

ANALYSIS OF CLARIFIER SLUDGE GENERATION AND COMPRESSIBILITY AS A BASIS FOR SLUDGE REMOVAL OPTIMIZATION

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Graphical abstract



ABSTRACT

Clarifiers in Water Treatment Plants (WTPs) generate sludge through the accumulation of suspended particles and chemical coagulants, making sludge estimation essential for efficient plant operation. This study investigates the relationships between clarifier influent characteristics, sludge generation, and sludge compressibility to optimize sludge discharge operations. A quantitative experimental approach was employed by measuring turbidity, Total Suspended Solids (TSS), and sludge volume through Imhoff cone sedimentation tests conducted at intervals of 10–120 minutes. Twenty samples were purposively collected from the clarifier inlet over two weeks. Linear regression analysis revealed a strong relationship between turbidity and TSS ($R^2 = 0.9936$), expressed as $TSS\ (mg/L) = 1.2634 \times Turbidity\ (NTU) + 2.3212$. TSS also strongly correlated with sludge volume ($R^2 = 0.9269$), following the equation $Sludge\ Volume\ (mL/L) = 0.06 \times TSS\ (mg/L) - 0.782$. Sedimentation observations indicated a transition from flocculent settling to compression settling at higher TSS concentrations, resulting in reduced sludge volume due to interparticle pressure. These findings supported the development of a dynamic mathematical model of sludge accumulation and compressibility, integrated into a Microsoft Excel-based monitoring dashboard. The proposed approach provides a practical tool for estimating sludge generation, supporting sludge discharge scheduling, and improving operational control of WTP clarifiers.

Keywords: Clarifier, Sludge Generation, Sludge Compressibility, Total Suspended Solids, Water Treatment Plant.

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1. INTRODUCTION

The provision of drinking water that meets quality standards is a necessity for supporting public health and sustainable development. To produce water suitable for consumption, a water treatment system is needed that can reduce the levels of physical, chemical, and biological contaminants in raw water (Darmasetiawan, 2024).

One of the key processes in a water treatment system is coagulation–flocculation and sedimentation (Smith & Scott, 2005). In this process, suspended particles and colloids in raw water are destabilized through the addition of a coagulant, then aggregated into larger flocs so they can be settled by gravity in the sedimentation tank (Tchobanoglous & Burton, 2003). The effectiveness of the sedimentation process significantly affects the quality of the treated water, particularly in reducing turbidity and Total Suspended Solids (Davis, 2010).

The process of treating raw water into clean water produces sludge as the main waste from various production units (Azzahra et al., 2014). In reducing the suspended solids content, the sedimentation process produces sludge as a byproduct formed from the accumulation of suspended particles, flocs resulting from the coagulation reaction, and residues of chemicals used in the treatment process (Azizah et al., 2022). The characteristics of suspended particles vary in mass and size and are influenced by flow conditions. At high flow velocities, larger particles may remain carried by the flow, whereas as the velocity decreases, particles will settle according to their size and mass (Spellman, 2004).

According to Davis (2010), sedimentation is classified into four types based on particle characteristics and flow conditions: discrete settling, flocculent settling, zone settling, and compression settling.

The volume of sludge produced is influenced by the quality of the raw water, production capacity, and the concentration of impurities in the water body (Alfa Julian & Lindu, 2015). Estimating and evaluating sludge generation are critical aspects of planning and operating water treatment plants. Sludge generation calculations can be performed using the mass balance approach, the correlation between turbidity and TSS, or water balance analysis within the treatment (Shao et al., 2023). A mass balance for sludge and sludge volume can be established from the source of production—namely, the sedimentation tank—through to the final sludge treatment unit (Nurul (Nurul Aulia et al., 2023)). The relationship between the sedimentation and compression processes is also explained by Usher and Scales (2005) who combined predictions of free sedimentation with suspension compression to model solids flux.

Although various estimation methods have been developed, calculations of sludge generation under actual operating conditions often show variations influenced by raw water characteristics and sedimentation process efficiency (Shao et al., 2023). These conditions highlight the need for a more specific analysis of the sedimentation unit under study in order to obtain more representative estimates.

