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Design simulation waste water treatment plant with off-site system method in pulp and paper company

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Abstract

The pulp and paper industry processes wastewater through an Integrated Wastewater Treatment Plant (IPAL) by utilizing a Wastewater Treatment Plant (WWTP) to treat liquid waste before discharging it into river basins (DAS). Wastewater treatment technologies in industrial settings can be applied using biological, chemical, or physical methods, depending on the characteristics of the waste. This study focuses on wastewater treatment in the pulp and paper industry using an off-site system with a filtration model. Water quality is evaluated using the Biochemical Oxygen Demand (BOD) parameter, which indicates the amount of oxygen required to decompose organic matter contaminating the river basin (DAS). The calculation of BOD in the river basin system is conducted by designing a simulation model employing a waterfall flow system and volume control. Verification results reveal that, in general, the pollutant concentration at 24 sampling points in the river basin (DAS) is consistently lower in the simulation model compared to actual measurements. The simulation model design yielded a BOD value of 11.648 µg/m^3, while the actual measurement was 16.56 µg/m^3. Similarly, the SO_2 concentration was 6.17 µg/m^3 based on the simulation model, compared to 16.12 µg/m^3 in the actual measurements. These findings demonstrate that the wastewater treatment units employed are effective in significantly reducing pollutants in the wastewater. The treated wastewater complies with quality standards, as evidenced by parameters such as pH, TSS, Fe, Cu, Cr, Zn, PO_4, free chlorine, and oil and grease, all of which meet regulatory thresholds.

Keywords: *concentration reduction, filtration method, off-site system, river water quality, wastewater treatment plant*

1. Introduction

The pulp and paper industry is currently faced with the challenge of managing a substantial amount of solid waste (Daniel et al., 2022). The largest contribution comes from sludge generated during wastewater treatment, as every process unit in the pulp and paper industry produces liquid waste that is collectively treated in the Wastewater Treatment Plant (WWTP) within the effluent treatment unit (Bhambhani et al., 2025). Industrial liquid waste treatment technologies and methods can be applied biologically, chemically, or physically, depending on the type of waste (Willy & Mukono, 2023b). To minimize waste, three key actions must be taken: altering industrial raw materials, modifying production processes, and recycling waste (Purwaningrum et al., 2023). Altering raw materials and modifying production processes aim to reduce the amount of waste generated, including improving the efficiency of material usage during production. If the production process still generates waste, efforts to minimize it are carried out through recycling or reusing the waste produced.

Waste minimization is implemented to reduce both the quantity and pollution levels of waste generated during a production process through reduction, utilization, and treatment of waste. Waste reduction is achieved by improving or optimizing the efficiency of processing equipment, optimizing treatment facilities and infrastructure such as piping systems, and eliminating leaks, spills, and the disposal of materials and waste.To reduce the waste discharged into rivers, a device is designed to precipitate waste within pipeline channels. Waste treatment in the pulp and paper industry is conducted using an off-site system with a filtration model (Williams & Ceallaigh, 2024). The treatment of waste from the pulp and paper industry using an off-site system with a filtration model is carried out in two stages (Dazmiri & Hamzeh, 2023). The first stage involves assessing and optimizing the remaining production by-products. The second stage focuses on designing a filter to minimize the waste concentration before it is discharged into the river, ensuring that the river's water quality is maintained. Water quality can be measured using the Biochemical Oxygen Demand (BOD) parameter, which indicates the amount of oxygen required to decompose organic matter contaminating the river water (Arisandi, 2020). The calculation of BOD in a river system can be measured using a plunge flow model with volume control (Zhang et al., 2025).

