

The Relationship between Rainfall and Total Suspended Solids (TSS) in Stormwater Runoff within a Coal Mining Stockpile Area

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ABSTRACT

This study aimed to analyze the relationship between rainfall characteristics and Total Suspended Solids (TSS) concentrations in stormwater runoff within a coal mining stockpile area. The study is considered important because it provides a scientific basis for understanding the influence of rainfall on TSS concentrations, while also supporting the evaluation of sediment control measures, operational improvements, and the development of sustainable environmental management policies. The data used in this study consisted of inlet TSS concentrations and daily rainfall records, which were categorized into rainfall measurements on the same day as TSS sampling (H0), rainfall measurements one day prior to TSS sampling (H1), rainfall measurements two days prior to TSS sampling (H2), and the cumulative rainfall from these three rainfall measurement variations. Observations were conducted at a monitoring point located in Loa Kulu Kota Village, Loa Kulu District, during the 2019–2025 period. The analysis was performed using polynomial regression statistics and correlation tests. The results showed that the average TSS concentration was relatively low (<100 mg/L), although several extreme spikes reaching up to 750 mg/L were recorded. In contrast, rainfall exhibited a more stable pattern (<150 mm). Polynomial regression analysis produced low coefficients of determination (R^2), with the highest value observed under the H0 condition ($R^2 = 0.1476$), while H1 and H2 yielded only 0.0242 and 0.0088, respectively. Correlation tests further indicated that there was no statistically significant relationship between rainfall and TSS concentrations ($p > 0.05$). These findings suggest that increases in TSS concentrations are more strongly influenced by non-hydrological factors, such as mining operational activities, land cover conditions, and the effectiveness of sediment control infrastructure.

INTRODUCTION

Coal mining activities have the potential to generate environmental pollution, particularly affecting water quality components. One of the key parameters used in water quality assessment is Total Suspended Solids (TSS), which refers to solid particles transported by surface runoff. Mining operations, especially within stockpile areas, expose large portions of soil surfaces, making them highly susceptible to erosion. Rainfall acts as a driving force in the processes of erosion and sediment transport into receiving water bodies (Effendi, 2003; Bilotta & Brazier, 2008). However, several previous studies have indicated that

rainfall is not the sole determinant of elevated TSS concentrations. Other factors, such as operational activities, drainage management, and the effectiveness of sediment control infrastructure, may play more significant roles (Ghose & Majee, 2001; Tumiwa & Budianta, 2015).

Recent studies have further reinforced these findings. A study conducted in Tanah Bumbu Regency reported that TSS concentrations in open-pit mining settling ponds ranged from 76–801 mg/L, with variability likely influenced by rainfall and runoff dynamics (Handayani et al., 2023). Another study on mine water management at PT Antang Gunung Meratus found extremely high TSS concentrations prior to treatment (approximately 4,788 mg/L), which decreased drastically to around 23 mg/L after management interventions, emphasizing the crucial role of operational practices and infrastructure in reducing TSS levels (Azhari et al., 2023). Furthermore, a geospatial modeling study conducted in Pekalongan demonstrated that TSS dynamics increased alongside rainfall intensity and terrestrial runoff, with concentrations ranging from 40.3–85.4 mg/L in 2021 to 64.7–140.5 mg/L in 2022, and were strongly influenced by land use patterns (Prasetyo, Wulandari, & Setyawan, 2022). Meanwhile, a study conducted at Besut Campus Lake revealed that although rainfall and erosion affected water quality, the relationship between rainfall and TSS tended to be weak and was more strongly associated with Total Dissolved Solids (TDS), indicating that non-hydrological factors such as land use and human activities remained significant contributors (Rahman, Ahmad, & Abdullah, 2024).

