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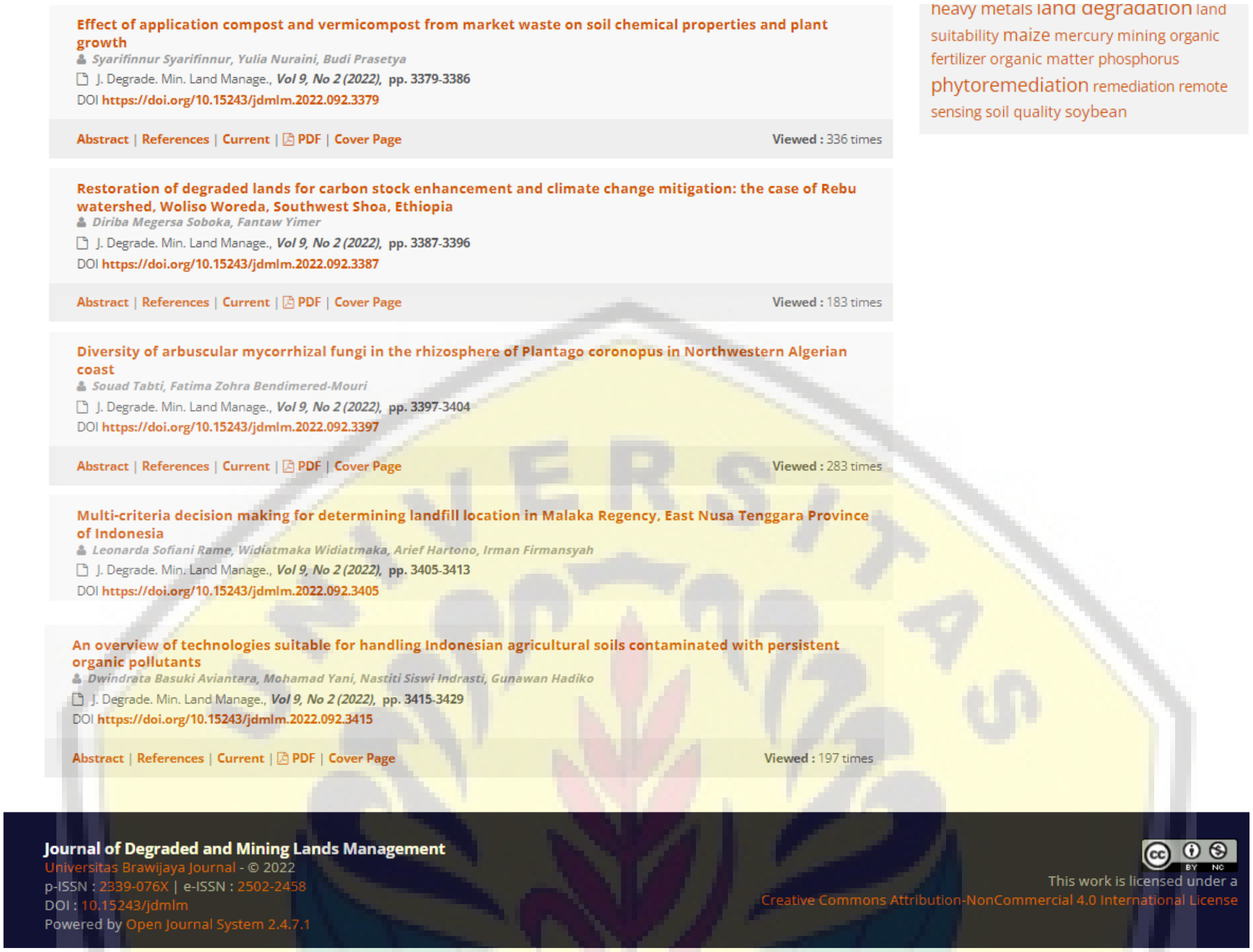

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Research Article

Simulation for water quality management using system dynamics modeling in the Bedadung Watershed, East Java, Indonesia

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Abstract

The potential for pollution of rivers is influenced by river-water discharge and the distribution of pollution sources. This research aimed to examine recommendations for water quality management in the Bedadung River segment of the Patrang, Sumbersari, and Kaliwates Districts as an urban area of Jember Regency refer to simulations of the total pollution load capacity for 10 years (2016-2026) using a system dynamics modeling. The preparation of a system dynamics modeling used Powersim 5.0 software. It could represent holistic environmental management modeling. The input data were total suspended solid (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD) and the streamflow of the Bedadung River. The model scenarios were the business of usual, moderate, and optimistic scenarios involving environmental and socio-economic aspects. The medium-term and long-term recommendations for water quality management of the Bedadung River based on system dynamics simulation were respectively moderate scenario and optimistic scenario. The strategies of the moderate scenario were application of the best management practice method in agricultural cultivation, improving sanitation and domestic wastewater treatment, implementing clean production in the field of livestock and industry, as well as waste management on riverbanks. These alternative strategies for river water quality management can be used as consideration for protecting surface water sources in urban areas.

