liter}$$

$$\text{PPL Domestic } BOD_5 = 5.126 \times 0.81 \times 0.81 \times 1277{,}3 = 4295.7 \text{ mg/month}$$

$$\text{PPL Domestic COD} = 5.126 \times 1.65 \times 0.81 \times 4458 = 3054.1 \text{ mg/month}$$

$$\text{PPL Domestic DO} = 5.126 \times 0.90 \times 0.81 \times 129 = 4820.5 \text{ mg/month}$$

Submodel for agriculture toward Malang Suko Reservoir water quality

The submodel for agricultural wastewater pollution was constructed based on the land area surrounding the reservoir. In this study, the agricultural pollution were considered as the dominant pollutant source in the DTA, with an area of 350 hectares discharging into the reservoir.

Several variable factors affected water quality due to agricultural activities. To determine the agricultural wastewater load calculation results, the following equation was used (Table 4):

$$\text{PPL Agriculture} = \text{land area} \times \text{FE} \times \text{load transfer/liter}$$

$$\text{PPL Domestic } BOD_5 = 350 \times 0.81 \times 1277.3 = 3{,}621.5 \text{ mg/month}$$

$$\text{PPL Domestic COD} = 350 \times 1.65 \times 4458 = 2.574 \text{ mg/month}$$

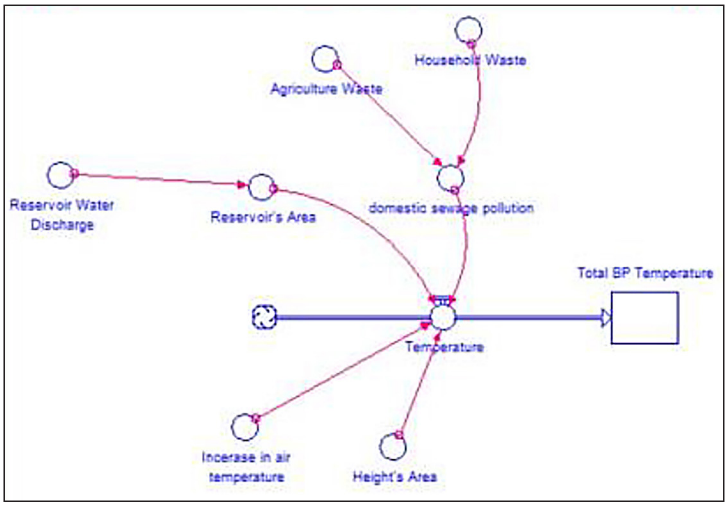

Fig. 8. Sub-model for temperature increase load factor in the Malang Suko Reservoir waters (Source: Analysis using STELLA Software 2023)

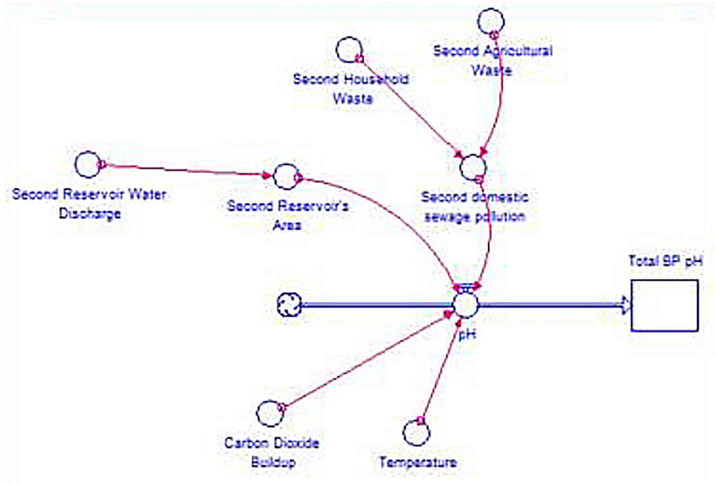

Fig. 9. Sub-model for pH increase load factor in the Malang Suko Reservoir waters (Source: Analysis using STELLA Software 2023)