Understanding the influence of rainfall on TSS is highly beneficial for environmental management in mining operations, as it can serve as the basis for designing more effective sediment control systems, support compliance with water quality standards, and promote sustainable mining practices. The urgency of this study lies in the adverse impacts of elevated TSS concentrations on water quality, light penetration, photosynthesis, and aquatic habitats, which may ultimately reduce biodiversity (Kang et al., 2022; Azhari et al., 2023). Without a proper understanding of the relationship between rainfall and TSS, mitigation and control measures may become ineffective, particularly during the rainy season. Therefore, this study was conducted to evaluate the extent to which rainfall characteristics influence TSS concentrations in stormwater runoff within coal mining stockpile areas.

METHODOLOGY

Research Location

This study was conducted in the ROM stockpile area of a coal mining operation, specifically at the LKCT 02 settling pond (Figure 1). Administratively, the LKCT 02 settling pond is located in Loa Kulu Kota Village, Loa Kulu District. The study was carried out over a three-month period, from March to May 2025, and included field observations, identification of wastewater characteristics in the settling pond, wastewater sampling and laboratory testing, as well as data processing and analysis.

The research location was selected because the available facilities are relatively comprehensive, including the presence of a rainfall monitoring station. In addition, the pollutant load from coal mining activities currently regulated specifically originates from stockpile washing activities, particularly for the TSS parameter. In this study, wastewater sampling was focused on the inlet section of the settling pond.

Data Analysis

The data used in this study consisted of inlet Total Suspended Solids (TSS) concentrations measured in mg/L and daily rainfall data categorized into four groups: rainfall occurring on the same day as TSS sampling (H0), rainfall one day prior to sampling (H1), rainfall two days prior to sampling (H2), and the cumulative rainfall from these three periods. The analyzed dataset covered the period from January 2019 to May 2025.



Figure 1. Research location map

Data analysis was conducted in several stages. First, descriptive analysis was applied to illustrate fluctuations in TSS concentrations and rainfall in order to identify the general distribution patterns of the data. Second, polynomial regression analysis was employed to examine the non-linear relationship between rainfall and TSS concentrations, considering that the relationship between these variables is not always linear. Third, a model fit approach using Structural Equation Modeling (SEM) was applied to evaluate the suitability of the rainfall–TSS relationship model against empirical data, thereby providing a more comprehensive understanding of the factors influencing TSS dynamics within the study area.

RESULT AND DISCUSSION

TSS and Rainfall Patterns

The analysis results showed that TSS concentrations tended to fluctuate, with an average value of <100 mg/L. However, several extreme events were recorded, including a peak concentration of 750 mg/L in March 2025. This spike indicates the occurrence of a *first flush* phenomenon, in which sediments accumulated during dry periods are transported by runoff during subsequent rainfall events. In contrast, daily rainfall and cumulative rainfall values were relatively stable, generally remaining below 150 mm.

These findings indicate that the relationship between rainfall and inlet TSS is complex. Elevated TSS concentrations are not solely determined by rainfall magnitude, but are also influenced by anthropogenic and environmental factors. Therefore, water quality control strategies should not only consider rainfall intensity, but also focus on land-use management, revegetation efforts, and the development of effective sediment control infrastructure.

