



## Runoff Discharge and Sedimentation Yield Assessment for Mine Drainage Design in Lateritic Nickel Mining

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### Abstract

Laterite nickel mining using the open-pit method removes vegetation cover and exposes loose limonite materials, thereby increasing surface runoff and accelerating erosion and sedimentation. Without a quantitatively designed mine drainage system, these conditions may disrupt mining operations and reduce the quality of receiving water bodies. This study aimed to analyze runoff discharge, erosion rate, and sedimentation potential within a nickel mining area in Langgikima District, North Konawe Regency, Southeast Sulawesi, and to utilize the results as the basis for designing open channels and settling ponds. Twenty-one years of rainfall data (2005-2025) were analyzed to determine design rainfall and intensity using the Gumbel distribution and Mononobe equation. Runoff discharge, erosion, and sedimentation potential were estimated using the Rational Method, USLE, and SDR, respectively, and subsequently used to design mine drainage channels and settling ponds based on Manning's equation and Stokes' Law. The design rainfall was 187.26 mm with an intensity of 25.76 mm/h, classified as very heavy—six catchment areas ranging from 0.39 to 1.91 km<sup>2</sup> produced runoff discharges of 2.25 to 7.67 m<sup>3</sup>/s. Erosion rates were only 0.08 ton/ha/year in vegetated areas but increased to 66.47- 140.30 ton/ha/year in barren areas, with a total sedimentation potential of 4,012.7 m<sup>3</sup>/year. The combined channel carrying 13.288 m<sup>3</sup>/s requires a flow depth of 2.037 m and a bottom width of 2.353 m, whereas the settling pond requires an area of 1,247.7 m<sup>2</sup> and a storage volume of 6,238.3 m<sup>3</sup>, achieving a sediment removal efficiency of 91.23%.

**Keywords:** *Runoff Discharge, Erosion, Sedimentation, Mine Drainage, Settling Pond*

### INTRODUCTION

Indonesia is one of the world's largest nickel producers and is actively promoting a mineral downstream processing program that requires a significant increase in nickel ore production. Most of the country's nickel resources occur as laterite deposits formed by the weathering of ultramafic rocks, with the largest distribution in southeastern Sulawesi Island, which forms part of the East Sulawesi Ophiolite Belt (Simandjuntak, 1986; Surono, 1994; Rusmana et al., 1993).

Laterite nickel deposits are generally near the surface, making open-pit mining the most suitable extraction method (Sofiannur et al., 2026). Mining activities begin with land clearing and overburden removal, which eliminate vegetation cover and reduce surface infiltration capacity, thereby increasing the proportion of rainfall that becomes surface runoff. This effect is amplified by the study area's tropical humid climate, where annual rainfall ranges from 1,331 to 2,913 mm and rainy days range from 99 to 208 per year, as recorded over a 21-year observation period (Ananda et al., 2026).

Increased surface runoff leads to two interrelated technical consequences: it disrupts mining operations, reduces slope stability, and impairs equipment performance (Riyadi et al., 2026b; Riyadi et al., 2026a); and it detaches soil particles from loose limonite materials, generating higher erosion rates and elevated sediment loads in water bodies (Wischmeier & Smith, 1978; Renard et

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al., 1997). Elevated total suspended solids (TSS) are among the most common environmental impacts of laterite nickel mining and are subject to strict regulatory standards for mine wastewater quality (Dwiarsiana et al., 2025).

Mine drainage systems typically control these issues through diversion channels and settling ponds (Marwan et al., 2020). Diversion channels redirect runoff away from active mining areas, while settling ponds reduce suspended solids before discharge. The effectiveness of these facilities depends largely on their dimensional accuracy, which site-specific hydrological and sediment load analyses must determine (Tamar et al., 2026; Chow, 1959; Riyadi & Cahyadi, 2024).

Undersized channels may overflow during high-intensity rainfall, while inadequately sized ponds may not provide sufficient retention time for fine particles to settle. Effective mine drainage design requires site-specific analyses of runoff, erosion, and sedimentation because mining activities can affect surrounding water systems. Consequently, quantitatively assessing these parameters is essential for sustainable water management and reliable drainage infrastructure design (Winde & Newman-Portela, 2026; Arenas-Collao et al., 2024).