Responsible and sustainable waste and environmental management is an essential action to preserve the environment and ensure the continuity of human life in the future. One of the actions taken is related to the management of hazardous and toxic waste (B3), as addressed in this study, which refers to Government Regulation No. 101 of 2014 on the Management of Hazardous and Toxic Waste (B3) (Willy & Mukono, 2023a). In addition, the foundation for managing hazardous and toxic waste (B3) is also driven by the ESG (Energy, Social, Governance) principles, which emphasize the importance of sustainability in all business activities of a company (Jamal, 2024). If a company is able to implement ESG, investor confidence in the company increases, and ESG-based companies are considered relatively more resilient, having a higher capacity to withstand crises. Additionally, they can create long-term value and profitability (Jamal, 2024). The pulp and paper industry is considered one of the most polluting industries in the world (K. et al., 2011). The pulp and paper industry processes its waste through an Integrated Wastewater Treatment Plant (IPAL), which treats liquid waste before it is discharged into the river basin (DAS)(Busyairi et al., 2020). Here is the simulation system diagram of the wastewater treatment plant (IPAL) for the pulp and paper industry, which serves as the general standard, shown in Figure 1 .

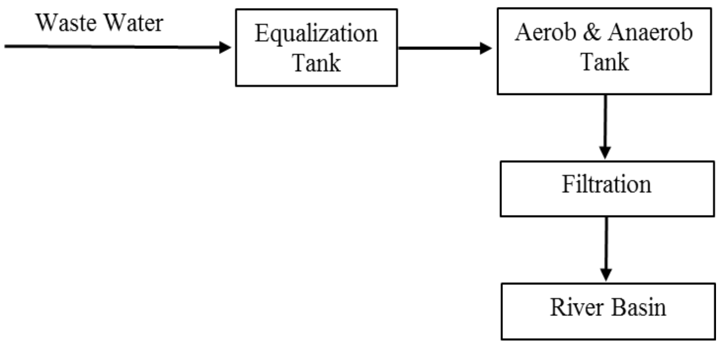

Figure 1. Waste water treatment plant concept

To reduce the waste concentration discharged into the river basin (DAS), a device is designed to precipitate waste within the pipeline. The wastewater treatment of the pulp and paper industry using the off-site system with a filtration model is carried out in two stages: first, by assessing and optimizing the remaining production by-products, and second, by designing a filter to minimize the waste concentration before being discharged into the river, ensuring that the river's water quality is maintained. Effluent quality standards are necessary as a reference for wastewater treatment before discharge to prevent environmental damage and harm to aquatic life. The quality standards used by this pulp and paper company are outlined in the Minister of Environment Decree No. 08 of 2009 on Effluent Quality Standards. Table 1 below shows the allowed effluent standards for discharge into the sea (Republic of Indonesia Government, 2009).

Table 1. Effluent standards allowed for discharge into the sea

No	Parameter	Maximum Allowed Concentration
1	Ph	6 - 9
2	Total Solid Suspend (TSS)	100 mg/dl
3	Oil and Grease	10 mg/dl
4	Free Chlorine (Cl_2)*	0.5 mg/dl
5	Total Chromium (Cr)	0.5 mg/dl
6	Copper (Cu)	1 mg/dl
7	Iron (Fe)	3 mg/dl
8	Zinc (Zn)	1 mg/dl
9	hosphate (PO_4)**	10 mg/dl

Note: *If the cooling tower blowdown is discharged into the wastewater treatment plant (IPAL), **If phosphate injection is carried out.
Source: Government of the Republic of Indonesia (2009)

Waste treatment must be carried out before being discharged or released into the environment. Waste must be treated because it contains pollutants that are harmful or can contaminate and damage the environment, potentially posing a threat to human health (Blanco et al., 2023). Waste, whether in large or small quantities, and over short or long periods, can cause changes or even damage to the environment, which can directly impact humans. Wastewater treatment can be carried out in two ways. First, naturally, by creating stabilization ponds. In stabilization ponds, wastewater is treated naturally to neutralize pollutants before being discharged into water bodies. Common types of stabilization ponds include anaerobic ponds, facultative ponds (for treating wastewater contaminated with concentrated organic materials), and maturation ponds (used for destroying disease-causing microorganisms). Second, artificially, using a Wastewater Treatment Plant (IPAL). This treatment process is carried out in three stages: primary treatment, secondary treatment, and tertiary treatment. Primary treatment, the first stage of treatment, aims to separate solid and liquid substances using filters and sedimentation tanks. (Kassa et al., 2023). The equipment used may include slow sand filters, multimedia filters, microstraining, rapid sand filters, vacuum filters, and percolation filters. Secondary treatment, the second stage of treatment, aims to coagulate, remove colloids, and stabilize organic substances in the wastewater. The decomposition of organic materials is carried out both aerobically and anaerobically. (Khan et al., 2024). Tertiary treatment, the final stage of treatment, aims to remove nutrients or essential elements, particularly nitrates and phosphates, as well as to add heat to kill pathogenic microorganisms (Rasool et al., 2023).