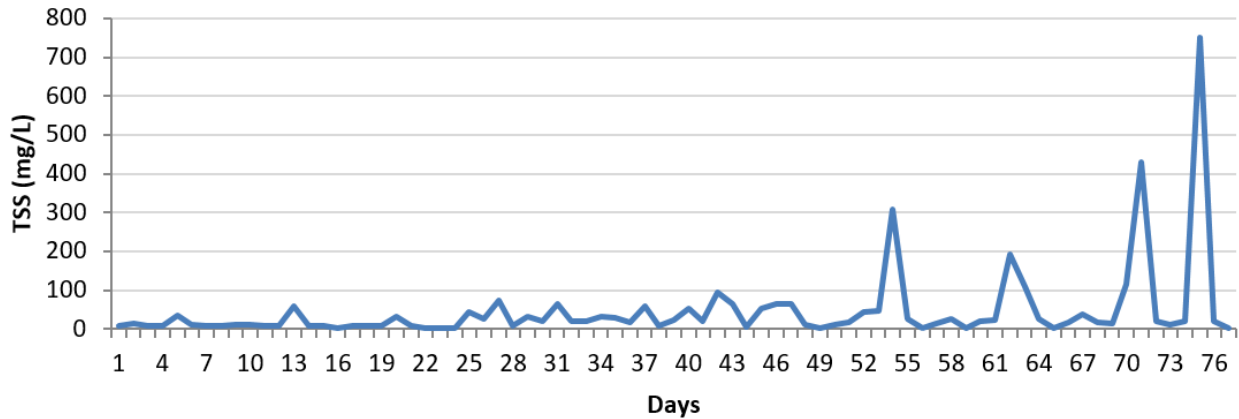


Figure 2. TSS Graph

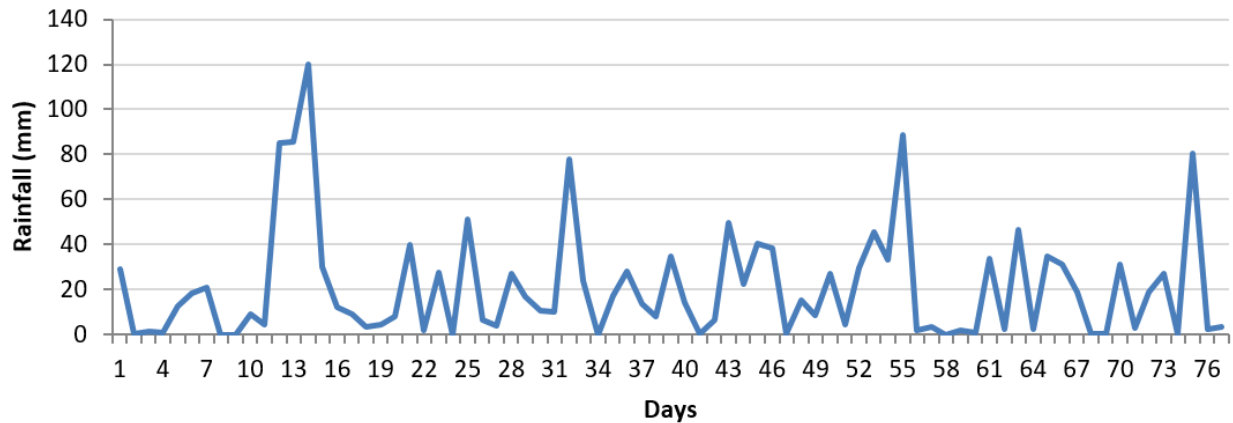


Figure 3. Cumulative Rainfall Graph

Polynomial Regression Analysis

The regression analysis results demonstrated that the relationship between rainfall and TSS concentrations ranged from weak to very weak. Under the H0 condition (rainfall occurring on the same day as TSS sampling), the coefficient of determination (R^2) was 0.1476, indicating the presence of a relationship, although still relatively weak compared to the other conditions. Under the H1 condition (rainfall occurring one day prior to TSS sampling), the R^2 value was only 0.0242, suggesting a very weak relationship. Meanwhile, under the H2 condition (rainfall occurring two days prior to TSS sampling), the R^2 value further decreased to 0.0088, indicating almost no relationship. For cumulative rainfall from H0, H1, and H2, the R^2 value was 0.0593, which also indicated a weak relationship, although there was a slight tendency for TSS concentrations to increase during periods of relatively high rainfall. These findings confirm that TSS variability is more strongly influenced by non-hydrological factors than by rainfall alone.

H0 rainfall refers to the daily rainfall measured on the same day that the TSS water sample was collected. H1 rainfall represents the daily rainfall occurring one day prior to TSS sampling, while H2 rainfall refers to rainfall occurring two days before TSS sampling. Cumulative rainfall represents the total rainfall from the H0, H1, and H2 periods combined.