Estimating and evaluating sludge generation are critical aspects of the planning and operation of water treatment plants. Previous studies, such as those conducted by Shao et.al. (2023), focused on sludge formation mechanisms and the factors influencing them, which were analyzed using machine learning algorithms; three categories of data were collected: water quality data, sludge quantity data, and environmental data. The primary quality indicators used included COD, BOD₅, suspended

solids, ammonia nitrogen, total nitrogen, and total phosphorus. Previous studies were still static in nature, rather than dynamic, and did not utilize a sludge compressibility approach that could be used as control logic for clarifier sludge dewatering.

Estimating sludge generation is also necessary to determine the required sludge hopper capacity and to design the clarifier sludge discharge pipe. Sludge generation that exceeds the sludge hopper's capacity can cause sludge to be carried toward the clarifier outlet, resulting in turbid supernatant water. Research conducted by Koken and Buyukkamaci (2024) found that conventional clarifier sludge discharge pipes cannot handle high sludge volumes, which can damage the sludge layer and result in lower concentrations of discharged solids.

Therefore, an evaluation approach is needed that can link raw water characteristics, sludge generation, and more adaptive sludge removal strategies. This study is expected to contribute both technically and operationally by leading to more efficient operational control in water treatment management.

Based on this background, the research questions in this study are to investigate the relationship between turbidity and total suspended solids (TSS) content in raw water; the relationship between TSS content and clarifier sludge generation; the degree of clarifier sludge compressibility; and the mathematical modeling of sludge compressibility, so that a calculation program for estimating clarifier sludge disposal can be developed using Microsoft Excel software.

The study aims to determine the relationship between turbidity and total suspended solids (TSS) content in raw water, identify the relationship between TSS content and clarifier sludge generation, determine the extent of clarifier sludge compressibility, and develop a clarifier sludge drainage operation program using Microsoft Excel.

2. MATERIALS AND METHODS

This study was designed to analyze the relationship between clarifier influent characteristics and sludge formation as a means of operational control over clarifier sludge disposal at a Water Treatment Plant (WTP). The study employed a quantitative experimental approach with direct observation of water quality parameters and sludge sedimentation dynamics. The study site was selected using purposive sampling at a clarifier unit equipped with an inclined plate settler system, as this unit was deemed capable of representing operational conditions consistent with the study's objectives Sugiyono (2013). The site selection also took into account the significant variation in raw water turbidity, which would provide representative data on sludge formation behavior in the clarifier.

Sampling was conducted using a purposive sampling method at the clarifier inlet at a depth of 20–30 cm from the surface to maintain the stability of the flocs formed during the coagulation–flocculation process. Sampling was performed twice daily—in the morning and afternoon—for two consecutive weeks on weekdays, resulting in a total of 20 samples. Samples were collected using clean containers, following the direction of flow to prevent damage to the floc structure. A 1-liter sample was used for sedimentation observation using an Imhoff cone (Hach, 2015), while a 500-mL sample was used for laboratory analysis of turbidity and Total Suspended Solids (TSS) using the Hach 8006 test method (Hach, 2014). Sampling point location can be seen in figure 1.

The research variables consist of independent variables, dependent variables, and control variables. The independent variables include turbidity, Total Suspended Solids (TSS), and settling time, with observation intervals every 10 minutes up to the 120th minute. The dependent variables are the volume of settled sludge, the rate of sludge sedimentation, and the empirical relationship between TSS and sediment volume. Meanwhile, the control variables include the sampling points and depths, sample volume, sampling method, instrument conditions, and sample transport procedures, all of which were kept constant throughout the study to ensure consistency in every test conducted.



Figure 1. Sampling point

Data analysis was conducted in several stages, beginning with a data quality check to ensure consistency, the validity of measurement results, and the identification of outliers. Outliers were identified using standardized residual analysis on a linear regression model between turbidity and Total Suspended Solids (TSS). Standardized residuals were calculated for each data point and compared with the limits of the normal distribution at a 95% confidence level ($\alpha = 0.05$), namely ± 1.96 . If the standardized residual value from the test data exceeded the ± 1.96 limit, the data was categorized as an outlier and eliminated from further correlation analysis.