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Introduction

Decreases in quality and quantity will threaten the sustainable availability of water sources. Pollution from domestic, agricultural, and industrial activities is the cause of the decline in the quality of surface water sources in the Asian region (Evans et al., 2012; Fullazaky et al., 2014; Dwivedi, 2017). Including pollution of surface water sources such as rivers in Indonesia. Although Indonesia has large surface water reserves, some of its rivers are in poor condition (Asian Development Bank, 2016). Several studies have stated that major rivers in Indonesia, such as the Citarum, Cisadane, Ciliwung, Musi, Brantas, and Barito, are not suitable for use as raw water sources based on assessments using the water quality index (Asian Development Bank, 2016; Sutadian et al., 2018).

Despite watershed quality management policies, including the Clean River Program (Program Kali Bersih or Prokasi), effective and integrated river programs have not been put in place, and so the phenomenon of decreasing river-water quality is still occurring. Efforts that can be directed toward maximizing the effectiveness of policy include periodical monitoring and controlling of environmental quality (Marselina and Burhanudin, 2017). According to Ministry of Environment Decree No. 1 (2010), the potential for pollution of rivers is influenced by river-water discharge and the distribution of pollution sources. Efforts to manage water quality in the Bedadung River in Jember Regency have been limited to monitoring the quality of water based on the total of its pollution load capacity and its pollution index (Pradana et al., 2019b; Pradana et al., 2020). This approach provides static-stochastic results but is not dynamically representative; effective water quality protection of the Bedadung River therefore also needs to address the issue of source pollution. This approach is expected to enable a dynamical-representation policy of environmental management to impact on the water quality conditions of the Bedadung River.

Environmental pollution dynamics can be described or modeled using a system dynamics approach that refers to the cause-and-effects relationships between natural phenomena and human activities (Forrester, 1987; Ford, 1999; Sterman, 2001; Sharawat et al., 2014). Such an approach is considered applicable to the modeling of the impact of policies on environmental sustainability, both in terms of capability and feasibility. System dynamics modeling has been applied in several countries in Asia in sustainable environmental management and holistic approaches, including aspects of social, economic, and environmental relations (Xiang et al., 2014; Liu et al., 2015; Huang et al., 2017). Other research studies indicate that a system dynamics approach can holistically represent the influence on water quality in water bodies of pollution sources from industry (or other point sources) and pollution control policies (Yang et al., 2011; Sukruay and Chaysiri, 2017). According to Suwari et al. (2011), holistic water quality dynamics and pollution control scenarios on the Surabaya River can be represented by a system dynamics model.

This research aimed to examine recommendations for water quality management in the Bedadung River segment of the Patrang, Sumbersari, and Kaliwates districts (the urban area of Jember Regency), referring to simulations of the dynamics of pollution source impact on the total pollution load capacity (TPLC) for a 10-year period (2016–2026) using system dynamics modeling.

Materials and Methods

Study area and input data

Jember Regency is located in East Java Province. The area has several large watersheds, such as those of the Bedadung, Mayang, and Tanggul rivers. The urban area of Jember Regency is located in the Bedadung watershed and includes the Patrang, Sumbersari, and Kaliwates districts. Land use in the research location consists of settlements, paddy fields, fields, and city forests (Pradana et al., 2019a; Pradana et al., 2020).

The major river located in the Bedadung watershed is the Bedadung River itself. The river serves a vital function for the community as a source of water for washing, bathing, and irrigation. The Bedadung River is also used as a source of raw water for the Municipal Water Works of Jember Regency. Assessment of the water quality of the Bedadung River in 2016 using the pollution index method in the urban area segment placed the river in the 'moderately polluted' category (Pradana et al., 2020). Another study stated that inspection of exposure to organic matters in the form of COD in the 2017 observation period for one of the water intakes of the Municipal Water Works of Jember Regency exceeded the Class I quality standard (Pradana et al., 2019b). The present study was conducted in the Bedadung River in the Bedadung Watershed, as shown in (Figure 1**)**. The research location was the Bedadung River segments of the Patrang, Sumbersari, and Kaliwates districts. The length of the Bedadung River that passes through this Jember Regency urban segment is ± 5 km. The data input used in this research were stream flow, total suspended solid (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), and the distribution of pollution sources. The Bedadung River streamflow trend data for the 2001–2018 observation period was obtained from the Public Works Agency-Water Resources Management of Jember Regency, while the water quality data was obtained from the results of monitoring by the Jember Regency Environmental Agency in the 2016–2018 observation period. According to the Ministry of Environment Decree No. 1 (2010), the key water quality parameters observed in the River Clean Program are TSS, BOD, and COD. These three parameters are considered capable of reflecting the dynamics of river-water quality (Davis and Cornwell 2008).