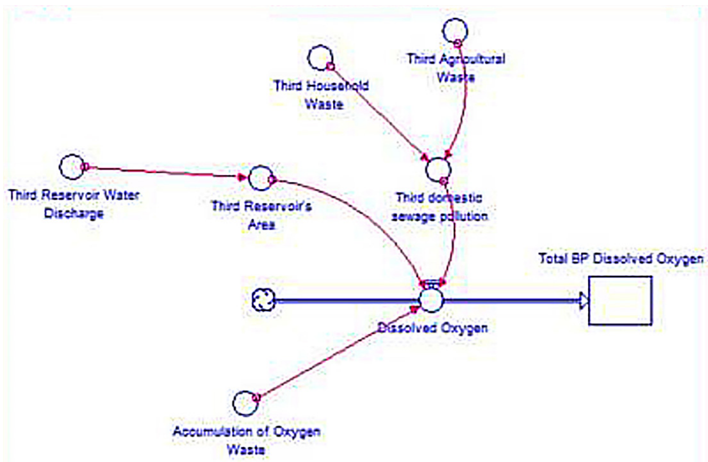

Fig. 10. Sub-model for DO increase load factor in the Malang Suko Reservoir waters (Source: Analysis using STELLA Software 2023)

Table 3. Results of annual BP calculation of Malang Suko Reservoir flow due to settlements

No.	Month	BP/Month			Population number	Fe			REC
		BOD	COD	DO		BOD	COD	DO	
1	January				5.126	0.81	1.65	0.90	0.81
2	February				5.126	0.81	1.65	0.90	0.81
3	Damage				5.126	0.81	1.65	0.90	0.81
4	April				5.126	0.81	1.65	0.90	0.81
5	May				5.126	0.81	1.65	0.90	0.81
6	June	4295.775	30541.31	48.20542	5.126	0.81	1.65	0.90	0.81
7	July				5.126	0.81	1.65	0.90	0.81
8	August				5.126	0.81	1.65	0.90	0.81
9	September				5.126	0.81	1.65	0.90	0.81
10	Okay				5.126	0.81	1.65	0.90	0.81
11	November				5.126	0.81	1.65	0.90	0.81
12	December				5.126	0.81	1.65	0.90	0.81
Total BP/L		1277.3	4458	12.9					
Domestic PBP = Population x FE x REC x transfer load/L									

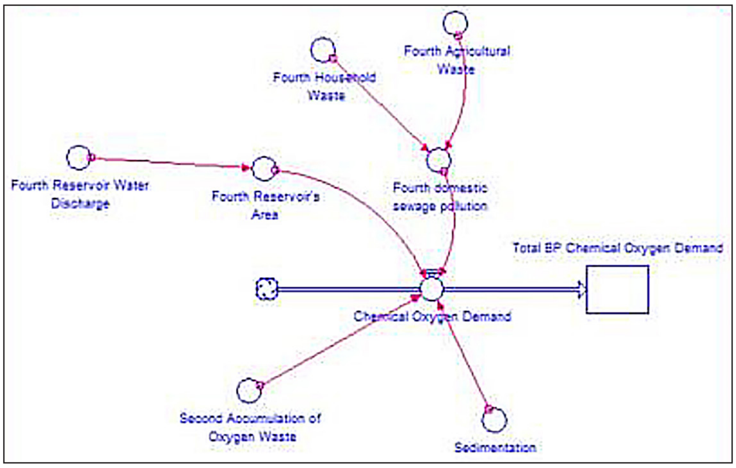

Fig. 11. Sub-model for COD increase load factor in the Malang Suko Reservoir waters
(Source: Analysis using STELLA Software 2023)

