

A Weighted Engineering Geological Framework for Evaluating Post-Mining Land Reclamation Suitability Based on Slope, Material Properties, and Drainage

(Kerangka Evaluasi Geologi Teknik Berbobot untuk Menilai Kesesuaian Reklamasi Lahan Pascatambang Berdasarkan Lereng, Sifat Material, dan Drainase)



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Abstract: Post-mining reclamation often underperforms when land is considered ready for revegetation without prior engineering geological screening. This study develops and demonstrates a weighted engineering geological framework for evaluating reclamation suitability based on slope condition, material properties, and drainage performance. A descriptive-evaluative design was used by combining land-unit delineation, field observation parameters, basic geotechnical indicators, drainage appraisal, and weighted scoring. To transparently demonstrate the analytical model, simulated but technically plausible data were assigned to four engineering geological zones. The model weights slope at 40%, material properties at 35%, and drainage at 25%. The resulting suitability scores classify Zone A as very suitable (87.2), Zone B as moderately suitable (72.6), Zone C as conditionally suitable (56.9), and Zone D as unsuitable (41.6). The novelty of the study lies in operationalizing slope, material, and drainage variables into a transparent zone-based suitability score, and in positioning engineering geology as the first diagnostic layer of reclamation planning rather than a post-planting correction. The framework helps identify dominant limiting factors and supports staged interventions such as regrading, drainage rehabilitation, material improvement, and phased revegetation. The model is suitable as a pre-screening tool and should be calibrated with site-specific field data in future applications.

Keywords: engineering geological suitability; weighted scoring; slope stability; drainage appraisal; post-mining reclamation.

Abstrak: Reklamasi lahan pascatambang sering tidak optimal ketika lahan dianggap siap direvegetasi tanpa penyaringan awal berbasis geologi teknik. Penelitian ini mengembangkan dan mendemonstrasikan kerangka evaluasi geologi teknik berbobot untuk menilai kesesuaian reklamasi berdasarkan kondisi lereng, sifat material, dan kinerja drainase. Rancangan penelitian bersifat deskriptif-evaluatif dengan menggabungkan deliniasi satuan lahan, parameter observasi lapangan, indikator geoteknik dasar, evaluasi drainase, dan skoring berbobot. Untuk menunjukkan model analitis secara transparan, digunakan data simulasi yang secara teknis masih masuk akal pada empat zona geologi teknik. Model memberikan bobot 40% pada lereng, 35% pada sifat material, dan 25% pada drainase. Hasilnya mengklasifikasikan Zona A sebagai sangat sesuai (87,2), Zona B sebagai cukup sesuai (72,6), Zona C sebagai sesuai bersyarat (56,9), dan Zona D sebagai tidak sesuai (41,6). Kebaruan penelitian ini terletak pada pengoperasionalan variabel lereng, material, dan drainase ke dalam skor kesesuaian berbasis zona yang transparan, serta penempatan geologi teknik sebagai lapisan diagnostik pertama dalam perencanaan reklamasi, bukan sekadar koreksi setelah penanaman. Kerangka ini membantu mengidentifikasi faktor pembatas dominan dan mendukung intervensi bertahap, seperti perataan ulang



lereng, rehabilitasi drainase, perbaikan material, dan revegetasi bertahap. Model ini layak digunakan sebagai alat pra-penapisan dan perlu dikalibrasi dengan data lapangan spesifik lokasi pada penelitian selanjutnya.

Kata kunci: *geologi teknik; skoring berbobot; stabilitas lereng; evaluasi drainase; reklamasi lahan pascatambang.*

Introduction

Mining activities substantially modify natural landscapes through excavation, backfilling, soil stripping, haul-road construction, and the creation of engineered slopes. As a result, post-mining land commonly exhibits artificial relief, heterogeneous surface materials, and altered drainage pathways. Under such conditions, reclamation success cannot be judged only from topsoil placement or vegetation cover; it must also be grounded in an engineering geological diagnosis of land stability, material behavior, and runoff control (FAO, 1976, 2007; Hancock et al., 2020).

Recent reclamation research increasingly treats post-mining recovery as a coupled physical-ecological process rather than a simple revegetation program. Geomorphic rehabilitation studies have shown that stable landform geometry and hydrologically functional drainage are prerequisites for long-term recovery, while ecosystem reconstruction studies emphasize that slope form, soil rebuilding, and drainage design interact over time (Hancock et al., 2020; Tibbett, 2024; Zapico et al., 2018). In parallel, broader reclamation assessments now integrate soil, vegetation, and ecological indicators, often through weighted or multi-indicator models (Tang et al., 2025; Végsöová & Glova, 2025; Wang et al., 2023).