Therefore, this study integrates rainfall analysis, runoff estimation, erosion assessment, and sedimentation prediction into a comprehensive framework for designing mine drainage facilities (Riyadi & Cahyadi, 2025) within a mining operation plan covering approximately 1,597 ha in Langgikima District, North Konawe Regency, Southeast Sulawesi Province. The surrounding environment is predominantly forested, though some areas have already been cleared.

This study is conducted during the feasibility stage and aims to: (1) determine design rainfall and intensity; (2) calculate runoff discharge for each catchment; and (3) determine the dimensions of open channels and settling ponds based on analytical results. This study addresses technical aspects only and does not cover economic or broader environmental impact assessments.

## LITERATURE REVIEW

The study area is located in the Southeast Arm of Sulawesi, which forms part of the East Sulawesi Ophiolite Belt. The study area comprises ultramafic rocks (peridotite, harzburgite, dunite, gabbro, serpentinite) (Simandjuntak, 1986; Surono, 1994). The IUP area covers the Pandua (Tmpp), Salodik (Tems), Matano (Km), and Ophiolite Complex (Ku).

The morphology includes gentle slopes (8–15%) and dissected hills (>45%) at 245–445 m a.s.l., which govern water circulation and weathering. The laterite profile (overburden, limonite, saprolite, boulder) has an upper limonite zone rich in fine-grained iron, highly susceptible to erosion when exposed. Similar laterite resource estimation approaches have been applied in adjacent regions within the same ophiolite belt (Sofiannur et al., 2026).

Design rainfall for hydraulic structures used Gumbel frequency analysis:

$$X_t = \bar{X} + kS, \text{ with } k = \frac{Y_t - Y_n}{S_n}$$

(where  $\bar{X}$  = mean,  $S$  = std. dev.,  $Y_t$  = reduced variate,  $Y_n$  = reduced mean,  $S_n$  = reduced std. dev.). Rainfall intensity ( $I$ , mm/h) was estimated via Mononobe:

$$I = \frac{R_{24}}{24} \left( \frac{24}{t} \right)^{2/3}$$

(where  $R_{24}$  = 24-h design rainfall, mm/day;  $t$  = rainfall duration in hour; classified per Sosrodarsono and Takeda (2003)). Peak runoff ( $Q$ , m<sup>3</sup>/s) was calculated using the Rational Method:

$$Q = 0.278 \times C \times I \times A$$

(where  $C$  = runoff coefficient,  $I$  = rainfall intensity, mm/h,  $A$  = Catchment Area, km<sup>2</sup>). The Rational Method is commonly applied in drainage system planning because of its simplicity and effectiveness in estimating peak runoff from relatively small catchments ([Riyadi & Cahyadi, 2025](#)).

The potential erosion rate ( $E$ , ton/ha/yr) was calculated using the Universal Soil Loss Equation (USLE) ([Wischmeier & Smith, 1978](#)):

$$E = R \times K \times LS \times C \times P$$

where  $R$ = rainfall erosivity factor,  $K$ = soil erodibility factor,  $LS$ = slope length and slope steepness factor,  $C$ = vegetation cover factor, and  $P$ = land management or conservation practice factor. The rainfall erosivity ( $R$ ) factor was determined using the empirical equation proposed by [Bols \(1978\)](#):

$$EI_{30} = 6.1199 \times P_m^{1.21} \times N_m^{-0.47} \times P_{max}^{0.53}$$

where  $P_m$  = average monthly rainfall (cm);  $N_m$  = average monthly rainy days (days);  $P_{max}$  = monthly ma. daily rainfall (cm). The soil erodibility factor ( $K$ ) was determined based on the mean particle diameter using the method proposed by [Renard et al. \(1997\)](#).

The mean particle diameter ( $D_g$ ) was calculated from grain-size distributions obtained through sieve and hydrometer analyses. The  $LS$  factor was calculated according to [Wischmeier and Smith \(1978\)](#), while the  $C$  and  $P$  factors were assigned based on field observations of vegetation cover and land management practices.