Measurement of total pollution load capacity

The total pollution load capacity (TPLC) of a river is the river's ability to accept pollutants that do not exceed the quality standard according to a particular designation. The quality standard used in this study is the Class I quality standard for clean or domestic water sources stipulated by Government Regulation No. 82 (2001). The equation for determining the total pollution load capacity of the river is $TPLC = PL_{min} - PL_{observed}$ (TPLC = total of pollution load capacity (kg/day); PL_{min} = pollution load meeting quality standard (kg/day); and $PL_{observed}$ = pollution load observed (kg/day) (Djoharam et al., 2018).

System dynamics construction

Scenario formulation and simulation was created through system dynamics modeling using Powersim

5.0 software. The limits of this model were the research segments of the watershed and the urban area segment, together with the potential pollution load of the segment observations. This method allows a system dynamics modeling of total potential load pollution (TPLP) fluctuation from urban area activities and industry and agricultural-influenced total pollution load capacity (TPLC) of the Bedadung River. It represents holistic relationships between TPLP and TPLC in the river's urban area segment.

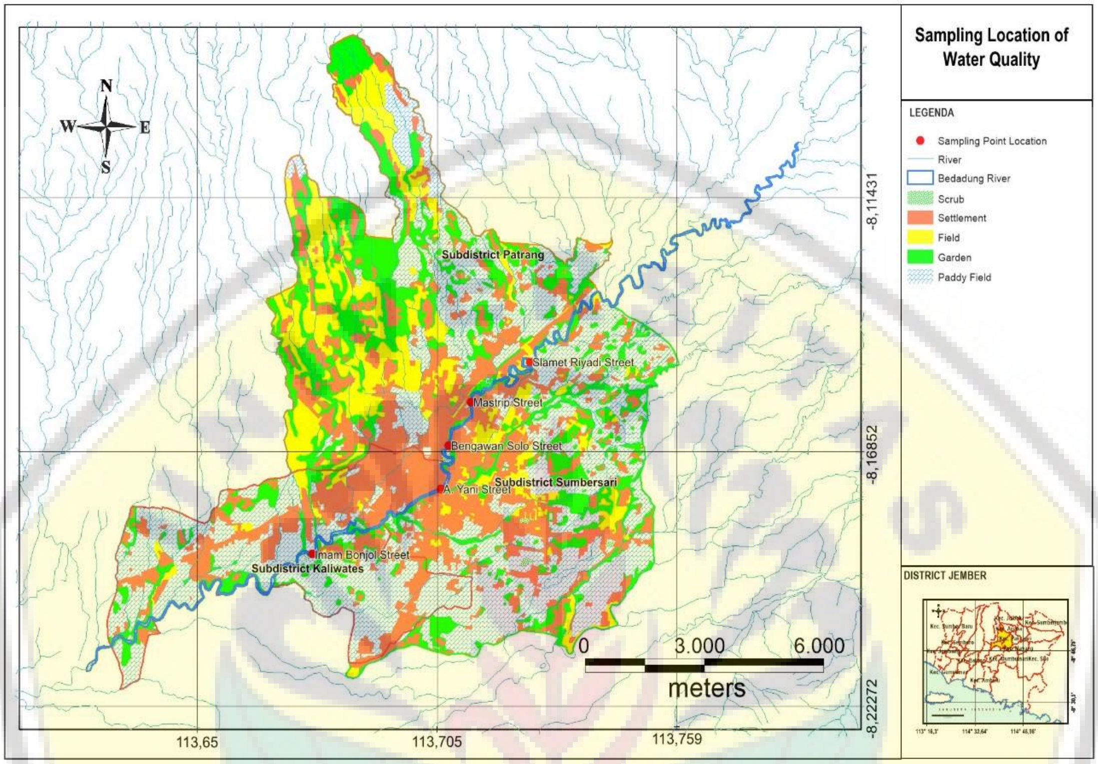

Figure 1 Geographic location of the study area; map of the Bedadung watershed in the Regional Activity Center (Pusat Kegiatan Wilayah-PKW) segment of Jember Regency, East Java Province, Indonesia.