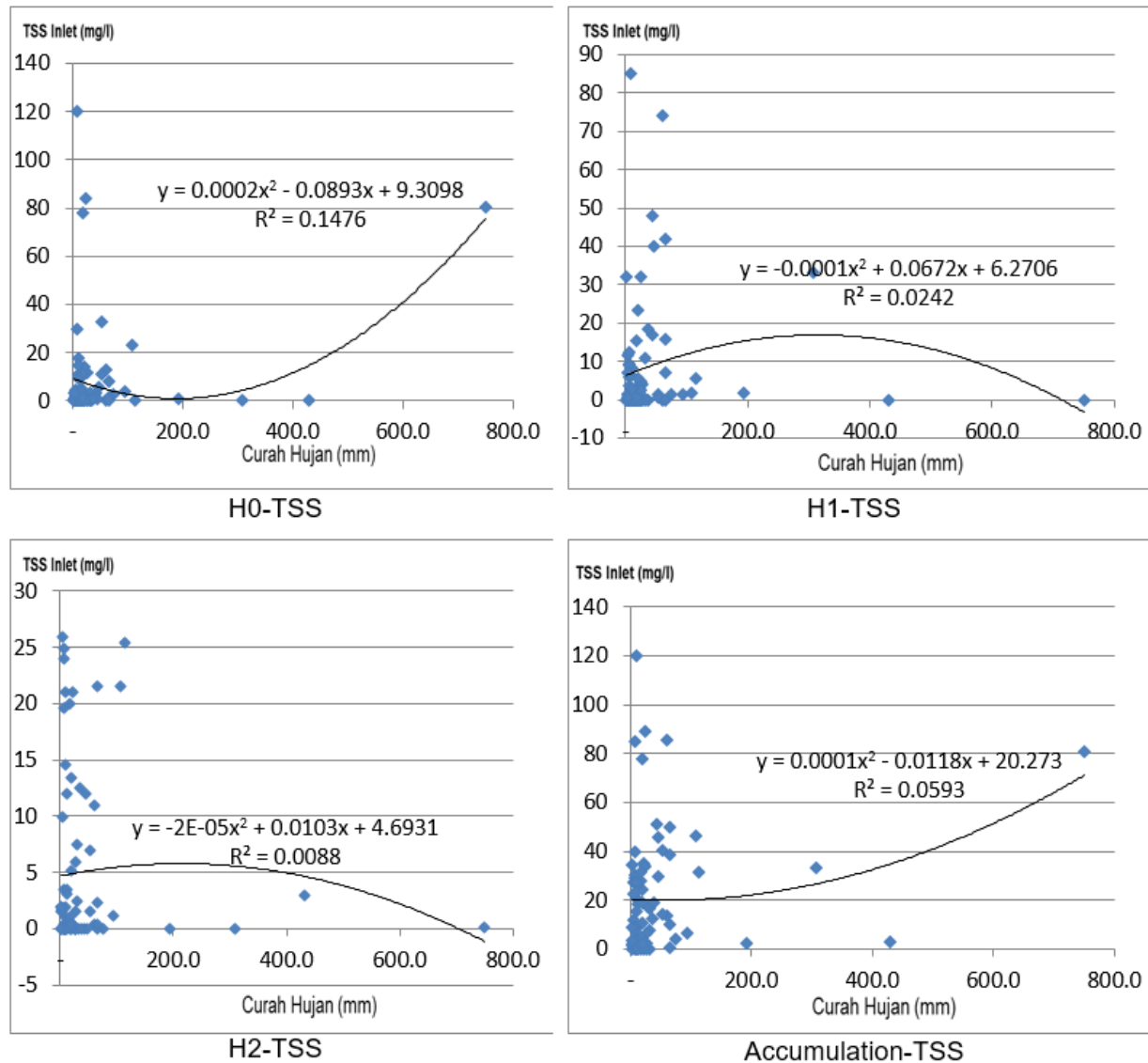


Figure 4. Polynomial Regression Graphs of TSS and Rainfall

Various studies have shown that land management practices and the implementation of sediment control infrastructure often play a more decisive role in determining Total Suspended Solid (TSS) loads than rainfall intensity or duration alone. In the context of open-pit mining, the effectiveness of settling ponds and erosion control channels has been proven to significantly reduce sediment transport, even during periods of high rainfall. Studies by Ghose & Majee (2001) and Tumiwa & Budianta (2015) emphasized that failures or weaknesses in the design and maintenance of sediment control infrastructure may result in substantial increases in TSS concentrations, even when rainfall events are not extreme. These findings are consistent with more recent studies indicating that sediment concentration variability in many watersheds is more closely associated with sediment source availability resulting from land-use change and management practices than with climate variability alone (Zhang et al., 2022; Li et al., 2021).

In addition to technical infrastructure, the presence of vegetation cover also plays a consistent role in reducing erosion and sediment transport. Vegetation contributes through physical protection mechanisms, such as canopy cover that reduces the kinetic energy of raindrops, as well as root systems that strengthen soil aggregation and enhance infiltration. A meta-analysis conducted by Deng et al. (2023) across 88

ecosystem studies demonstrated that vegetation restoration significantly reduced runoff and soil loss. More recent experimental studies further confirmed that vegetation components, including litter, stems, and roots, substantially reduce sediment loads even under moderate rainfall intensity conditions (Wang et al., 2024). These findings are in agreement with the earlier study by Effendi (2003), which emphasized that vegetation cover functions as an effective sediment control factor.