The USLE estimates the amount of soil detached by erosion but does not represent the quantity of sediment delivered to receiving water bodies. Therefore, the Sediment Delivery Ratio (SDR) was estimated based on catchment area using the equation proposed by [Boyce \(1975\)](#):

$$SDR = 0.3740 \times A_c^{-0.2382}$$

where  $A_c$ = catchment area (ha). The sediment yield/year ( $Y$ , m<sup>3</sup>/year) was subsequently calculated as:

$$Y = \frac{SDR \times A_c \times E}{\rho}$$

where  $A_c$ = catchment area (ha),  $E$ = erosion rate (ton/ha/year),  $\rho$  = limonite bulk density ton/m<sup>3</sup>). This approach provides a more realistic estimate of sediment volume that reaches drainage channels and settling ponds. For open-channel flow (steady and uniform), Manning's equation was used:

$$v = \frac{1}{n} R^{2/3} S^{1/2} \text{ and } Q = A \times v$$

where  $v$ = flow velocity (m/s),  $n$ = Manning roughness coefficient,  $R$ = hydraulic radius (m),  $S$ = channel bed slope,  $Q$ = discharge (m<sup>3</sup>/s), and  $A$ = wetted cross-sectional area (m<sup>2</sup>). For a trapezoidal channel section:

$$A = d(b + md) \text{ and } P = b + 2d\sqrt{1 + m^2}$$

where:  $d$ = flow depth (m),  $b$ = bottom width (m),  $m$ = side slope ratio,  $P$ = wetted perimeter (m).

The trapezoidal section is commonly selected because it offers good hydraulic efficiency and

slope stability. In practical design, a freeboard of approximately 20-30% of the flow depth should also be provided to prevent overtopping during peak-flow events. Quantitative assessments of open-channel flow in similar mining areas have also used synthetic unit hydrograph approaches to support drainage design (Cahyadi et al., 2024).

A settling pond reduces suspended-solid concentrations through gravitational sedimentation. For fine particles under laminar-flow conditions, settling velocity can be calculated using Stokes' Law:

$$v = \frac{gd^2(\rho_p - \rho_w)}{18\mu}$$

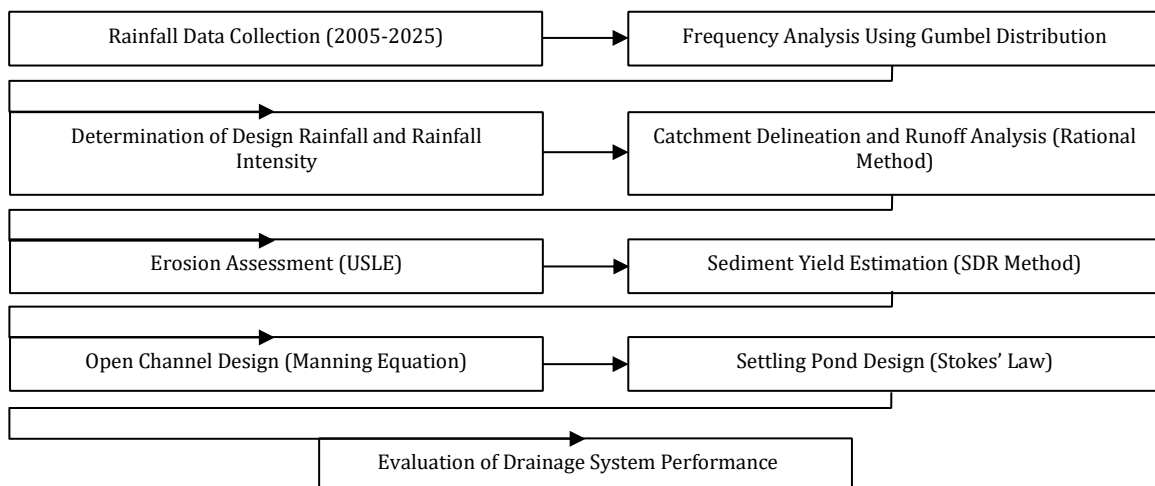
where  $v$ = particle settling velocity (m/s),  $g$ = gravitational acceleration ( $\text{m/s}^2$ ),  $d$ = particle diameter (m),  $\rho_p$ = particle density ( $\text{kg/m}^3$ ),  $\rho_w$ = water density ( $\text{kg/m}^3$ ),  $\mu$ = dynamic viscosity of water ( $\text{kg/m}\cdot\text{s}$ ). Particles are considered effectively settled when the time required for a particle to reach the pond bottom ( $t_v$ ) is less than the hydraulic residence time of water flowing through the pond ( $t_h$ ).