Descriptive statistical analysis then performed on the parameters of turbidity, TSS, settling time, and sludge volume to determine the general characteristics of the research data. The relationships among the variables were analyzed using simple linear regression and nonlinear regression approaches when the data relationships were not linear. These analyses were used to derive a mathematical model capable of describing the relationship between influent characteristics and the dynamics of sludge formation in the clarifier. The research results are presented in the form of tables, regression graphs, scatter plots, and flowcharts of the mathematical model within an Excel dashboard. Flow diagram of this research can be seen in figure 2.

In this study, the following equipment was used to support activities ranging from sample collection and testing to data processing:

1. Grab sampler
2. Turbidimeter, HACH TL2300
3. Spectrophotometer, HACH DR3900
4. Imhoff Cone
5. Microsoft Excel software

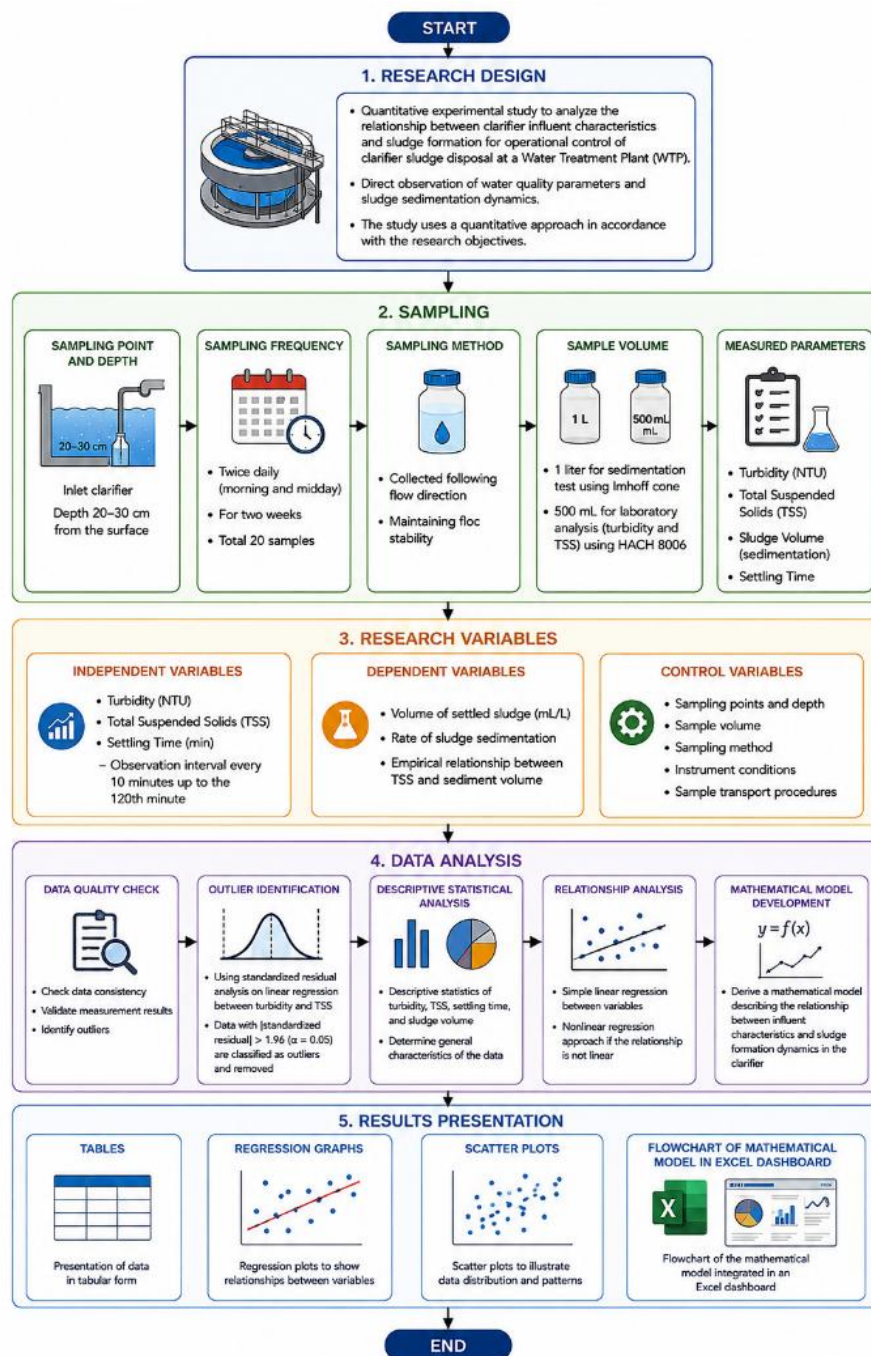


Figure 2. Research flow diagram

3. RESULT AND DISCUSSION

Observations were conducted on 20 samples during the period from February 12, 2026, to February 27, 2026, with the main parameters being turbidity (NTU), Total Suspended Solids (TSS), and the volume of sediment resulting from settling using an Imhoff cone, with observation intervals every 10 minutes up to the 120th minute. This approach was used to describe sedimentation behavior as a time series so that changes in the sedimentation mechanism could be clearly observed.

An analysis of the relationship between turbidity and TSS was conducted using linear regression to evaluate the correlation between the two parameters as indicators of suspended solids in raw water. Theoretically, an increase in the concentration of suspended particles will increase light