2. Methodology

The research was conducted at a pulp and paper company over a period of one month, from August 2 to September 2, 2024. This is a descriptive study that describes the wastewater treatment process using the Wastewater Treatment Plant (WWTP) method at the pulp and paper company. The study employed a direct observation approach at the WWTP site, as well as a review of relevant regulations and laws (Crini et al., 2019). The calculation of the liquid waste flow rate for the pulp and paper company is determined by calculating the capacity of the waste disposal tank at the pulp and paper company (Tchobanoglous et al., 2014), The liquid waste flow rate for the pulp and paper company can be calculated using the following equation:

$$Q = \frac{V}{t} \qquad \text{...(1)}$$

Note : V : volume (m^3); Q : debit of wastewater (m^3/day); t : time (day)

Descriptive analysis of the characteristics of pulp and paper company liquid waste in the form of BOD (Biochemical Oxygen Demand), COD (Chemical Oxygen Demand), TSS (Total Suspended Solids) and pH (Potential Hydrogen) (Shobriyah & Pramestyawati, 2022). A quantitative descriptive study aims to describe or explain events or data in the form of meaningful numbers (Apelabi et al., 2021). Sampling takes into account a composite location, considering several factors, including matching all the dye substances used completely at one time, and ensuring the same quantity of dye substances are used across different locations. Sampling was carried out during peak hours in the morning, from 09:00 AM to 10:00 AM WIB. The peak time was chosen to determine the peak flow rate, which allows for the determination of the optimal dimensions for the wastewater treatment tank. The wastewater treatment process used by the pulp and paper company is:

a. Equalization tank

The Equalization Tank functions as a reservoir for liquid waste before treatment. The purpose of using this tank is to regulate fluctuations in both the quality and quantity of the wastewater. The design criteria for the storage tank can be seen in Table 2.

Table 2. Design criteria for the equalization tank

No	Criteria	Units	Value
1	Surface Load	m^3/m^2.day	32-48
2	Dam Load	m^3/day	125-500
3	Retention Time	Hours	1-4
4	Tank Depth	1016	2.5-3.7

Source: (Tchobanoglous et al., 2014)

b. Anaerobik tank

The anaerobic tank is where wastewater treatment is carried out biologically. This process uses bacteria to break down pollutants in the wastewater, and these bacteria can live and reproduce without the need for oxygen. According to (Apriliyani et al., 2023), The calculation for the anaerobic tank is carried out using the following equations, Equation 2 and Equation 3:

$$\text{Media Volume} = \frac{\text{Processing load of BOD}}{\text{Load standard of BOD}} \quad \text{.............................(2)}$$

$$\text{Residence Time} = \frac{\text{Reactor Volume}}{\text{Q x 24 Hour/day}} \quad \text{..................................(3)}$$

c. Aerobik Tank

The aerobic tank is a wastewater treatment unit that uses attached microorganisms, where the aeration unit is continuously supplied with oxygen. The decomposition process in the aerobic tank continuously takes place. (Apriliyani et al., 2023). The design criteria for aerobic treatment can be seen in Table 3.

Table 3. Aerobic processing design criteria

No	Criteria	Units	Value
1	BOD Load per Media Unit	Gr BOD/m^2.day	5 – 30
2	Sludge Space Height	m	125-500
3	Microbial Growth Media Bed Height	m	1-4
4	Water Height Above Media Bed	m	2.5-3.7
5	Maximum Retention Time	hours	

Source: (Tchobanoglous et al., 2014)

d. Filtration

Filtration is a wastewater treatment process used to remove or reduce the amount of solids by using a filter (Aprilianto & Oktaviananda, 2024). The type of filter used is a membrane filter. The pore diameter size and the molecular limits that can be separated by various membranes are shown in Table 4.