Therefore, recent literature reinforces the view that TSS control in open-pit mining areas cannot rely solely on rainfall characteristics. Land management practices, the effectiveness of sediment control infrastructure, and the implementation of revegetation techniques provide more dominant contributions in reducing sediment loads. This perspective is also reflected in Indonesian national regulations, such as the Decree of the Minister of Energy and Mineral Resources No. 1827 K/30/MEM/2018, which requires mining companies to integrate land reclamation, revegetation, and erosion–sedimentation control facilities as part of good mining practice implementation.

Correlation Analysis

The regression analysis using the Structural Equation Modeling (SEM) approach with the Maximum Likelihood method showed that the relationships among variables in the model exhibited different patterns in terms of significance. Based on the regression table, the H0 variable was found to have a significant effect on TSS, with an estimated value of 0.219, a critical ratio (C.R.) of 3.613, and a significance level of $p < 0.001$. These results indicate that H0 is an important predictor in explaining variations in TSS concentrations, whereas the other variables did not demonstrate substantial contributions (Byrne, 2010).

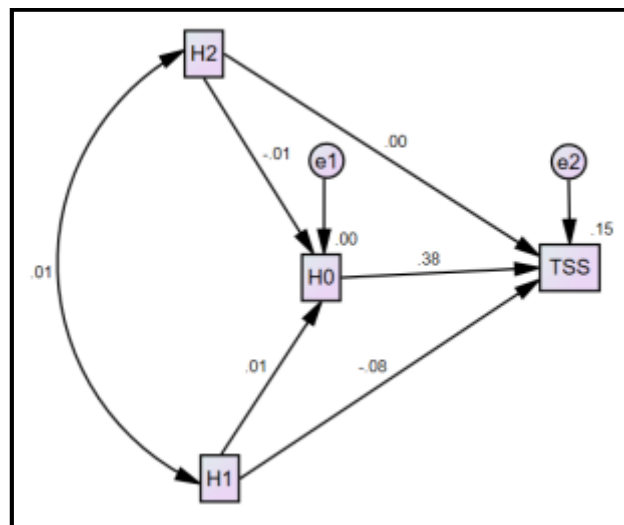


Figure 5. Path Diagram in Structural Equation Modeling (SEM)

In contrast, the relationships between H1 and TSS and between H2 and TSS were not statistically significant. The estimated value for the $H1 \rightarrow TSS$ relationship was -0.070 ($p = 0.454$), while the $H2 \rightarrow TSS$ relationship yielded an estimated value of -0.002 ($p = 0.989$), indicating that both pathways did not contribute significantly to TSS variation. Similarly, the relationships $H1 \rightarrow H0$ (estimate = 0.011 , $p = 0.951$) and $H2 \rightarrow H0$ (estimate = -0.044 , $p = 0.898$) were also not significant. Therefore, it can be concluded that the roles of H1 and H2 within the model structure were relatively weak (Kline, 2015).