Therefore, settling pond dimensions must provide sufficient retention time for particle sedimentation before discharge into receiving waters (Riyadi & Cahyadi, 2025). Fractured media hydraulic conductivity, critical for both slope stability and seepage assessment, has been effectively characterized through field slug and packer tests, supplemented by sensitivity analysis, to inform proper pond siting and seepage control (Cahyadi et al., 2026; Riyadi et al., 2026a; Riyadi et al., 2026b)

## RESEARCH METHOD

### Research Framework

The overall research workflow can be summarized as follows:



**Figure 1.** Research Framework Summary

### Data Collection

The study utilized both secondary and primary data. Secondary data included monthly rainfall records and the number of rainy days over 21 years (2005-2025), obtained from the nearest meteorological observation station. Additional secondary data included topographic maps, regional geological maps, and exploration drilling logs.

Primary data were collected through field investigations, including observations of land cover conditions and slope characteristics within four planned mining areas (north, west, south,

and east sectors). Soil samples were collected for sieve and hydrometer analyses to determine particle-size distribution. In addition, infiltration tests were conducted using a double-ring infiltrometer with a ring area of 346.185 cm<sup>2</sup> to evaluate the infiltration characteristics of surface materials.

### Data Processing and Analysis

The analytical procedures were carried out through the following stages:

1. Annual maximum daily rainfall data were analyzed using the Gumbel Distribution to determine design rainfall values for various return periods. A 10-year return period was selected based on the mine's planned operational life.
2. The 24-hour design rainfall was converted into rainfall intensity using the Mononobe equation based on the average rainfall duration observed in the study area.
3. Catchment areas were delineated from topographic maps by considering ridge-line configurations and slope directions to determine runoff flow paths.
4. The runoff coefficient for each catchment area was determined by combining the effects of relief, soil infiltration capacity, vegetation cover, and surface storage characteristics. Peak runoff discharge was then calculated using the Rational Method.
5. The factors required for the Universal Soil Loss Equation (USLE) were determined for each planned mining area. The rainfall erosivity factor (R) was calculated from monthly rainfall and rainy-day records; the soil erodibility factor (K) was determined from laboratory grain-size analyses; the slope length and steepness factor (LS) was derived from field measurements of slope length and elevation differences; and the vegetation cover (C) and conservation practice (P) factors were determined through field observations.
6. Sedimentation potential was estimated using the Sediment Delivery Ratio (SDR) approach, which represents the proportion of eroded material transported to the drainage network.

## FINDINGS AND DISCUSSION

### Rainfall Analysis: Design Rainfall and Intensity

The study area exhibits a tropical climate with distinct wet and dry seasons. Based on 21-year rainfall records (2005-2025), annual rainfall ranged from 1,331 mm to 2,913 mm, with 99-208 rainy days per year (average 157 days). Annual maximum daily rainfall ranged from 59 mm to 213.3 mm (average 106.95 mm), indicating considerable inter-annual variability that necessitates probabilistic design approaches rather than reliance on average values.

Frequency analysis using the Gumbel Distribution produced design rainfall values for various return periods. A 10-year return period was selected based on the planned mine life of approximately 20 years, yielding a design rainfall of 187.26 mm—balancing acceptable hydrological risk and construction cost (Table 1).

**Table 1.** Design Rainfall for Different Return Periods

| Return Period (Years) | Probability  | Design Rainfall (mm) |
|-----------------------|--------------|----------------------|
| 1                     | 1.000        | 52.44                |
| 2                     | 0.500        | 120.03               |
| 3                     | 0.333        | 139.17               |
| 4                     | 0.250        | 151.41               |
| 5                     | 0.200        | 160.48               |
| <b>10</b>             | <b>0.100</b> | <b>187.26</b>        |
| 20                    | 0.050        | 212.95               |

Using the Mononobe equation with an average rainfall duration of four hours per event (based on field observations), the rainfall intensity was calculated as 25.76 mm/h. According to Sosrodarsono's classification, this falls within the very heavy rainfall category, indicating that ponding and drainage overflow are likely without adequate facilities.