Table 4. Pore diameter and molecular weight limits of membranes

Parameter	Unit	Test Results		
		Average	Maximum	Minimum
BOD_5	mg/L	357.75	559	124.43
COD	mg/L	2,551.1	4,760	625
TSS	mg/L	2,399.5	5,076	95
pH	mg/L	7.05	.8,97	6.35

Source: (Tchobanoglous et al., 2014)

3. Result and Discussion

This pulp and paper company has several characteristics of liquid waste, including its dark and grayish or colored appearance, distinctive odor, high levels of dissolved solids and suspended solids, high Chemical Oxygen Demand (COD) and resistance to biological oxidation (Shobriyah & Pramestyawati, 2022). Before being discharged into the river, the wastewater treatment process is carried out. The Wastewater Treatment Plant (WWTP) at the pulp and paper company consists of 14 tanks, each with different treatment processes. The flowchart of the liquid waste treatment system at the pulp and paper company can be seen in Figure 2.

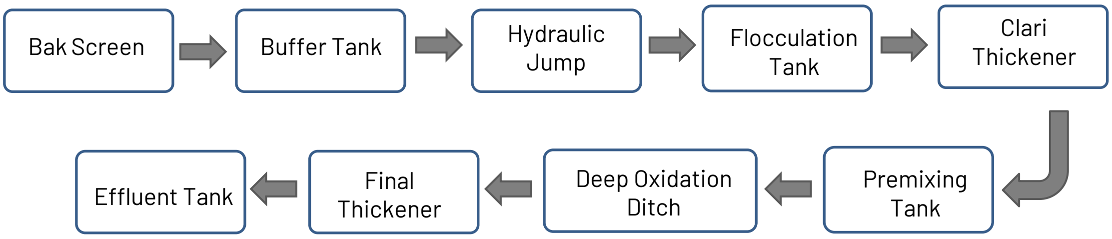

Figure 2. Flowchart of the wastewater treatment process at the pulp and paper company

a. Wastewater quality standars

The wastewater that undergoes various treatment processes and quality testing can be evaluated to determine whether its contents meet the established standards. In other words, it should not exceed the upper or lower limits of the quality standards specified in the Indonesian Ministry of Environment Regulation No. 5 of 2014 concerning Wastewater Quality Standards. The recap of the average, maximum, and minimum values for the contamination indicators is shown in Table 4.

Table 4. Recap of the average, maximum, and minimum values for contamination indicators

Parameter	Unit	Result Test		
		Average	Maximum	Minimum
BOD_5	mg/L	357.75	559	124.43
COD	mg/L	2,551.1	4,760	625
TSS	mg/L	2,399.5	5,076	95
pH	mg/L	7.05	8.97	6.35

Source: Company production data

b. Efficiency of the wastewater treatment plant (WWTP)

As the industrial sector grows, the emergence of various negative impacts on the surrounding environment becomes inevitable. These impacts include the degradation of environmental quality, such as the deterioration of river water quality. River water that is suitable for supporting life typically has a pH range of 6.5 – 7.5. Wastewater and by-products from industrial activities discharged into rivers can alter the water's pH, ultimately disrupting the life of aquatic organisms (Busyairi et al., 2020). Water pollution fundamentally arises from a certain concentration of pollutants in water over an extended period, leading to harmful effects. In response to environmental issues, pulp and paper companies implement various treatments through their Waste Water Treatment Plant (WWTP), which processes wastewater before being discharged into river systems. The river basin (Daerah Aliran Sungai or DAS) has been identified as one of the critical river basins in the Spatial Planning Plan (Purwaningrum et al., 2023). This placement is based on the indication that the condition of the stilling basin is inadequate, leading to significant sedimentation of sludge in the main channel. Additionally, there is still a high level of water pollution caused by industrial wastewater.