scattering, causing turbidity values to rise as TSS increases (APHA et al., 2023). The results of the first-stage linear regression analysis showed a linear equation with a coefficient of determination of $R^2 = 0.8924$. Although the relationship between the two parameters was quite strong, outliers were still identified using standardized residuals at a 95% confidence level. The calculation results show that the data point with a turbidity of 133 NTU and a TSS of 289 mg/L has a standardized residual value of 1.972, which exceeds the ± 1.96 threshold. Therefore, this data point was categorized as an outlier and excluded from further correlation analysis. Deviations may occur due to variations in particle size, the composition of suspended material, or natural aggregation, which can cause an increase in TSS that is not always accompanied by a proportional increase in turbidity; this phenomenon is suspected to be the cause of the deviation in these data points.

After eliminating outliers, the coefficient of determination increased to $R^2 = 0.9936$, with the linear regression equation $\text{TSS (mg/L)} = 1.2634 (\text{NTU}) + 2.3212$. In the book *Quantitative Data Analysis*, Indartini and Mutmainah (2024) explain that the coefficient of determination indicates the percentage of the relationship between the dependent variable and the independent variable. In this data analysis, the turbidity value of the raw water accounts for 99.36% of the variation in TSS; therefore, the turbidity parameter can be used as an estimate of TSS in water treatment operations. Julian et al. (2015) found in their study that the correlation between TSS and turbidity in the Cengkareng Drain is $\text{TSS (mg/L)} = 1.02 (\text{NTU})$, while a study conducted by Kusari (2017) showed the relationship expressed by the equation $\text{TSS (mg/L)} = 0.8572 (\text{NTU}) + 3.6805$.