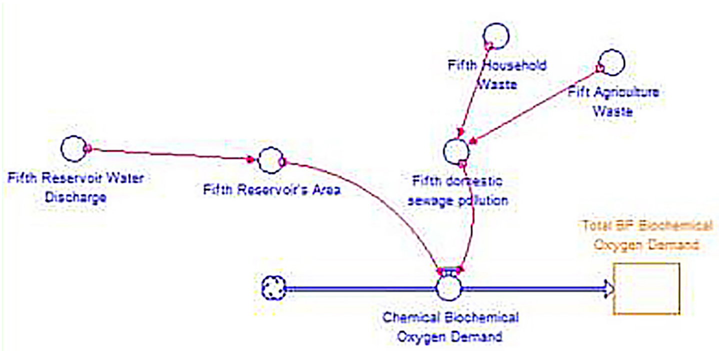

Fig. 12. Sub-model for BOD_5 increase load factor in the Malang Suko Reservoir waters
(Source: Analysis using STELLA Software 2023)

PPL Domestic DO = 350 × 0.90 × 129 = 4.063 mg/month

For the calculation of the total pollution load (PL), the following equation is presented:

Total inlet reservoir PL = Total settlement PL + Total agricultural PL

Total inlet reservoir PL BOD = 4.295 + 3.621 = 7.916

Total inlet reservoir PL COD = 2.980 + 2.300 = 6.114

Total inlet reservoir PL DO = 4.800 + 3.890 = 8.893

Model validation test

The model simulation was scheduled for June. The accuracy of the simulation was influenced by the quantity and validity of the data used. The more data obtained, the better the accuracy of the model (Erma, 2017). Validation was a statement regarding the representation of the accuracy level of the built system model.

Structural validation test

Structural validity test was conducted in two ways, namely structural and construction validity. Construction validity was confidence in the scientifically constructed model, while structural stability was the applicability or strength of the structure over time. The presence of sub-models for pollution management efforts in the Malang Suko Reservoir serves as confirmation of structural validity.

Simulation results of total pollution load in Malang Suko Reservoir:

$$PL_{flow} = \frac{\text{Settlement wastewater PL} + \text{Agricultural wastewater PL}}{2}$$

$$= \frac{36.6+28.6}{2} = 32.6$$

Total PL = Settlement wastewater PL + Agricultural wastewater PL = 36.6 + 28.6 = 65.2

Performance validation test

Performance validity aimed to obtain confidence in the accuracy of the model when

Table 4. Annual BP calculation results for Malang Suko Reservoir flow due to agriculture

No.	Month	BP/month			Land area (m^2)	Fe		
		BOD	COD	DO		BOD	COD	DO
1	January				350	0.81	1.65	0.90
2	February				350	0.81	1.65	0.90
3	Damage				350	0.81	1.65	0.90
4	April				350	0.81	1.65	0.90
5	Possible				350	0.81	1.65	0.90
6	June	362115	2574495	4064	350	0.81	1.65	0.90
7	July				350	0.81	1.65	0.90
8	August				350	0.81	1.65	0.90
9	September				350	0.81	1.65	0.90
10	October				350	0.81	1.65	0.90
11	November				350	0.81	1.65	0.90
12	December				350	0.81	1.65	0.90
Total BP/L		1277.3	4458	12.9				
Domestic BP = agricultural land area x FE x transfer load/L								

compared to the actual performance of the system, hence, fulfilling the criteria as a scientific model based on facts. Performance validity analysis was conducted by comparing the simulation model and actual data.

Settlement submodel

Simulation in the settlement submodel was accomplished using the initial population of 76,892 people obtained in 2022. Furthermore, it was conducted based on the number of people who directly discharge wastewater into the drainage channels (Table 5).

$$MAPE = (A–F)/A \times 100\% = 923.668/922.836 \times 100\% = 0.010804396 \times 100\% = 0.1\% \text{ (very accurate)}$$

where: MAPE – mean absolute percentage error,
A – actual data value,
F – predicted data value.

