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Research Article

Study on Mud Management West Banko Area at PT Bukit Asam

Andrew[1,a*)], Bogireddy Chandra[2,b)]

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Abstract

This study investigates mud management in the West Banko area at PT Bukit Asam, focusing on predicting erosion rates, estimating mud volumes, and evaluating sediment pond (KPL) capacity. The methodology integrates field data collection (rainfall, runoff, and soil properties), the Universal Soil Loss Equation (USLE) approach—considering rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), and cover-management (C)—and sediment delivery ratio (SDR) analysis to estimate sediment yield. Results indicate that the predicted annual erosion rate reached 10,818,825.04 m³/year in Pit SJS, 3,190,396.61 m³/year in Pit E, and 1,642,899.98 m³/year in Pit 3 East. After applying SDR values, the corresponding estimated mud (sediment yield) volumes were 3,129,918.88 m³/year (Pit SJS), 971,015.11 m³/year (Pit E), and 500,266.05 m³/year (Pit 3 East). These findings highlight the significant sediment load generated by mining activities, requiring large-capacity sediment ponds to maintain sump functionality and prevent pump inefficiency. The scientific contribution of this study lies in providing a comprehensive quantitative framework for predicting erosion and sediment yield in dynamic open-pit mining environments. By combining hydrological, soil, and slope factors into an integrated mud management system, the research enhances environmental engineering practices by supporting optimized sump design, sediment pond planning, and sustainable water management strategies. Overall, effective mud management not only ensures operational efficiency and slope stability but also minimizes environmental risks, aligning coal mining operations with good mining practices and regulatory compliance.

Keywords: *Environmental Engineering; Mud Management; Open-Pit Mining; Sediment Yield*

INTRODUCTION

PT Bukit Asam, as one of Indonesia's leading coal mining companies, continuously strives to implement sustainable and efficient mining operations in line with good mining practices. One of the key environmental and operational challenges faced in open-pit coal mining is the effective management of mud (sediment-laden water), which results from surface runoff, rainfall, and mining activities. The accumulation of mud in mine pits, sumps, and drainage channels can significantly disrupt mining productivity, reduce pump performance, and pose risks to slope stability and environmental quality [1].

In open-pit coal mines, the influx of water from precipitation, surface runoff, and groundwater often transports fine sediments into pits, sumps, and drainage systems. If left unmanaged, accumulated mud reduces sump storage capacity, increases pump wear, causes frequent operational interruptions, and poses environmental hazards via suspended solids discharge. Because mining front advancement continually reshapes catchment boundaries, a static sediment management design may quickly become obsolete. Although numerous studies have applied the Universal Soil Loss Equation (RUSLE / MUSLE) and Sediment Delivery Ratio (SDR) models to estimate sediment yield in agricultural and watershed contexts, their use in dynamic open-pit mining environments especially with field validation and direct linkage to operational design parameters has been limited. Moreover, while sedimentation ponds (KPL) are widely recommended, very few studies evaluate long-term capacity decline, dredging frequency, or coupling with pump/sump performance in large-scale mining settings. who assessed sediment pond performance in an open-pit mine, but they lacked high-resolution, long-term pond capacity loss data [2].

Recent work in erosion and sediment control underscores both methodological advances and practical gaps. Introduced flow convergence routing strategies for engineered topography to enhance sediment retention in disturbed landscapes [3]. Studied runoff and sediment yield reductions achieved by ecological restoration on steep excavated slopes, showing reductions up to ~53 % for sediment yield [4]. Combined satellite-based land use change mapping with sediment transport simulations to demonstrate how forest loss (35 %) drove increased erosion in steep catchments [5]. The chemistry and toxicity of sediments in mining-impacted rivers have also gained interest: Assessed toxicological profiles of river sediments downstream of open-pit coal mines, highlighting that sediment quantity alone is insufficient for environmental management [6]. Finally, the broader importance of catchment characteristics on pit lake sediment and nutrient dynamics is discussed, demonstrating that catchment morphology and vegetation affect sedimentation patterns in mine lakes [7].