Various technologies and methods for handling industrial wastewater can be applied biologically, chemically, or physically, depending on the type of waste. The capabilities and availability of existing technologies in industrial waste management form the basis for determining the standard wastewater quality standards for industries. Numerous studies have been conducted on wastewater treatment, including separating chemical solutions into anolyte and catholyte using IONAC MA 4375 and Tokuyama ACS membranes (Pramitasari, 2017). Water purification using Constructed Wetlands (CW) relies on four key components for success: vegetation, an optimal water pond, suitable substrates or media, and the presence of specific microorganisms. Regarding the research on the pulp and paper company, three main strategies are employed to minimize waste: changes in raw materials, changes in the production process, and waste recycling. The aim of modifying raw materials and production processes is to reduce the amount of waste generated, which includes improving the efficiency of auxiliary materials used in production. If the production process still generates waste, minimization efforts are made through recycling or reusing the waste produced.

Waste minimization is an implementation aimed at reducing the quantity and level of pollution of waste generated from a production process through reduction, utilization, and treatment of waste (Rahmadi et al., 2021). The reduction of waste is carried out through improvements or optimization of the processing infrastructure, such as the piping system, eliminating leaks, spills, and waste materials. To reduce the waste levels discharged into rivers, a device is designed to precipitate waste in the pipeline. In this study, the treatment of pulp and paper industry waste aims to minimize the waste concentration before it is discharged into the river, thereby maintaining the river's water quality. Water quality can be expressed by the Biochemical Oxygen Demand (BOD) parameter, which measures the amount of oxygen required to decompose organic matter that pollutes the river water. This filtration-based off-site system treatment approach consists of two stages. First, assessing and optimizing the residual by-products from production. Second, Designing a filter to minimize the waste concentration before being discharged into the river, ensuring that the river's water quality is preserved (Arisandi, 2020). The calculation of Biochemical Oxygen Demand (BOD) in river systems can be approximated using the plung flow model with volume control as shown in Figure 3.

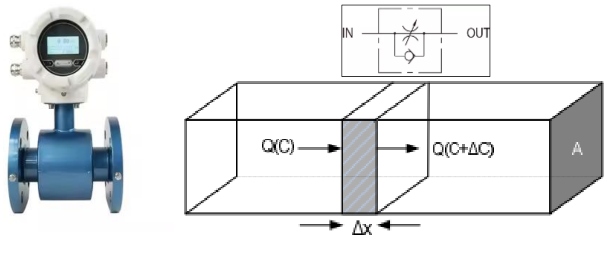

Figure 3. Volume control in the plung flow system

Based on the illustration in the above image, which represents the simulation of Volume Control in the Plung Flow System, the following equation model can be formulated:

Calculation of volume control: Accumulation = Inputs-Outputs+Reactions

$$\frac{d(VC)}{dt} = QC - Q(C + \Delta C) - kCV \text{ ....(X)}$$

$$C\frac{dV}{dT} + V\frac{dC}{dT} = QC - Q(C + \Delta C) - kCV \text{ ....(XX)}$$

The equation (X) divided by V for V = A Ωx and dV / dt = 0 yields:

$$\frac{dC}{dt} = \frac{QC}{A\Delta x} - \frac{QC}{A\Delta x} - \frac{Q\Delta C}{A\Delta x} - kC \text{ ....(XXX)}$$

For limit $\Delta x \rightarrow 0$, maka $\frac{dC}{dt} = \frac{QdC}{Adt}$ - kC, bila $\frac{Q}{A} = \bar{u}$

So: $\frac{dC}{dt} = \bar{u}\frac{dC}{dt} - kC$

Where: Q river discharge, C pollutant concentration, V volume, A cross-sectional area, t time, K biodegradation reaction constant, ũ water flow velocity and X length of the river segment.

The measurement results of pollutant concentration after filtration show a decrease in concentration at several sampling points. The pollutant concentration is influenced by the wastewater discharge from the industry into the river. In analyzing pollutant concentrations in the Watershed (DAS) of a pulp and paper company, initial conditions and boundary conditions are used as input for the model. The distribution model to determine pollutant concentration is an application of these three equations, built using Matlab software. The analysis results of concentration intervals at 24 sampling points are shown in Figure 4.