Based on the standardized regression coefficients, the effect of H0 on TSS produced a β value of 0.382, indicating that every one standard deviation increase in H0 would increase TSS by 0.382 standard deviations. This coefficient can be considered relatively strong within the context of social and environmental studies, where coefficients above 0.30 are often regarded as substantively meaningful (Hair et al., 2019). In contrast, the effects of the other variables exhibited very small β values, approaching zero, which indicates weak and statistically insignificant relationships.

Overall, these results suggest that the research model primarily emphasizes the role of H0 as the main determinant of TSS, whereas H1 and H2 do not provide meaningful contributions. These findings are consistent with the principles of Structural Equation Modeling (SEM), which emphasize the evaluation of significant pathways as the basis for model interpretation (Hoyle, 2012). Therefore, further discussion should focus on how H0 influences TSS and on the possible mediating or moderating factors that may explain the weak influence of H1 and H2 within the research model.

Interpretation of Results

The findings of this study are consistent with previous studies indicating that water quality in mining areas is more strongly influenced by non-hydrological factors (Ghose & Majee, 2001; Tumiwa & Budianta, 2015). Ineffective sediment control infrastructure and exposed land without vegetation cover have been shown to increase the potential for water pollution. Recent studies further confirm that vegetation plays an important role in reducing sediment runoff (Deng et al., 2023; Wang et al., 2024). Therefore, these findings provide additional empirical evidence that water quality control cannot rely solely on rainfall characteristics, but is also highly dependent on land management practices and local environmental conditions.

The implications of these findings are highly significant for environmental management in coal mining areas. The observation that TSS concentrations are more strongly influenced by non-hydrological factors than by rainfall emphasizes that control strategies should focus on land management and infrastructure optimization. Such measures include improving the effectiveness of settling ponds, enhancing drainage systems, and accelerating reclamation and revegetation programs to reduce erosion and sediment transport rates. Through more integrated management practices, the risk of water pollution can be minimized even under relatively high rainfall intensity conditions, thereby maintaining water quality and ecosystem balance. These findings may be utilized by mining companies to improve operational systems, by local governments and environmental agencies as a basis for supervision and regulation, and by surrounding communities as a form of environmental transparency regarding mining impacts.

For future studies, a more comprehensive approach is required by incorporating additional variables such as runoff discharge, soil quality, and the level of mining operational activities. GIS-based hydrological and sedimentation modeling, as well as event-based monitoring approaches, would greatly assist in understanding TSS dynamics, particularly during extreme rainfall events or following prolonged dry periods that trigger the *first flush* phenomenon. Furthermore, comparative studies across different mining sites are necessary to evaluate the effectiveness of environmental management strategies, including the implementation of innovative sediment control technologies. Such efforts are expected to generate more applicable recommendations and support sustainable mining practices.

CONCLUSION

TSS concentrations tended to fluctuate, with average values generally below 100 mg/L; however, extreme spikes of up to 750 mg/L were observed under certain conditions. The relationship between rainfall and TSS was relatively weak. Polynomial regression analysis showed that the highest coefficient of determination (R^2) was only 14.76% under the H0–TSS condition, while the H1 and H2 conditions demonstrated almost no relationship.

Correlation analysis confirmed that rainfall was not the dominant factor influencing TSS concentrations, but rather acted primarily as a driving force. Non-hydrological factors, such as mining operational activities, land cover conditions, the effectiveness of settling ponds, and the presence of vegetation, played a more significant role in determining TSS concentrations.

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