However, a practical gap remains. Many post-mining assessments still begin from vegetation performance, land-cover recovery, or broad land-use suitability mapping. Those approaches are useful, but they are often too late or too coarse to answer the first engineering question: Is the land physically ready to be reclaimed? Remote-sensing monitoring can identify the success or failure of established reclamation, yet it does not directly diagnose whether slope geometry, near-surface material behavior, and drainage configuration are already adequate before planting begins (Wang et al., 2023). Likewise, general land-suitability and ecosystem-service models help with strategic zoning, but they do not always provide a field-scale diagnostic of slope instability, material weakness, ponding risk, or runoff concentration (Wang et al., 2017; Sukarman & Gani, 2020).

This gap is especially relevant in Indonesia, where post-mining reclamation is mandatory and technically regulated, but operational screening tools that translate engineering geological conditions into simple and defensible reclamation-readiness classes remain limited. Recent policy guidance from the Ministry of Energy and Mineral Resources requires reclamation and post-mining planning to be technically accountable, which means that slope configuration, spoil behavior, and drainage performance should be evaluated explicitly rather than assumed from administrative compliance alone (Kementerian Energi dan Sumber Daya Mineral, 2025). Reviews of reclamation practice in tropical and subtropical countries also show that Indonesia still faces recurring implementation challenges in site-specific design, long-term monitoring, and the consistency of field execution (Pambudi et al., 2025).

Accordingly, this study addresses the following research question: How can post-mining land be evaluated for reclamation readiness through an operational engineering geological framework based on slope condition, material properties, and drainage systems? The novelty of the study lies in translating those three parameter groups into a transparent weighted scoring model that functions as a pre-revegetation diagnostic framework. Rather than replacing ecological assessment, the framework is intended to precede it by identifying where direct reclamation is feasible, where conditional reclamation is possible, and where engineering intervention is still required.

The objectives of the study are therefore fourfold: (1) to characterize post-mining land in terms of slope, material, and drainage attributes; (2) to formulate a weighted engineering

geological scoring model; (3) to classify land into reclamation suitability classes; and (4) to identify dominant limiting factors that can guide zone-specific reclamation action. By doing so, the article responds directly to the need for a more explicit engineering geological foundation in post-mining land evaluation.

Methods

This study used a descriptive-evaluative design to formulate and demonstrate an engineering geological suitability model for post-mining reclamation. The unit of analysis was an engineering geological zone, defined as a relatively homogeneous land segment in terms of slope geometry, dominant surface material, and drainage condition. To transparently demonstrate the framework, the article uses four hypothetical zones (Zone A to Zone D) with technically plausible values. The methodological contribution of the paper lies in the evaluation framework itself; therefore, the simulated dataset is used only to show how the method works step by step.

In an actual field application, zone delineation would be carried out using topographic maps, mine plans, orthophotos or drone imagery, lithological information, and preliminary reconnaissance. The conceptual setting adopted in this article is an open-pit post-mining area that has entered the early land-regrading stage. The observation logic assumes one dry-season reconnaissance campaign followed by short wet-season verification so that drainage performance is assessed not only from visible channels, but also from runoff response, ponding, and local erosion after rainfall.

Data collection was structured into three streams. First, secondary data were reviewed to identify landform design, excavation history, rainfall context, and drainage plans. Second, field observations were designed for slope angle, slope height, morphology, visible instability indicators (tension cracks, rilling, toe erosion, seepage), and drainage functionality (channel continuity, ponding, sediment accumulation, outlet adequacy, and erosion evidence). Third, disturbed and semi-disturbed material samples were assumed to be tested for bulk density, plasticity index, cohesion, and internal friction angle because these indicators reflect compaction level, moisture sensitivity, and resistance to deformation (Liu et al., 2017; Shrestha & Lal, 2011).

Measurement validity and reliability were incorporated into the framework by specifying calibration and cross-check procedures. In field implementation, clinometers and measuring tapes should be calibrated before use; slope readings should be repeated at representative points within each zone; and drainage observations should be checked in both dry and wet conditions. Field descriptions of loose, saturated, or compacted materials should then be cross-validated against laboratory outputs. To reduce operator bias, the same observation sheet, parameter thresholds, and scoring rules should be applied across all zones.

The methodological steps adopted in this study are summarized below and visually synthesized in [Figure 1](#).

Methodological Steps

1. Delineation of engineering geological zones. Post-mining land is divided into relatively homogeneous units using topographic interpretation, mine-layout information, and reconnaissance observations.
2. Slope assessment. Each zone is assessed for slope angle, slope height, morphology, and visible indicators of instability that may influence runoff concentration and failure risk.
3. Drainage appraisal. Existing channels, local ponding, sedimentation, erosion scars, and outlet effectiveness are examined to judge whether rainfall is safely conveyed or concentrated destructively.
4. Material characterization. Representative material is described and tested for bulk density, plasticity index, cohesion, and friction angle to capture compaction, moisture

sensitivity, and shear resistance.

5. Weighted scoring. Scores are assigned to slope, material, and drainage components and then combined into a final suitability value using a transparent weighting system.
6. Classification and diagnosis. Final scores are translated into suitability classes, and the dominant limiting factor in each zone is identified to support practical reclamation decisions.