Despite these advances, gaps remain in mining-focused sediment management research, particularly (1) validating predictive models against field measurements in rapidly changing mining catchments, (2) quantifying pond capacity loss and dredging schedules, and (3) integrating predicted sediment loads into pump/sump design and operational simulations. This study addresses the following specific research problems in the West Banko area of PT Bukit Asam:

1. How accurately do predicted sediment yields (SY, in m³/yr) from the modified RUSLE + SDR model align with measured sediment accumulation in KPL and sump systems?
2. What is the annual capacity loss of sediment ponds (KPL) due to sediment deposition, and what dredging frequency is required to preserve operational capacity?
3. How does predicted sediment inflow affect sump design and pump performance (efficiency loss, head requirements) under peak rainfall conditions?
4. Can integrating pre-treatment or staged sedimentation (or biological controls) improve suspended solids removal efficiency beyond conventional KPL design?

By combining predictive modeling, spatial analysis, and field validation, the research aims to produce not only more reliable sediment forecasts but also operationally relevant guidelines for sustainable mud management in tropical open-pit coal mining.

This study aims to address these gaps by validating sediment yield predictions using field data from rapidly changing mining catchments. The research will quantify the annual capacity loss of sediment ponds and determine the dredging frequency required to maintain operational capacity. It will also assess how predicted sediment inflows impact sump design and pump performance (including efficiency loss and head requirements) under peak rainfall conditions. Furthermore, the study will investigate whether integrating pre-treatment or staged sedimentation (or biological controls) can improve suspended solids removal efficiency beyond conventional sediment pond design. By combining predictive modeling, spatial analysis, and field validation, this research aims to provide more reliable sediment forecasts and operationally relevant guidelines for sustainable mud management in tropical open-pit coal mining.

METHODS

The research was conducted over a 12-month period from January to December 2024, covering both the wet and dry seasons to capture seasonal variability in rainfall, runoff, and erosion dynamics. This timeframe ensured that the dataset incorporated peak monsoonal rainfall events as well as low-flow dry periods, providing a comprehensive representation of hydrological and erosion processes within the study pits. This study applied the Revised Universal Soil Loss Equation (RUSLE) to estimate erosion rates in the West Banko mining area of PT Bukit Asam. The RUSLE model, widely adopted in soil erosion and sediment yield studies [8], is expressed as:

$$\mathbf{A=R\times K\times LS\times C\times P} \qquad (1)$$

where A is the predicted soil loss (t/ha/yr), R the rainfall erosivity factor, K the soil erodibility factor, LS the slope length and steepness factor, C the cover management factor, and P the conservation practice factor.

Data sources included:

a. Rainfall data from the Indonesian Meteorology, Climatology, and Geophysics Agency (BMKG), processed into monthly and annual rainfall erosivity indices following approaches in tropical regions [9].

b. Soil maps from the Indonesian Geospatial Information Agency (BIG) and laboratory soil sampling for texture, structure, and organic matter analysis to determine the erodibility factor [10].
c. Topographic data from high-resolution DEMs (5–10 m), allowing extraction of slope length and steepness (LS factor) using ArcGIS spatial analyst tools.
d. Land cover and land use data from Landsat 8/9 satellite imagery, classified into mining, settlement, forest, agricultural land, and grassland to assign the C factor [11].
e. Field surveys for validation of erosion-prone zones, sump sedimentation, and drainage conditions.

Analytical tools included ArcGIS 10.8 for spatial modeling of RUSLE parameters, Excel 2021 for erosion calculation, and HEC-HMS for sediment delivery ratio (SDR) estimation and hydrological modeling. This integrated approach allowed the quantification of spatial erosion risk and the estimation of sediment yield reaching sumps and sediment ponds.

The research workflow followed sequential steps:
1. Data collection (rainfall, soil, DEM, land cover, field survey).
2. RUSLE factor analysis (R, K, LS, C, P).
3. Erosion rate estimation (ArcGIS-based spatial overlay).
4. Sediment yield estimation using SDR modeling.
5. Validation using bathymetric survey of sediment ponds.
6. Operational analysis for sump capacity, pond design, and dredging requirements.

This methodological integration addresses the research gap in applying RUSLE-based spatial sediment modeling in Indonesian open-pit mining, where dynamic land disturbance requires adaptive sediment control strategies [12].

RESULT AND DISCUSSIONS

The Rainfall Erosivity Factor (R) refers to the ability of rainfall to cause soil erosion. It represents the impact of raindrop energy and the intensity of rainfall that contributes to the detachment and transport of soil particles. To determine the erosivity value in a study area, accurate rainfall data is essential. In this study, rainfall erosivity is assessed based on recorded rainfall intensity and the resulting surface runoff, both of which are key contributors to sediment generation and erosion processes in mining environments [13], [14].