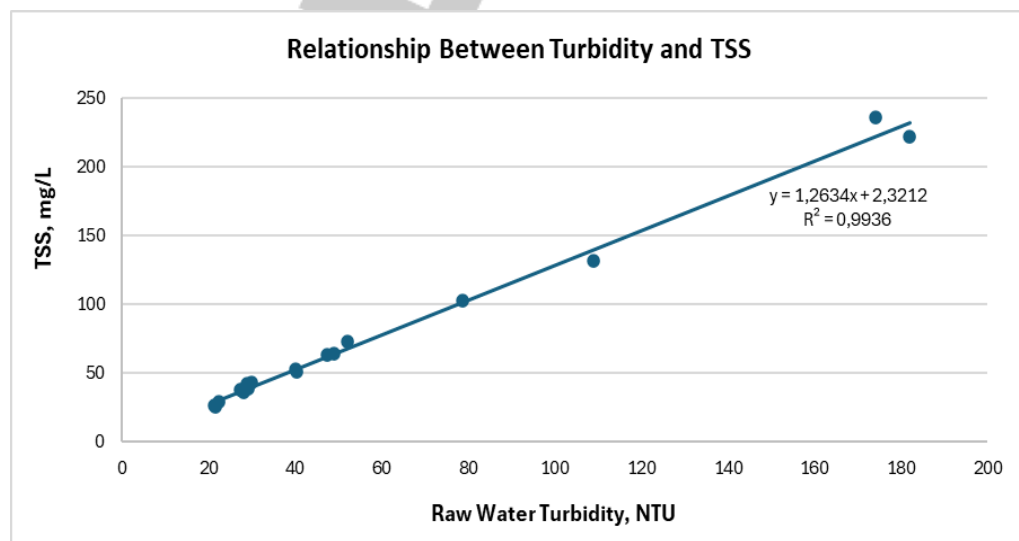


Figure 3. Relationship curve between raw water turbidity and TSS

The relationship between TSS and sludge generation indicates that sludge volume can be estimated using the equation $y = 0.061x - 0.782$, where y is the sludge volume (mL) and x is TSS in mg/L, with a coefficient of determination of $R^2 = 0.9269$. This value indicates that an increase in the concentration of suspended solids will increase the volume of sludge formed during the sedimentation process.

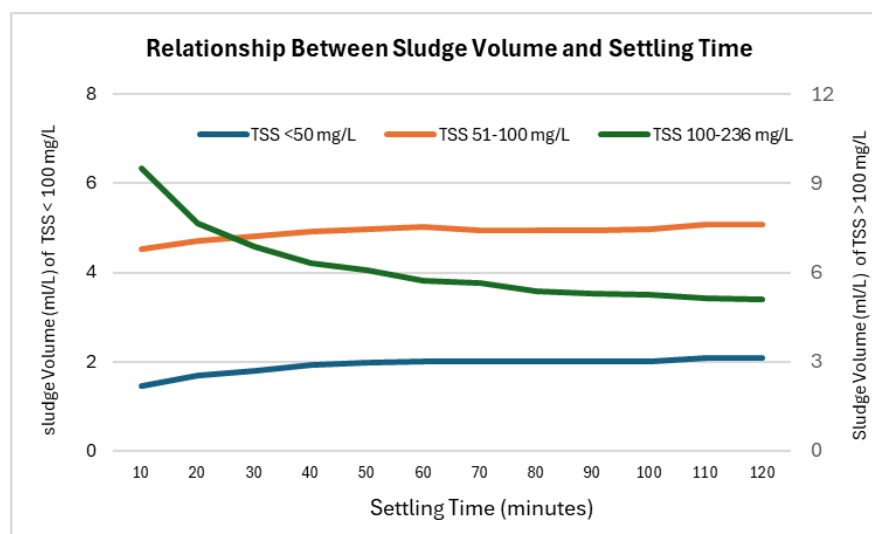


Figure 4. Effect of settling time on sludge volume

The results of the time-series observations of sludge volume, as shown in Figure 4, indicate a change in the sedimentation mechanism across each TSS concentration range. At low TSS levels, the sludge volume increases gradually before reaching a steady state. This phenomenon indicates the dominance of the flocculent settling mechanism, in which suspended particles still move individually and take time to form larger flocs. In the medium TSS range, the sludge volume tends to stabilize after the initial settling phase. In this phase, a sludge blanket begins to form, but the interparticle pressure is not yet sufficient to cause further compaction. Thus, the system is in a transitional state between flocculent settling and compression settling. At high TSS concentrations in samples 132, 222, and 236 mg/L, a progressive decrease in sludge volume occurred over the observation period. This phenomenon indicates sludge compressibility (compression settling), in which settled particles experience effective pressure due to the weight of the overlying sludge layer (Stickland, 2015). This pressure causes pore water to be expelled from the floc structure, resulting in a reduction in the total sludge volume. This compressibility phenomenon is important to note because it directly affects the estimation of sludge hopper capacity and the frequency of sludge removal from the clarifier.