Table 5. Water flow discharge of the Malang Suko Reservoir

Malang Suko Reservoir flow rate (m^3/sec)				
Month: June 2023				
No.	Jam	Overload dam	Air door II	Down
1	06.00	1.50	1.52	1.52
2	09.00	1.55	1.60	1.63
3	13.00	1.56	1.62	1.63
4	16.00	1.55	1.58	1.58
Average		1.54	1.58	1.59

Agricultural submodel

The initial simulation data for the agricultural submodel around the reservoir considered a land area of 674 hectares on a moderate scale. Validation of the this submodel was based on the increase in agricultural area utilization (Table 6).

$$MAPE = (A–F)/A \times 100\% = 8.088/8.088 \times 100\% = 0 \times 100\% = 0\% \text{ (very accurate)}$$

Management effort scenarios for the reservoir

In this study, management effort scenarios were conducted to address the possible future conditions. The types of scenarios are as follows:

- Pessimistic scenario is a simulation based on the existing conditions observed during the study.
- Moderate scenario is a simulation aimed at improving the existing conditions.
- Optimistic scenario is a simulation based on real conditions in the field.

Table 6. Total reservoir inlet pollution load

No.	Pollution	MARK			Total
		I	II	I, I, I	
1	Number of BP directors	7.916	7.695	7.052	22.663
2	Total BP COD	6.114	5.280	4.800	16.194
3	Number of BP DO	8.893	8.690	7.577	25.160
4	pH	226.1	225	199	650

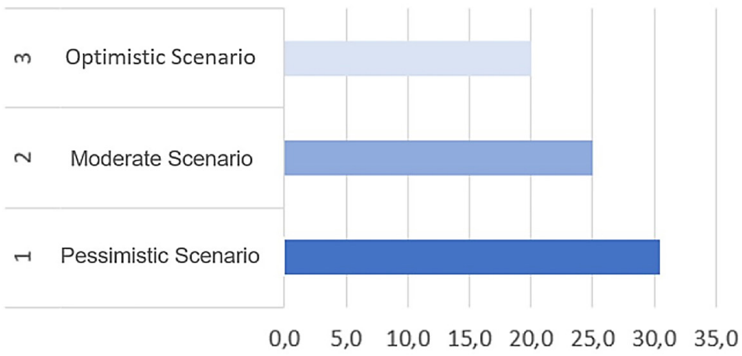

Fig. 13. Comparison of scenario simulation result

Analysis of management effort scenarios

The simulation results for each scenario were presented in Figure 13. On the basis of each scenario, it was evident that the optimistic scenario had the lowest population load; hence, was selected in the management effort for mitigating wastewater pollution in the Malang Suko Reservoir. This scenario was chosen because it can significantly reduce the wastewater entering the reservoir with the lowest pollution load of 20 kg/year.

CONCLUSIONS

The water quality status of the Malang Suko Reservoir was moderately polluted, as determined by the pollution index calculation with average pollution load concentrations of COD, BOD_5, DO, pH, and temperature at 149 mg/L, 42.6 mg/L, 4.3 mg/L, 7.5, and 28°C, respectively.The total pollution load in the Malang Suko Reservoir waters from all three points during the simulation month were BOD_5, COD, and DO at 22 kg/month, 16 kg/month, and 25 kg/month, respectively. This originated from domestic pollution sources with an average BOD_5, COD, and DO of 4.29 kg/month, 3.05 kg/month, and 4.82 kg/month, respectively. Agricultural pollution contributed with an average BOD_5 load, COD, and DO of 3.7 kg/month, 2.6 kg/month, and 4 kg/month. The dynamic subsystem simulation had a high level of accuracy with a MAPE percentage of 1.1 and 0% for the settlement and agricultural submodels, respectively. This dynamic model can be carried out on other reservoirs with environmental characteristics similar to the Malang Suko Reservoir.

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