Infiltration testing using a double-ring infiltrometer at a vegetated shrub area revealed a constant infiltration rate corresponding to a hydraulic conductivity of approximately  $1.67 \times 10^{-5}$  m/s (60.1 mm/h)—exceeding the design rainfall intensity. This confirms that increased runoff within mining areas is primarily attributable to vegetation removal and surface compaction rather than the inherent properties of lateritic material.

### Catchment Discharge, Erosion & Sedimentation Analysis

Six catchment areas were delineated with a total drainage area of 6.37 km<sup>2</sup>. Runoff coefficients were determined by combining relief, soil infiltration capacity, vegetation cover, and surface storage characteristics following [TxDOT \(2016\)](#) guidelines. Table 2 summarizes the results. Cleared areas (CA II and III) exhibited the highest runoff coefficients (0.72 and 0.80). In contrast, vegetated catchments ranged from 0.56 to 0.62—indicating that land clearing increased runoff generation by approximately 43% compared with forested conditions.

The highest discharge occurred in CA I (7.67 m<sup>3</sup>/s) because of its large area (1.91 km<sup>2</sup>), while CA III generated only 2.25 m<sup>3</sup>/s despite having the highest runoff coefficient because of its small area (0.39 km<sup>2</sup>). This demonstrates that catchment area remains the primary factor controlling runoff discharge at the watershed scale, though land-cover conditions remain highly important for erosion and sediment yield.

Using the USLE, erosion rates were estimated for four planned mining areas (North, West, South, East sectors) located within CA II and III. The rainfall erosivity factor (R) ranged from 112.47 to 389.22 kJ/ha/year (average 210.72 kJ/ha/year). The soil erodibility factor (K) ranged from 0.0351 to 0.0370, indicating coarse-dominated materials (gravel 46.64–56.46%; coarse sand 27.86–38.51%; silt+clay <2.3%) resistant to raindrop detachment.

**Table 2.** Runoff Coefficients and Runoff Discharges for Each Catchment Area

| Parameter                                 | CA I        | CA II       | CA III      | CA IV       | CA V        | CA VI       |
|-------------------------------------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Land condition                            | Vegetated   | Bare land   | Bare land   | Vegetated   | Vegetated   | Vegetated   |
| Area, A (km <sup>2</sup> )                | 1.91        | 0.99        | 0.39        | 1.34        | 0.87        | 0.87        |
| Relief factor, Cr                         | 0.36        | 0.36        | 0.36        | 0.34        | 0.35        | 0.35        |
| Soil infiltration factor, Ci              | 0.08        | 0.12        | 0.16        | 0.12        | 0.12        | 0.12        |
| Vegetation factor, Cv                     | 0.06        | 0.12        | 0.16        | 0.08        | 0.06        | 0.06        |
| Surface storage factor, Cs                | 0.06        | 0.12        | 0.12        | 0.08        | 0.08        | 0.08        |
| <b>Runoff coef., C</b>                    | <b>0.56</b> | <b>0.72</b> | <b>0.80</b> | <b>0.62</b> | <b>0.61</b> | <b>0.61</b> |
| <b>Runoff disch., Q (m<sup>3</sup>/s)</b> | <b>7.67</b> | <b>5.12</b> | <b>2.25</b> | <b>5.93</b> | <b>3.80</b> | <b>3.81</b> |

The vegetated North area exhibited an erosion rate of only 0.08 ton/ha/year, whereas cleared areas ranged from 66.47 to 140.30 ton/ha/year—an increase of approximately 1,750 times. Vegetation cover was identified as the dominant factor controlling erosion, exerting greater influence than material properties or slope geometry.

Among cleared areas, the South area recorded the highest erosion rate despite having the shortest slope length (101.86 m), mainly because of its steep slope gradient (19.46°). These findings indicate that erosion-control efforts should prioritize slope steepness over the overall size of

disturbed land (Table 3).