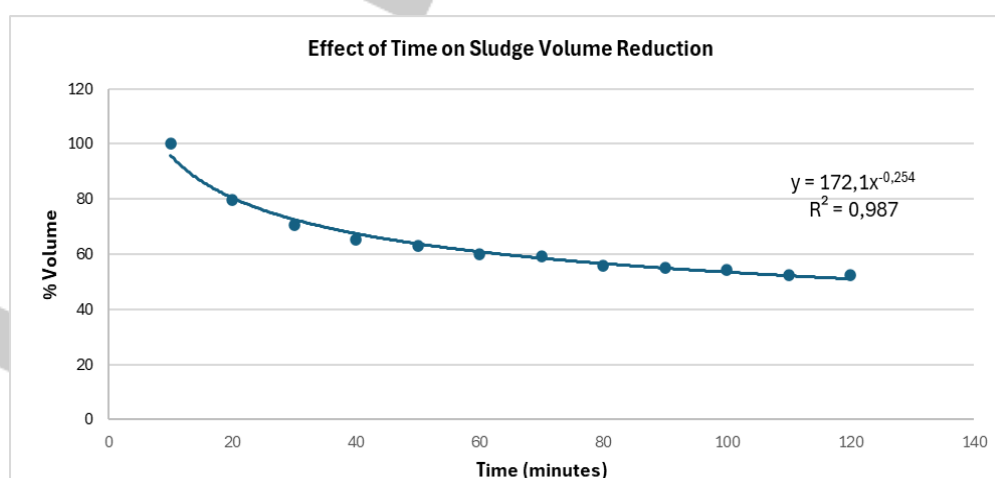


Figure 5. Effect of time on the percentage of sludge volume

Based on phenomenon in figure 5, the process of sludge accumulation in the sludge hopper is influenced not only by the amount of sludge generated but also by compressibility resulting from increased sludge age. Test results show that the sludge volume decreases gradually according to a power function, which represents the remaining sludge volume fraction relative to the initial volume. Thus, each layer of sludge formed at different times will exhibit a different degree of compressibility depending on its sludge age.

Based on this concept, a mathematical model was developed using the convolution integral approach, in which the actual mud volume is obtained from the accumulation of all mud elements formed continuously, each weighted by the experimentally determined compressibility function. In general, the model can be expressed as:

$$V_{comp}(t) = \int_0^t q_s(\tau) R(t - \tau) d\tau \quad (1)$$

where:

$V_{comp}(t)$ = volume of compressed sludge (m^3) at time t .

$q_s(\tau)$ = sludge formation rate at time τ (m^3/minute).

$R(t-\tau)$ = the fraction of sludge remaining after undergoing compression for a time of $(t-\tau)$.

t = observation time (minutes)

τ = sludge element formation time (minutes).

Based on the compressibility regression results obtained from laboratory testing, the compressibility function is expressed as:

$$R(t) = 1,721t^{-0,254} \quad (2)$$

Under operating conditions where the flow rate and raw water quality are considered constant during a single drainage cycle, the sludge formation rate can be assumed to be constant ($q_s = q_0$), so the equation can be simplified to:

$$V_{comp}(t) = q_0 \int_0^t 1,721(t - \tau)^{-0,254} d\tau \quad (3)$$

This model provides a more representative estimate of the actual sludge volume than conventional approaches that assume a constant sludge volume, because it considers the effect of sludge age on the compressibility process.

The results of the analysis and the mathematical model obtained were then used as the basis for developing a sludge generation monitoring dashboard using Microsoft Excel. The dashboard is designed to visually and integrally display the relationship between raw water turbidity, Total Suspended Solids (TSS), sludge formation rate, and changes in sludge volume due to compressibility. Since data collection was limited to sludge samples from the water treatment plant (WTP), this dashboard is restricted to the WTP clarifier unit fed by the coagulation and flocculation units. Data presentation in the dashboard is based on regression graphs and sedimentation time-series curves to facilitate the interpretation of sludge formation patterns. The dashboard display for clarifier sludge disposal settings can be seen in Figure 6 below.