Table 1. Rainfall Erosivity Value

Bulan	Pm (mm/bulan)	R (kJ/Ha)
Januari	333.88	262.19
Februari	362.56	293.30
Maret	337.39	265.96
April	289.05	215.51
Mei	263.65	190.17
Juni	133.21	75.15
Juli	120.29	65.41

Agustus	123.95	68.13
September	113.48	60.43
Oktober	207.30	137.13
November	328.51	256.48
Desember	333.07	261.33
Jumlah	**2946.34**	**2151.20**

2. Soil Erodibility Factor
   The Soil Erodibility Factor (K) indicates the resistance of soil particles to erosion caused by the kinetic energy of rainfall. This factor is determined based on the soil types that make up the slopes within the mining pit area. Approximately 42.23% of the MTBU IUP area consists of red-yellow podzolic soil, followed by alluvial soil covering about 26.03% of the IUP area. The erodibility values for podzolic and alluvial soils are 0.16 and 0.47, respectively [15].
3. Slope Length and Steepness Factor (LS Value)
   The Slope Length and Steepness Factor (LS) significantly affects the rate of soil erosion. Slope length influences the volume of surface runoff, meaning that the longer the slope, the greater the opportunity for water to erode the soil. Slope steepness affects the rate at which soil is detached, as steeper slopes increase the speed of surface runoff, resulting in faster and more intense soil transportation [16], [17].

Table 2. LS Value

Number	Slope Inclination (%)	Value of LS
1	0-5	2.79
2	5-10	4.41
3	10-15	9.16
4	15-20	16.86
5	20-25	19.18
6	25>	25.69

4. Cover and Land Use Conversion Factor (C Factor)
   The Cover and Conservation Practice Factor (CP) is a combined factor consisting of the C (Cover) factor and the P (Conservation Practice) factor. These two factors are combined when the assessment data for both are the same. The CP factor indicates the extent of erosion influenced by the type of vegetation cover and the soil conservation techniques applied. It reflects how effectively land cover and conservation measures reduce the potential for soil erosion [8], [10], [18].

Table 3. CP Factor Values for Various Land Management Aspects

Number	Land Use	Conversion Factor (CP)
1	Primary Forest	0,001
2	Secondary Forest	0,005
3	Rice Field	0,1
4	Bush Land	0,3
5	Upland Agriculture	0,5
6	Industrial Area	1
7	Mining Area	1
8	Residen Area	1

Based on the four parameters mentioned above, the predicted erosion rate (EA) can be determined for Pit SJS, Pit E, and Pit 3 East. From the predicted erosion rates, sediment yield can then be estimated by multiplying the erosion rate by the Sediment Delivery Ratio (SDR) [19], [20]. The SDR value is derived based on the slope gradient similarity on each side of the pit. This result serves as the basis for estimating the potential volume of sediment or mud material (SY) generated within the study area.

Table 4. Predicted Erosion Rate Value for Pit SJS

Segment	RM	K	LS	CP	EA (m^3/Ha)	Area (Ha)	EA (m^3/tahun)
1	2151.20	0.19	4.41	1	1,802.49	680.5	1,226,596.15
2	2151.20	0.19	16.86	1	6,891.16	296.7	2,044,607.72
3	2151.20	0.19	4.41	1	1,802.49	234.3	422,323.99
4	2151.20	0.19	9.16	1	3,743.95	854.7	3,199,956.36
5	2151.20	0.19	19.18	1	7,840.38	376.7	2,953,472.41
6	2151.20	0.19	4.41	1	1,802.49	224.5	404,659.57
7	2151.20	0.19	9.16	1	3,743.95	151.5	567,208.83
			Total				**10,818,825.04**

Table 5. Predicted Erosion Rate Value for Pit E

Segment	RM	K	LS	CP	EA (m^3/Ha)	Area (Ha)	EA (m^3/tahun)
1	2151.20	0.19	9.16	1	3,743.95	165.8	620,747.36
2	2151.20	0.19	16.86	1	6,891.16	227.8	1,569,806.66
3	2151.20	0.19	4.41	1	1,802.49	554.7	999,842.59
				Total			**3,190,396.61**