1. In this study, the model was developed using a top-down approach, the first step being the main model design. This is broken down into sub-models to determine the causal relationships between model components (Ford,1999; Sterman, 2001; Liu et al., 2015).
2. Three sub-models were developed in this study, namely the social sub-model, i.e. domestic activities (wastewater and garbage), economic sub-models (industrial, agricultural, and livestock activities), and environmental sub-models (total pollution load capacity or TPLC of a river).
3. Causal loop diagrams were used in the inventory of data from initial observations, and the results were then used to identify patterns of interaction between variables in the real system of river-water quality management. After this, a causal loop diagram was drawn up, as presented in (Figure 2). This diagram represents the reciprocal interaction between the components of the model, both positive and negative. The causal loop diagram contains the relationships of key variables, including water quality, economic activity, population, and environmental management costs. Good river-water quality conditions will reduce environmental management costs and thus create a substantial negative loop, in that the existence of environmental costs has a negative contribution to economic activity. The variables included in the causal loop diagram are generally still intact and are then detailed according to the needs in the stock and flow diagram. These variables are Bedadung River-water quality, land use, domestic activities, and economic activities in the Bedadung River Basin in Jember Regency.
4. Output validation modeling is a method used to determine feasibility from the results of a system dynamics simulation. Quantitative output validation of the simulation was by means of the value of mean absolute percentage error (MAPE) or mean absolute relative error (MARE) testing (Wei et al., 2012; Liu et al., 2015). The recommended ranges of values for the MAPE calculation are < 5% (very accurately describes real conditions) and 5–10% (accurately describes real or actual conditions) (Xi et al., 2013; Liu et al.,

2015). The calculation of the validation test for system modeling output is,

$$\text{MAPE} = \frac{1}{n}\sum\frac{|D_s - D_a|}{D_a} \times 100\%$$

(MAPE = mean percentage absolute error (%); n = period/volume data; D_s = simulation data (kg/day); and D_a = actual data (kg/day).

5. A sensitivity test was used to assess the suitability of the results of the system dynamics modellng with reference to the possibility of changing real conditions for possible policies. The assumptions were prepared based on the best and worst scenarios. The worst assumption was the river pollution load increasing by 10% from the initial value, while the best assumption was the pollution load decreasing by 10% from the initial value. The assumption was constructed by the relationship ratio of water quality standard IV and I. The water quality standard refers to Government Regulation No. 82 (2001).
6. Several scenarios, existing (ES), moderate (MS), and optimistic (OS), were simulated in the system dynamics modeling. The effects of these three scenarios on river TPLC were observed for the 10 years of the simulation. Details of the scenarios are presented in (Table 1). The most likely decisions were based on the simulation results of system dynamics modeling from the scenarios that have been prepared. River TPLC based on Class I quality standard was used as an indicator of environmental quality and as the basis for target achievement in the system dynamics model scenario for river environmental quality management.