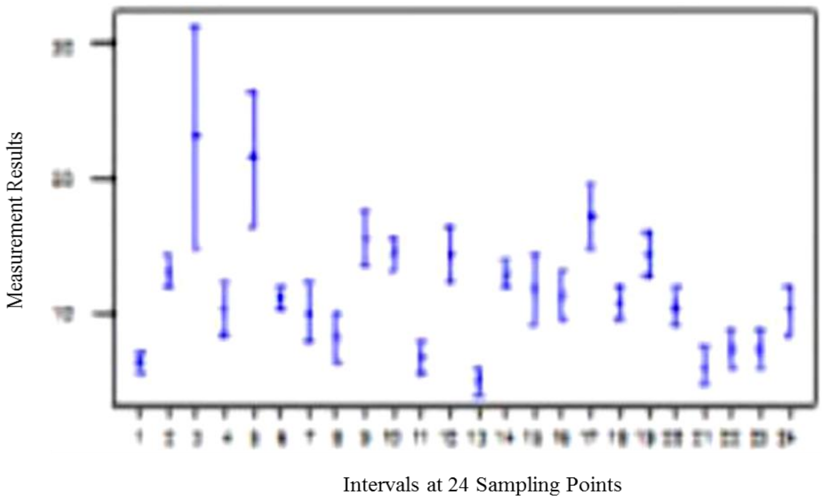

Figure 4. Pollutant concentration interval at 24 sampling points

The verification results indicate that, generally, the pollutant concentration at 24 sampling points in the Watershed (DAS) of the pulp and paper company shows that the model results are always lower than the measured values. For example, at one sampling point in the Watershed (DAS), the model predicts a concentration of 51.058 μg/m^3, while the measured value is 16.56 μg/m^3. A significant discrepancy occurs in various regions where the model predicts a concentration of 11.289 μg/m^3, whereas the measured concentration is 41.42 μg/m^3. Similarly, the model predicts a concentration of 7.168 μg/m^3, while the measured concentration is 19.78 μg/m^3. Additionally, the model estimates a SO_2 concentration of 6.17 μg/m^3, while the measured concentration is 16.12 μg/m^3. The differences between the model and the measurements are attributed to the fact that the model only considers pollutants discharged from the industry. The reduction in pollutant concentration in the water of the watershed area after filtration is shown in Figure 5.

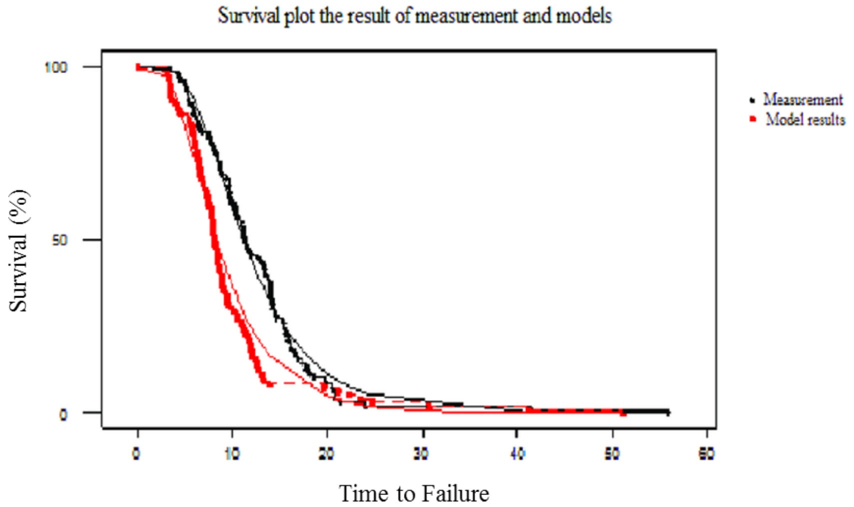

Figure 5. Reduction of water pollution concentration

In efforts to preserve the environment, wastewater treatment has become one of the priorities that must be addressed seriously. One solution to this issue is the operation of a Wastewater Treatment Plant (WWTP), a process aimed at purifying water and removing harmful contaminants to make it suitable for use (Mainardis et al., 2020). The treated water from this process is not only used for drinking but also for irrigation, river maintenance, and industrial water supply. Meanwhile, wastewater from industrial activities requires a separate, designated location. This is because industrial wastewater contains a higher level of contaminants, which are more hazardous. Therefore, a dedicated storage system is needed to ensure that the treated water does not mix with other, more sterile treated water. Enhancing the utility of water is crucial for human life, making it essential to understand the role of a Wastewater Treatment Plant (WWTP). Below are some of the functions of treating industrial wastewater from various manufacturing activities at factories or other commercial sites.