Table 6. Predicted Erosion Rate Value for Pit 3 East

Segment	RM	K	LS	CP	EA (m^3/Ha)	Area (Ha)	EA (m^3/tahun)
1	2151.20	0.19	4.41	1	1,802.49	129	232,521.53
2	2151.20	0.19	9.16	1	3,743.95	124	464,250.13
3	2151.20	0.19	4.41	1	1,802.49	524.9	946,128.32
				Total			**1,642,899.98**

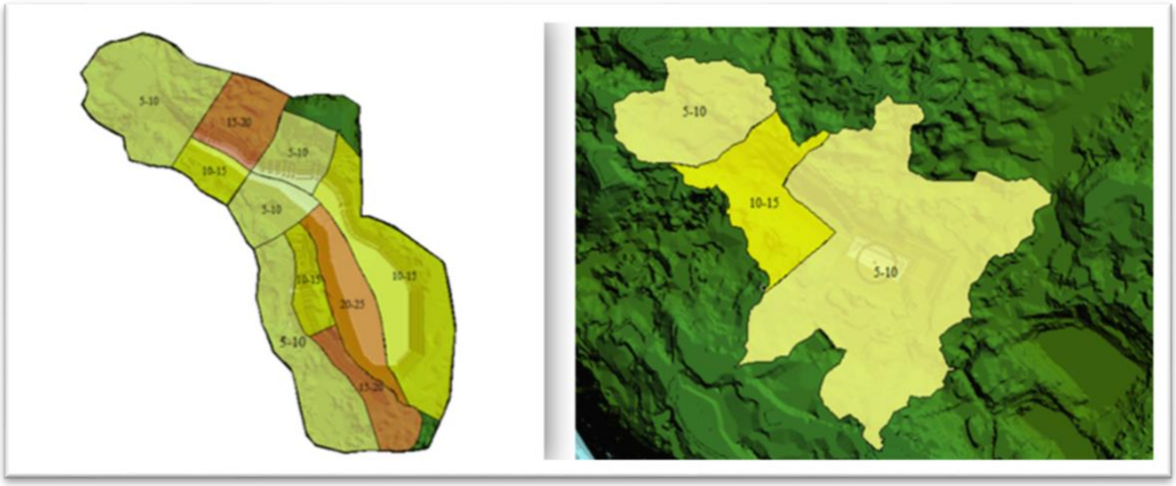

Figure 1. Soil Erosion Area and Sediment Delivery Ratio (SDR)

Table 7. Estimated Volume of Mud Material Generated at Pit SJS

Segment	EA (m^3/year)	SDR	SY (m3/year)
1	1,226,596.15	0.28	338,532.14
2	2,044,607.72	0.30	618,250.49
3	422,323.99	0.31	131,063.03
4	3,199,956.36	0.27	861,299.01
5	2,953,472.41	0.29	869,926.98
6	404,659.57	0.31	126,172.71
7	567,208.83	0.33	184,674.53
Total	**10,818,825.04**		**3,129,918.88**

Table 8. Estimated Volume of Mud Material Generated at Pit E

Segment	EA (m^3/year)	SDR	SY (m3/year)
1	620,747.36	0.32	200,110.55
2	1,569,806.66	0.31	488,680.11
3	999,842.59	0.28	282,224.45
Total	**3,190,396.61**		**971,015.11**

Table 9. Estimated Volume of Mud Material Generated at Pit 3 East

Segment	EA (m^3/year)	SDR	SY (m^3/year)
1	232,521.53	0.33	77,056.22
2	464,250.13	0.33	154,520.13
3	946,128.32	0.28	268,689.70
Total	**1,642,899.98**		**500,266.05**

The predicted erosion rates and sediment yields show significant variation among Pit SJS, Pit E, and Pit 3 East. Pit SJS records the highest annual erosion rate (10.82 million m^3/year) with an estimated mud yield of 3.13 million m^3/year, followed by Pit E (0.97 million m^3/year) and Pit 3 East (0.50 million m^3/year). This difference is mainly attributed to:

a. Catchment size: Pit SJS drains the largest contributing area (680–850 ha), resulting in greater cumulative runoff and sediment transport.
b. Slope steepness: Several segments in Pit SJS exhibit slopes >20%, corresponding to high LS factors (up to 19.18), intensifying erosion.
c. Land cover condition: Disturbed mining surfaces with minimal vegetation increase the C factor, amplifying erosion risks.

Pit SJS emerges as the most critical site for mud management due to its combination of large drainage area, steep slopes, and extensive disturbed land, which collectively lead to excessive sediment loads that threaten sump capacity and sediment pond performance.