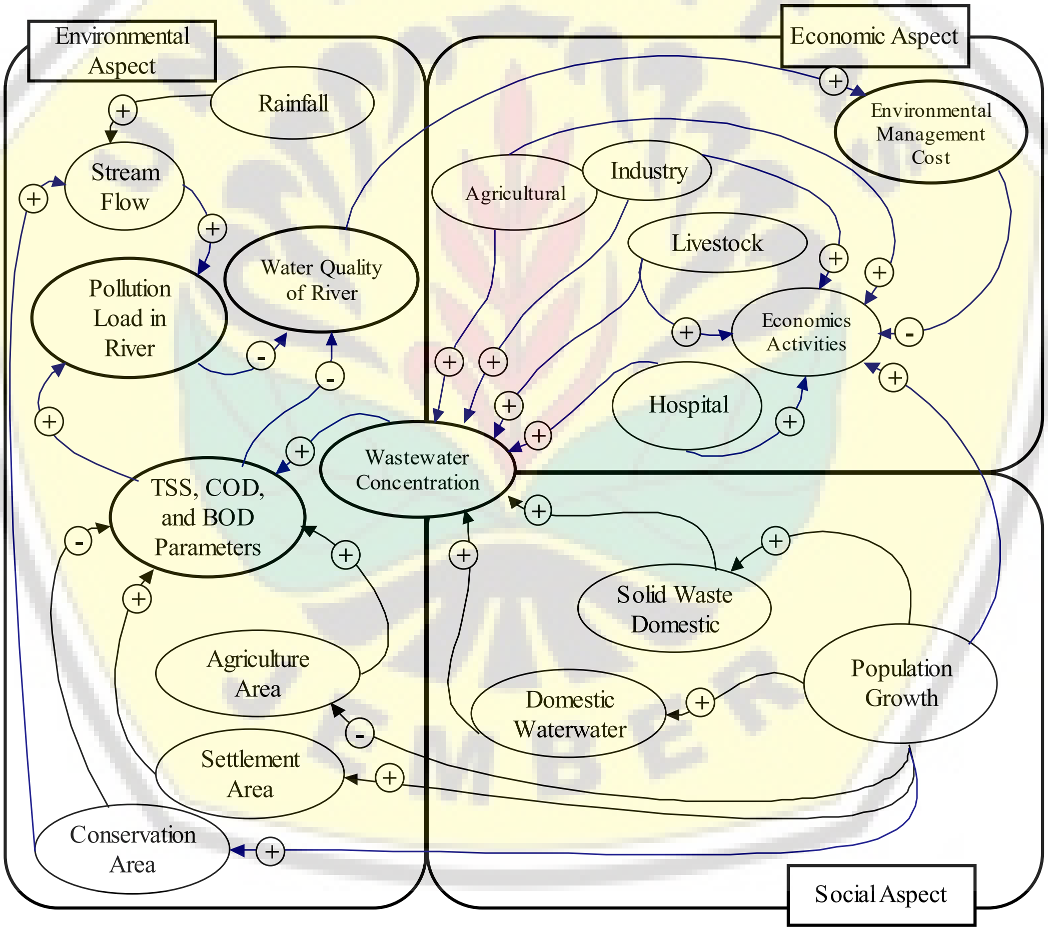

Figure 2. Causal loop diagram of surface water quality management in the Bedadung Watershed; urban area segment, i.e. Patrang, Sumbersari, and Kaliwates District; feedback of environmental, social, and economics aspect.

Table 1 Details of system dynamics scenario in water quality management modeling.

Scenario	Condition assumption of total pollution load potential (TPLP)	Alternative strategy	Characteristic of environmental management	References
Existing scenario (business as usual) (ES)	Existing condition or business as usual	1. The appeal does not pollute the river 2. The agreement does not dispose of solid waste in the river	On-site	(Pradana et al., 2020)
Moderate scenario (MS)	TPLP decreases by 50%	1. Best management practice (BMP) method in nonpoint source pollution (agricultural sector) 2. Sanitation improvement and septic tanks used for domestic wastewater 3. Cleaner production applied for livestock and industry (soybean processing) 4. Composting for organic solid waste, inorganic solid-waste management with a solid waste bank, and river clean-up	On-site	(Wulandari et al., 2017; Sari et al., 2018; Santos et al., 2018; Wang et al., 2019; Pradana et al., 2019b; Ayilara et al., 2020)
Optimistic scenario (OS)	TPLP decreases 90% and TPLC improvement	1. Best management practice (BMPs) method in nonpoint source pollution (agricultural sector) 2. Cleaner production applied for livestock and industry (soybean processing) 3. Integrated solid-waste management 4. Wastewater treatment plant and sludge treatment plant applied 5. River restoration in urban area segment	On-site and off-site	(Wohl et al., 2015; Wulandari et al., 2017; Sari et al., 2018; Santos et al., 2018; Mrozinka et al., 2018; Wang et al., 2019; Pradana et al., 2019b; Ayilara et al., 2020)

Results and Discussion

Model validation

The MAPE value represents the level of deviation from the prediction of the pollution load in the real river. The average deviation is not more than 5%, so the quantitative potential error from the overall simulation results in the system dynamics models do not have a significant effect. Details of the validation model are presented in (Figure 3).

TPLC simulation result for the existing condition

The value of TPLC tends to fluctuate, as can be seen in (Figure 4) and the BOD and COD pollution loads tend to exceed the TPLC of the river. The pressure of TPLP of BOD and COD damages the TPLC of the Bedadung River. The potential reduction in TPLC of the Bedadung River over the 10 years of the simulation in the existing (business as usual) situation is 30 to 60%. If there are no efforts to improve environmental management, the pressure of this pollution load will lower water quality and hence the feasibility of Bedadung River being used as a source of raw water. In line with these findings, the results of the study by Pradana et al. (2019a) explained that the degradation ability of organic matter in the form of BOD in the Bedadung River is fairly good, but that decline in river-water quality would still occur due to anthropogenic activities.