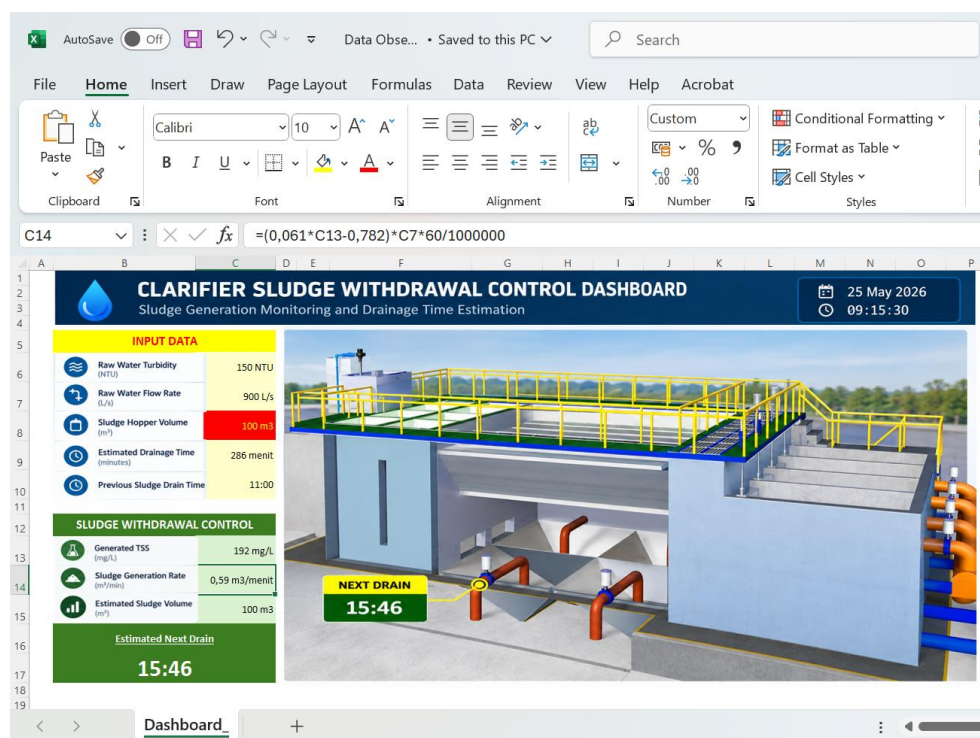


Figure 6. Clarifier sludge discharge settings dashboard

4. CONCLUSION

Based on the research results, the relationship between raw water turbidity and Total Suspended Solids (TSS) showed a very strong linear correlation after outlier elimination, with a coefficient of determination of $R^2 = 0.9936$. This relationship indicates that the turbidity parameter can be used as an approach for estimating TSS in the operations of a Water Treatment Plant. In addition, the relationship between TSS and the volume of sludge resulting from sedimentation also shows a strong correlation with an R^2 value of 0.9269, meaning that an increase in the concentration of suspended solids will be proportional to an increase in sludge production in the clarifier.

Analysis of the sludge volume time series reveals changes in the sedimentation mechanism based on the TSS concentration range. At low concentrations, flocculent settling dominates, whereas at high concentrations, compression settling occurs, characterized by a decrease in sludge volume due to compressibility. This phenomenon indicates that sludge characteristics significantly influence sedimentation dynamics and the capacity of the sludge hopper in the clarifier unit.

Based on the results of the empirical analysis and the mathematical model developed, this study can be used to design a sludge discharge estimation dashboard using Microsoft Excel. The program is designed to use parameters such as turbidity, raw water flow rate, and a timer to determine the timing of the next sludge discharge valve opening, thereby improving operational efficiency and sludge management at water treatment plants.

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