To assess system robustness under extreme events, a 20% increase in rainfall erosivity factor (R) was simulated, representing projected extreme rainfall due to climate variability. The results indicate:

a. Erosion in Pit SJS would increase from 10.82 million m^3/year to 12.96 million m^3/year.
b. Sediment yield would increase proportionally from 3.13 million m^3/year to ~3.76 million m^3/year.
c. Similar increases were observed for Pit E (0.97 → 1.16 million m^3/year) and Pit 3 East (0.50 → 0.60 million m^3/year).

This highlights the vulnerability of sump and sediment pond capacity during extreme rainfall, suggesting that current designs may be insufficient for future climate scenarios, especially in Pit SJS.

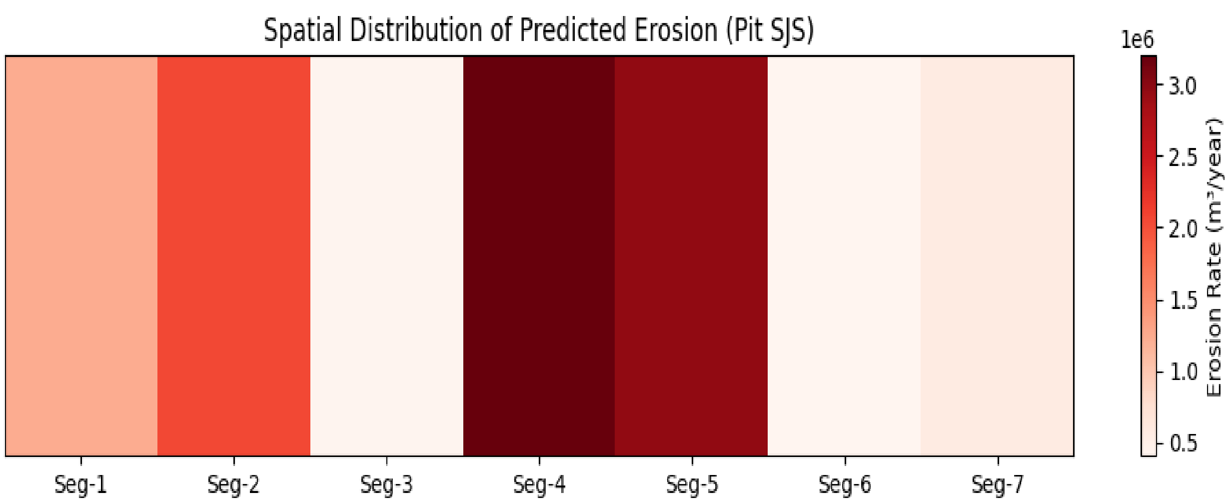

Figure 2. Spatial Distribution of Predicted Erosion (Pit SJS)

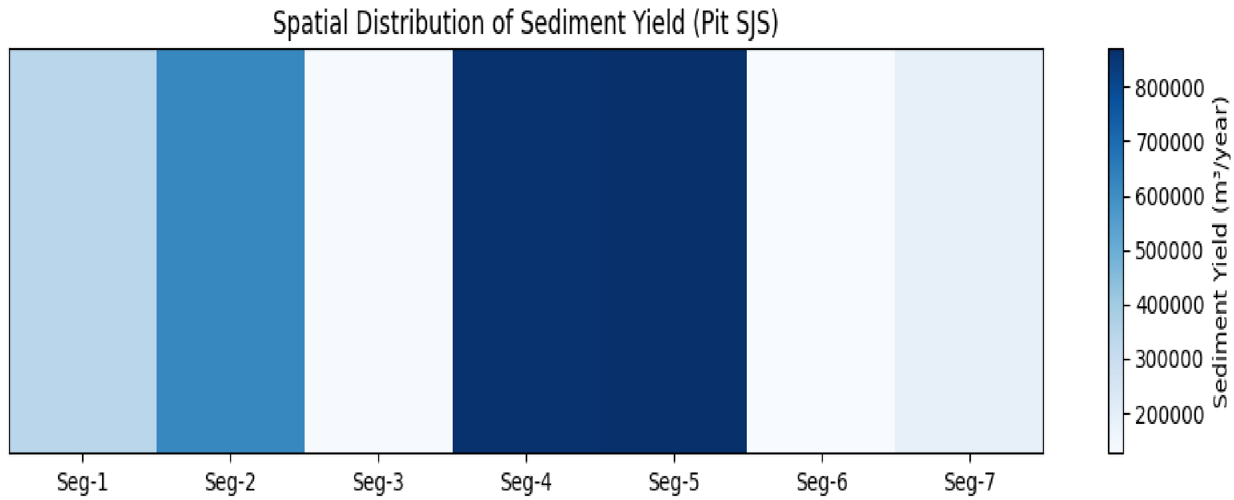

Figure 3. Spatial Distribution of Sediment Yield (Pit SJS)