**Table 3.** USLE Factors and Estimated Erosion Rates

| Area  | Slope Length (m) | Slope Angle (°) | K      | LS    | C     | P | Average Erosion Rate (ton/ha/year) | Maximum Erosion Rate (ton/ha/year) |
|-------|------------------|-----------------|--------|-------|-------|---|------------------------------------|------------------------------------|
| North | 166.22           | 12.22           | 0.0354 | 10.85 | 0.001 | 1 | 0.08                               | 0.15                               |
| West  | 145.43           | 13.90           | 0.0368 | 12.65 | 1     | 1 | 98.07                              | 181.14                             |
| South | 101.86           | 19.46           | 0.0351 | 18.97 | 1     | 1 | 140.30                             | 259.14                             |
| East  | 205.95           | 9.92            | 0.0370 | 8.52  | 1     | 1 | 66.47                              | 122.78                             |

Using the Sediment Delivery Ratio (SDR) approach, SDR values were 0.375 for areas with 99 ha catchments (North, East) and 0.468 for 39 ha catchments (West, South). Using a limonite bulk density of 1.7 ton/m<sup>3</sup>, total sedimentation potential was estimated at 4,012.7 m<sup>3</sup>/year under average conditions and 7,411.4 m<sup>3</sup>/year under maximum erosivity (Table 4).

**Table 4.** Sedimentation Potential for Each Area

| Area         | SDR   | Catchment Area, $A_c$ (ha) | Average Erosion Rate (ton/ha/year) | Average Sediment Yield (m <sup>3</sup> /year) | Maximum Sediment Yield (m <sup>3</sup> /year) |
|--------------|-------|----------------------------|------------------------------------|-----------------------------------------------|-----------------------------------------------|
| North        | 0.375 | 99                         | 0.08                               | 1.8                                           | 3.3                                           |
| West         | 0.468 | 39                         | 98.07                              | 1,052.9                                       | 1,944.9                                       |
| South        | 0.468 | 39                         | 140.30                             | 1,506.4                                       | 2,782.3                                       |
| East         | 0.375 | 99                         | 66.47                              | 1,451.6                                       | 2,680.9                                       |
| <b>Total</b> | -     | <b>276</b>                 | -                                  | <b>4,012.7</b>                                | <b>7,411.4</b>                                |

### Open Channel and Settling Pond Design

The drainage system was designed to divert runoff from Catchment Areas II, III, and IV (adjacent to the planned mining area), with design discharges of 5.10, 2.23, and 5.95 m<sup>3</sup>/s, respectively, for a combined discharge of 13.288 m<sup>3</sup>/s flowing through the main channel toward the settling pond.

The diversion channels were designed with trapezoidal cross-sections, side slopes at 60° ( $m=0.577$ ), native soil lining ( $n=0.03$ ), and channel bed slope ( $S=0.003$ ). A bottom-width-to-flow-depth ratio ( $b/d$ ) of 1.155 was adopted for hydraulic efficiency, with 30% freeboard added for extreme events. The main channel requires substantially larger dimensions (flow depth 2.037 m, bottom width 2.353 m) to convey combined runoff.

Flow velocities range from 1.184 to 1.849 m/s, with the main channel velocity exceeding the permissible velocity for unlined earth channels (1.849 m/s), indicating that protective lining (riprap, masonry, or concrete) should be installed to prevent erosion. The trapezoidal configuration provides structural stability in native soil and facilitates maintenance activities.

**Table 5.** Proposed Open Channel Dimensions

| Parameter                                 | CA II | CA III | Main Channel |
|-------------------------------------------|-------|--------|--------------|
| Design discharge, $Q$ (m <sup>3</sup> /s) | 5.10  | 2.23   | 13.288       |
| Side slope ratio, $m$                     | 0.577 | 0.577  | 0.577        |
| Manning coefficient, $n$                  | 0.03  | 0.03   | 0.03         |

|                                   |       |       |       |
|-----------------------------------|-------|-------|-------|
| Channel bed slope, S              | 0.003 | 0.003 | 0.003 |
| Flow depth, d (m)                 | 1.423 | 1.043 | 2.037 |
| Bottom width, b (m)               | 1.643 | 1.205 | 2.353 |
| Total depth with freeboard, h (m) | 1.850 | 1.356 | 2.648 |
| Wetted area, A (m <sup>2</sup> )  | 3.507 | 1.884 | 7.187 |
| Water surface width, B (m)        | 3.285 | 2.409 | 4.704 |
| Flow velocity, v (m/s)            | 1.454 | 1.184 | 1.849 |

The settling pond was designed to receive the entire combined runoff discharge of 13.288 m<sup>3</sup>/s. Particle settling velocity was calculated using Stokes' Law with particle density 2,600 kg/m<sup>3</sup>, water density 1,000 kg/m<sup>3</sup>, and dynamic viscosity  $1.31 \times 10^{-3}$  kg/m·s. The required surface area of 1,247.7 m<sup>2</sup> with a design depth of 5 m yields a storage volume of 6,238.3 m<sup>3</sup>. The pond achieves 91.23% sediment removal for particles >126 µm, the lower limit of effective gravitational settling.