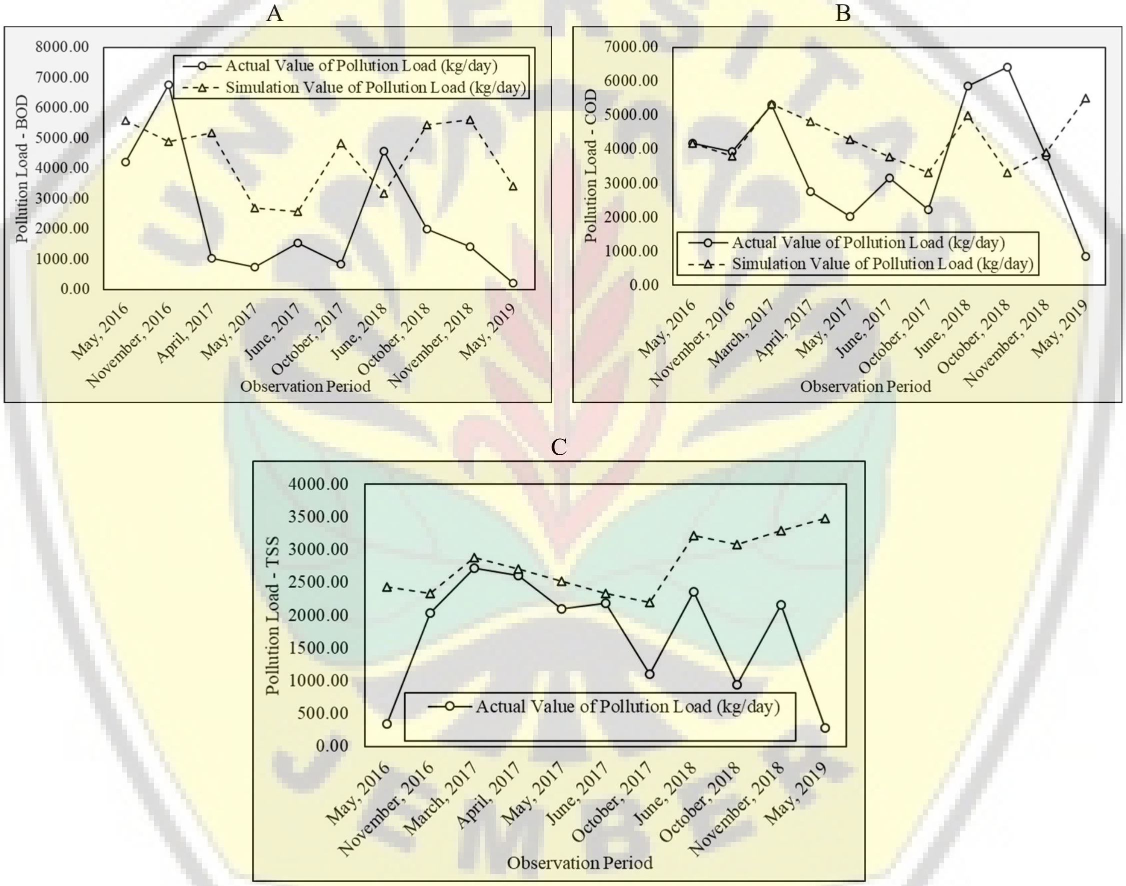

Figure 3. Validation output; A) pollution load of BOD, B) pollution load of COD, C) pollution load of TSS

Organic matter exposure in rivers has the potential to increase operational costs for water treatment by municipal waterworks (Yudo and Said, 2018). Alternative strategies for pollution control of rivers are monitoring of water quality, minimizing waste production, improving sanitation, wastewater treatment plants (WWTP), and increasing public awareness through socialization and education (Halmat et al., 2017; Yudo and Said, 2018). These findings can be used for reference in the water quality management strategy adopted for the Bedadung River to ensure that the river's pollution load does not exceed Class I quality standards.

TPLC simulation result for the scenarios

The scenarios in this study represent alternative strategies for water quality management in the Bedadung River. The simulations address the dynamics of TPLC of Bedadung River, as shown in (Figures 5 and 6). The moderate and optimistic scenarios (MS and OS) would be predicted to increase the TPLC of the river. The impact of moderate scenario (MS) on the improvement of water quality is indicated by the TPLC of the river. TPLC parameters for BOD and COD increase to 9% and 4% per year, respectively, while the optimistic scenario (OS) has a relatively larger impact on increasing river TPLC based on the organic matter parameters. In OS the increase in river TPLC in terms of BOD and COD parameters reached 30% and 4% per year, respectively. The values for increasing river TPLC to TSS parameters in both MS and OS are in the range of 2% per year.