Discussion

This study underscores the importance of effective sediment management in open-pit coal mining operations, particularly within PT Bukit Asam's West Banko area. The findings highlight significant variability in sediment yields across different mining pits, with Pit SJS recording the highest sediment load, which is attributed to its large drainage area, steep slopes, and extensive land disturbance. This combination results in an annual sediment yield of 3.13 million m^3, emphasizing the need for sediment management strategies tailored to specific pit conditions. The study further simulated extreme rainfall scenarios to assess system vulnerability, demonstrating a 19% increase in sediment yield in Pit SJS under projected climate change conditions, thus revealing that current sediment pond designs may prove inadequate for managing future sediment loads [21], [22], [23]. This highlights the necessity for adaptive sediment management systems that can accommodate dynamic catchment changes and fluctuating rainfall patterns [24], [25]. Furthermore, the research identifies the long-term decline in sediment pond capacity and the frequency of dredging required to maintain operational efficiency as significant challenges. This reinforces the need for continuous monitoring and optimization of sediment pond performance. Additionally, the potential of integrating pre-treatment or staged sedimentation, including biological controls, is explored to improve suspended solids removal beyond conventional sediment pond designs, though further research is required to validate these approaches. Overall, the study provides critical insights into sediment dynamics and offers operationally relevant guidelines for sustainable mud management in tropical open-pit coal mining, ultimately contributing to enhanced environmental protection and mining efficiency, particularly in light of anticipated climate change impacts.

CONCLUSION

This study provides crucial insights into the challenges and strategies for sediment management in the West Banko open-pit coal mining area of PT Bukit Asam. The findings highlight significant variability in sediment yields across different pits, with Pit SJS showing the highest sediment load due to its larger drainage area, steeper slopes, and extensive land disturbance. The research demonstrates that the vulnerability of sediment ponds to future climate scenarios is a critical concern, as the projected increase in rainfall erosivity leads to a rise in sediment yield, particularly in high-risk areas like Pit SJS. The study emphasizes the need for adaptive sediment management strategies that account for the dynamic nature of mining operations, including continuous monitoring of sediment pond capacity and optimization of dredging frequencies to maintain operational efficiency. Furthermore, the potential integration of pre-treatment or staged sedimentation, including biological controls, is explored to enhance suspended solids removal beyond conventional sediment pond designs, though further research is required to validate these techniques. Overall, this research offers operationally relevant guidelines for sustainable mud management, providing practical recommendations that can help PT Bukit Asam minimize sediment-related operational disruptions, improve environmental protection, and ensure long-term sustainability in its mining operations, especially in the face of climate variability.

AUTHORS INFORMATION

Corresponding Authors

Andrew – Mining Engineering Study Program, Faculty of Industrial Engineering, Institut Teknologi Sumatera (Indonesia)
Email: andrew@ta.itera.ac.id

Authors

Bogireddy Chandra – Department of Foreign Scientist, Academy of Logistics and Transport University (Kazakhstan)
Email: Hari2006chandra@gmail.com

AUTHORS CONTIBUTIONS

Andrew, as the corresponding author, led the overall design and conceptualization of the study, including the formulation of the research questions, methodology, and analysis. He also took primary responsibility for manuscript drafting, revisions, and submission. Bogireddy Chandra contributed to the development of the sediment modeling techniques and provided valuable insights into the methodological framework, particularly regarding the integration of field data with the predictive models. Additionally, Chandra supported the analysis of results and contributed to the interpretation of findings in the context of global mining practices. Both authors collaborated in the review of the literature, data interpretation, and the preparation of the final manuscript.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this article. All stages of research, from data collection to analysis and manuscript preparation, were conducted independently without any financial, commercial, or institutional influence that could be perceived as a potential conflict. The interpretations and conclusions presented in this study are solely those of the authors and do not reflect the views of any affiliated institution.

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