Given that silt and clay fractions comprise only 1.61-2.27% of lateritic material, fine-particle contribution is expected to be limited. Based on annual sediment yield of 4,012.7 m<sup>3</sup>/year and 91.23% removal efficiency, approximately 3,660 m<sup>3</sup>/year accumulates in the pond, reaching full capacity after 1.7 years without dredging. Dredging is recommended when sediment reaches one-third of pond depth to maintain detention time and removal efficiency.

**Table 6. Settling Pond Design Parameters**

| Parameter                                     | Value   |
|-----------------------------------------------|---------|
| Total inflow discharge, Q (m <sup>3</sup> /s) | 13.288  |
| Design particle diameter, d (µm)              | 126     |
| Settling velocity, v (m/s)                    | 0.01065 |
| Pond area, A (m <sup>2</sup> )                | 1,247.7 |
| Design depth (m)                              | 5       |
| Pond volume (m <sup>3</sup> )                 | 6,238.3 |
| Pond width (m)                                | 31.18   |
| Effective pond length (m)                     | 40      |
| Total length including dredging area (m)      | 52      |

## CONCLUSIONS

This feasibility-stage technical study addressed three primary objectives: determining design rainfall and intensity, calculating runoff discharge for each catchment, and dimensioning open channels and settling ponds based on the analytical results.

1. Design rainfall and intensity – Based on 21-year rainfall records and Gumbel frequency analysis, the 10-year return period design rainfall is 187.26 mm, corresponding to an intensity of 25.76 mm/h (very heavy rainfall).
2. Runoff discharge – Six catchments (0.39–1.91 km<sup>2</sup>) yield peak discharges of 2.25–7.67 m<sup>3</sup>/s. Cleared areas show runoff coefficients up to 43% higher than vegetated areas, with a combined main-channel discharge of 13.288 m<sup>3</sup>/s.
3. Channel and settling pond dimensions
  - a. Open channels (trapezoidal, 60° side slopes, 0.003 bed slope): CA II (1.423 m depth × 1.643 m width), CA III (1.043 m × 1.205 m), and main channel (2.037 m × 2.353 m). Main channel velocity (1.849 m/s) requires protective lining.
  - b. Settling pond: 1,247.7 m<sup>2</sup> surface area, 5 m depth, 6,238.3 m<sup>3</sup> storage (~31.18 m × 52 m), achieving 91.23% sediment removal for particles >126 µm.

This study demonstrates the importance of integrating runoff, erosion, and sedimentation assessments in mine drainage planning. The proposed channel and settling pond designs provide a quantitative basis for feasibility-stage planning and engineering design. However, this study does not cover economic and environmental evaluations.

### LIMITATIONS & FURTHER RESEARCH

This study identified several limitations that future investigations should address.

1. Land-cover dynamics – The analysis used static land-cover conditions and does not account for progressive mine development. Future studies should incorporate stage-by-stage drainage analyses following annual development plans and disturbance scenarios.
2. USLE applicability – The model predicts sheet and rill erosion but does not account for gully erosion, mass wasting, or slope failures on waste dumps and excavated slopes. Field validation using measured sediment production data is recommended to evaluate prediction accuracy under mining conditions.
3. Pond performance assumptions – Settling Pond evaluation assumed idealized hydraulics and single-particle settling. Actual performance may be affected by short-circuiting, turbulence, variable sediment characteristics, and seasonal conditions. Wet-season TSS monitoring at inlet/outlet is recommended to verify compliance and actual removal efficiency.
4. Erosion control effectiveness – Investigations into hydroseeding, cover crops, erosion blankets, bench terracing, and progressive reclamation are recommended to reduce sediment at the source. Comparative studies of passive vs. chemically enhanced settling could improve sediment management.
5. Adaptive management systems – Integration of hydrological modeling, GIS, and real-time rainfall monitoring is recommended for developing responsive mine-water management systems that adapt to changing conditions throughout mine life, enhancing long-term sustainability and resilience.

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