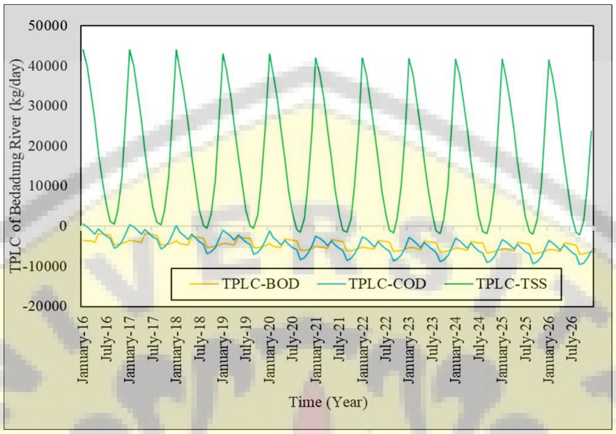

Figure 4. Simulation value of TPLC in the existing condition

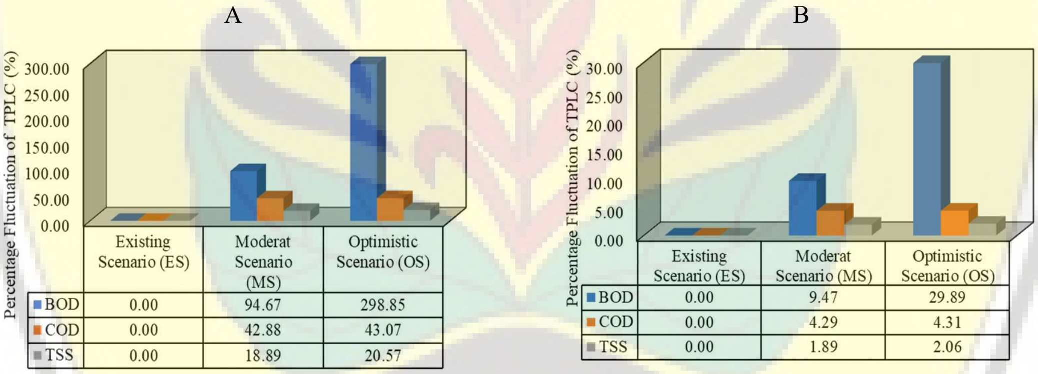

Figure 5. A) Dynamics of Bedadung River TPLC over 10 years. B) Dynamics of Bedadung River TPLC over 1 year.; minus sign = decline.

Recommendation analysis for water quality management policy

In general, sustainable water quality management must consider the roles of the community, other stakeholders, and government. The recommendation for the medium term is the moderate scenario (MS). This scenario has a strategy of controlling potential pollution load on-site until TPLP is reduced by 50% using detailed strategies as described in (Table 1). However, there is a possibility of decreasing water quality due to pressure from anthropogenic activities and natural processes still occurring. The deficit trend in TPLC is predicted to occur August–October at the end of the simulation period in 2026. This consequence can be minimized with river-water quality management and optimizing of raw water source treatment technology by the municipal waterworks of Jember Regency as adaptative actions (Pradana et al., 2019b).

In the MS the target of reducing TPLP can increase the TPLC of quite large rivers in comparison to the simulation results obtained for baseline or existing conditions. This positive result is supported by a strategy that is applied based on several studies, details of which can be seen in (Table 2).

1. Areas that are classified as medium-sized cities have 75% of their wastewater treatment carried out on-site (Supriyatno 2000). Domestic wastewater treatment by subsurface wastewater infiltration and septic tanks is fairly effective and efficient in areas that are not too densely populated. Population density is one of the considerations for the

application of both treatment methods. The technology is based on the principle of infiltration wells and the feasibility of its application is based on the depth of groundwater (Li et al., 2019). Thus, the optimization of environmental sanitation needs to be carried out through independent or centralized latrine development programs.

2. Domestic solid-waste management must consider community perceptions and the availability of facilities (Wulandari et al., 2017). Reducing the amount of solid waste disposed of into rivers can be carried out based on increasing public awareness of the environment, efforts to install waste banks, and improving urban solid-waste management facilities.
3. The area of agricultural land that has the potential to produce agricultural wastewater runoff is 116 ha, based on interpretations using Google Earth satellite imagery. The application of best management practice (BMPs) methods can reduce the use of production inputs in the form of fertilizers and pesticides (Wang et al., 2019). This method is thought to reduce the potential pollution load that will be generated from the agricultural sector.
4. Cleaner production applications in industries can reduce the amount of waste generated by 80% (Supriyatno, 2000; Santos et al., 2018). The alternative strategy for cleaner production in the soybean processing industry is minimizing the use of environmental pollutant raw materials and reusing the resulting organic waste to provide added value in the form of income for production costs or other income to support the industry.
5. The addition of pretreatment and optimization of the use of ultrafiltration as a secondary treatment is an adaptative recommendation that can be made by the municipal water works of Jember Regency in processing raw water sources from the Bedadung River. This pretreatment is in the form of biofilters that can reduce organic matter (Yudo and Said, 2018). Secondary treatment is carried out using a combination of coagulant treatments such as Poly Aluminum Chloride (PACl) and ultrafiltration. Such treatments can improve coagulant performance and reduce operational costs (Arhin et al., 2019). This approach was applied to the Tegal Besar water treatment plant in addressing the concentration of organic matter in the Bedsadung River exceeding Class I in the observation period in 2017 (Pradana et al., 2019b).

The moderate scenario (MS), if applied in the medium term, is predicted to increase river TPLC by 50% from the existing condition.