In analyzing the concentration at several points in the Watershed (DAS), initial conditions and boundary conditions are used as input for the model. To reduce the amount of waste discharged into the river, a device is designed to sediment the waste in the pipeline system (Peraturan Pemerintah, 2021). The Waste Water Treatment Plant (WWTP) addresses wastewater from the pulp and paper company through off-site system methods, with a filtration model carried out in two stages. First, the remaining production waste is analyzed and optimized. Second, a filter is designed to minimize the waste concentration before it is discharged into the river, ensuring that the river water quality remains maintained. The wastewater treated using the physical-biological treatment unit meets the quality standards set by the Ministry of Environment Regulation No. 5 of 2014. The concentration of industrial wastewater does not exceed the quality standards, which are: BOD < 60 mg/L, COD < 150 mg/L, TSS < 50 mg/L, oil < 3 mg/L, and pH > 6.0-9.0. The physical-biological wastewater treatment process has an effectiveness in reducing pollutants ranging from 56.73% to 97.65% (Busyairi et al., 2020). This indicates that the wastewater treatment with the used unit can optimally reduce pollutants in the wastewater. As a result, the treated wastewater can be properly managed, producing water with good quality, as indicated by parameters that are below the quality standards, including pH, TSS, Fe, Cu, Cr, Zn, $PO4$, free chlorine, as well as oil and grease. (Rangga et al., 2023).

4. Conclusion

To reduce the amount of waste discharged into the river, a device has been developed to sediment waste in the pipeline system. In this study, wastewater from the pulp and paper company is treated using an off-site system method with a filtration model. The treatment process for the pulp and paper company's wastewater through the off-site system with the filtration model is carried out in two stages. First, the remaining production waste is analyzed and optimized. Second, a filter is designed to minimize the waste concentration before being discharged into the river, ensuring that the river water quality remains maintained. The measurement results of pollutant concentration after filtration show a decrease in concentration at several sampling points. The pollutant concentration is influenced by the volume of wastewater discharged from the industry into the river. In analyzing pollutant concentrations in the Watershed (DAS), initial conditions and boundary conditions are used as input for the model. The pulp and paper company conducts various treatments through the Wastewater Treatment Plant (WWTP), which provides wastewater treatment before it is discharged into the Watershed (DAS). The technology and methods for treating industrial wastewater can be applied biologically, chemically, or physically, depending on the type of waste available.

In this study, the pulp and paper company applies various treatments through the Wastewater Treatment Plant (WWTP) to process wastewater before discharging it into the Watershed (DAS). Water quality can be expressed through the Biochemical Oxygen Demand (BOD) parameter, which refers to the amount of oxygen required to break down organic materials that contaminate the river water. BOD calculations in a river system can be approximated using a plunge flow model with volume control. The verification results indicate that, generally, the pollutant concentration at 24 sampling points in the Watershed (DAS) from the wastewater treatment of the pulp and paper company shows that the model results are always lower than the measured values. For example, the model predicts a concentration of 11.648 $\mu g/m^3$, while the measured value is 16.56 $\mu g/m^3$. Similarly, the model predicts a concentration of SO_2 at 6.17 $\mu g/m^3$, while the measured concentration is 16.12 $\mu g/m^3$. This indicates that the wastewater treatment process with the unit used can effectively reduce pollutants in the wastewater. As a result, the treated wastewater can be properly managed and results in high-quality water, as indicated by the wastewater parameters that meet the quality standards, including pH, TSS, Fe, Cu, Cr, Zn, $PO4$, free chlorine, as well as oil and grease.

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