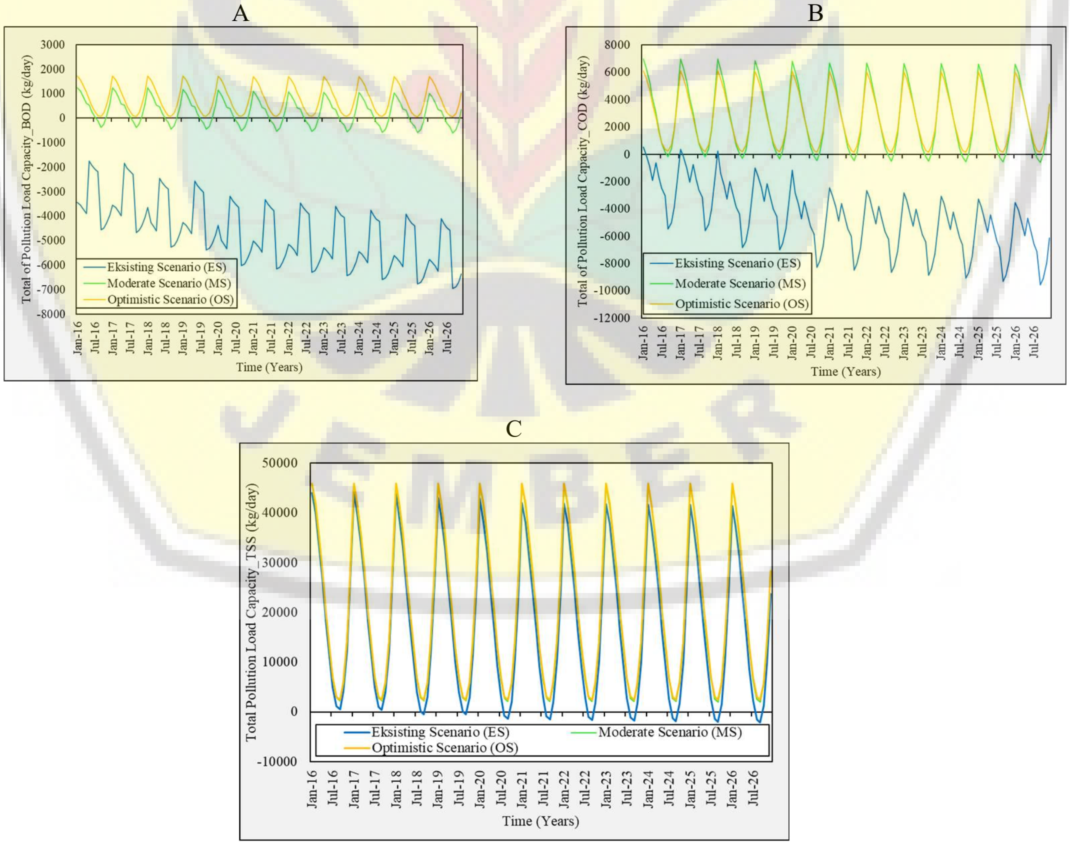

Figure 6. Scenario result; A) TPLC simulation value of BOD, B) TPLC simulation value of COD, B) TPLC simulation value of TSS.

Table 2. Details of system dynamics scenario in water quality management modeling.

Sector	Waste characteristic	Control efforts	References
Domestic	Wastewater	Wastewater treatment application and sanitation improvement on-site; subsurface infiltration system application; septic tank development (on-site and public)	(Government Regulation of the Republic of Indonesia No. 82, 2001; Statute No. 28, 2002; Statute No. 18, 2008; Statute No. 32, 2009; Regulation of Environment Ministry No. 8, 2010; Regulation of Environment and Forestry Ministry No. 10, 2018)
	Organic and inorganic solid waste	Solid waste bank implementation; consistency in implementing agreements not to throw garbage into the river; periodic solid waste clean-up in the Bedadung River	
Agricultural	Runoff from agricultural cultivation	Best management practices (BMPs) implemented in agricultural cultivation	
Industry and livestock	Wastewater	Application of cleaner production methods	
Hospital	Effluent from WWTP (Waste Water Treatment Plant)	Water quality monitoring and evaluation of WWTP performance	

Water quality management can also be carried out by increasing the TPLC of rivers through restoration efforts. Such efforts are reported to be able to increase reoxygenation and degradation of organic matter by up to 70% and sustainably improve river-water quality (Mrozinka et al., 2018). Therefore, the application of the optimistic scenario (OS) can also be considered for long-term sustainable river-water quality management. These efforts are carried out by increasing river TPLC and controlling the pollution load off-site and on-site in the form of individual and or communal wastewater treatment plants and sewage treatment plants. Considering their high investment and operational costs, efforts of this type need to involve various parties such as stakeholders and local and central government.

Conclusion

The existing results from the system dynamics simulation showed that there is a dynamic change in Total Pollution Load Capacity (TPLC) each month. The range of TPLC values in the Bedadung River is -6949.88 to -1747.85 kg/day BOD; -9563.51 to 515.53 kg/day COD; and -2130.40 to 44,089.65 kg/day TSS for the 10 years of the simulation (2016–2026). The simulation results for 10 years or times show that the Bedadung River TPLC has been exceeded refer to the BOD and COD parameters. It has the potential of water quality poor impact and threatens the vital function of the Bedadung River as one of the raw water resources in the Jember Regency. Then, the dynamics of this pollution load are thought to be due to fluctuations in the potential pollution loads from the agricultural, domestic, and industrial sectors. The results of the analysis of the system dynamics modeling in this study provide recommendations, namely the moderate scenario on-site for the medium term and the optimistic scenario for the long term, both on-site and off-site. This information can be used as considerations for planning and managing the water quality of surface water resources in Jember Regency.

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