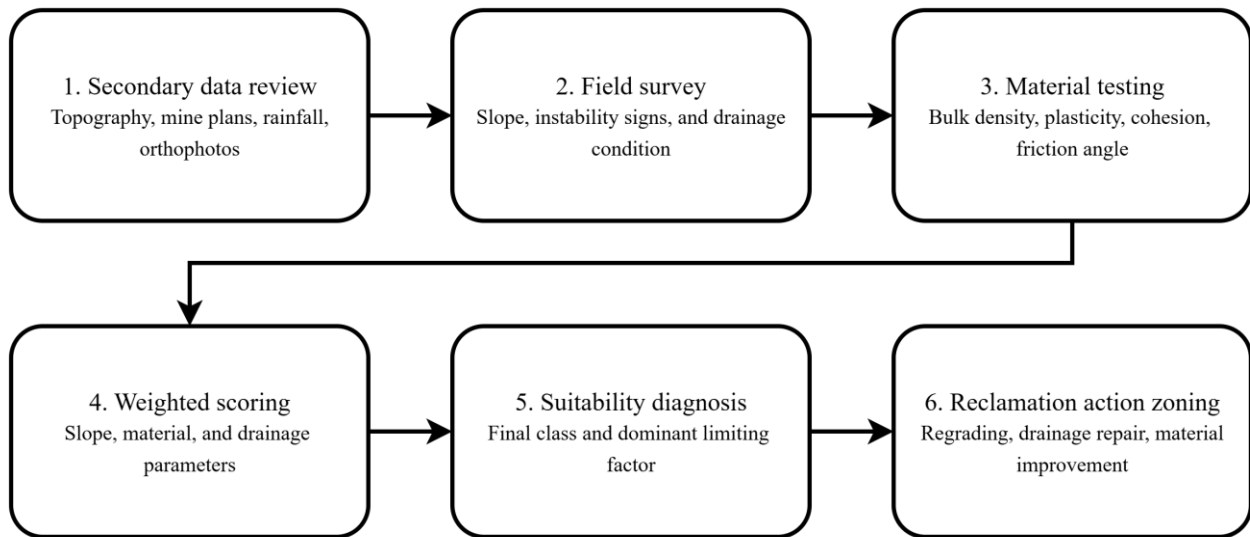


Figure 1. Methodological workflow for the weighted engineering geological evaluation framework

Scoring Model and Suitability Classes

The analytical procedure uses a weighted scoring model consisting of three major parameter groups: slope condition (SL), material properties (SM), and drainage system (SD). Because slope geometry is the first engineering control on stability and runoff concentration, slope was given a weight of 40%. Material properties were weighted at 35% because spoil density, plasticity, cohesion, and friction influence saturation response and deformation. Drainage was weighted at 25% because even mechanically acceptable slopes can deteriorate when runoff is poorly controlled (Hancock et al., 2020; Zapico et al., 2020).

The final suitability value was calculated as:

$$NK = (0.40 \times SL) + (0.35 \times SM) + (0.25 \times SD) \tag{1}$$

where NK is the final suitability score, SL is the slope score, SM is the material score, and SD is the drainage score.

The final values were interpreted using four suitability classes: very suitable (S1) for 85–100; moderately suitable (S2) for 70–84; conditionally suitable (S3) for 55–69; and unsuitable (N) for values below 55. The logic of this classification is operational rather than purely descriptive: S1 zones may proceed directly to reclamation; S2 zones require limited corrective action; S3 zones require clear engineering pre-treatment before revegetation; and N zones require major redesign or stabilization before reclamation can safely proceed.

Results

The simulated results show a clear engineering geological gradient from Zone A to Zone D. Zone A represents the most favorable condition, characterized by gentle slope geometry, denser and less plastic material, and effective drainage. Zone D represents the least favorable condition, combining steep and higher slopes with weaker, more plastic, and poorly drained

material. Zones B and C occupy intermediate positions, illustrating how reclamation suitability declines progressively as slope constraints, material weakness, and hydrological inefficiency accumulate.

Table 1 presents the input dataset used to demonstrate the framework. The values are not intended to represent one specific mine; rather, they are technically plausible contrasts designed to show how the method distinguishes favorable, moderate, conditional, and unsuitable post-mining conditions.

Table 1. Engineering geological characteristics of the evaluated zones

Zone	Slope (°)	Height (m)	Bulk Density (g/cm ³)	PI	Cohesion (kPa)	Friction Angle (°)	Drainage Condition
A	10	8	1.52	12	26	31	Good
B	17	10	1.46	18	22	28	Moderate
C	24	14	1.39	24	17	24	Poor
D	31	18	1.33	30	13	20	Very poor

The weighted scores are shown in Table 2 in addition to classifying suitability, the framework identifies the dominant limiting factor and the priority engineering response required before reclamation proceeds.

Table 2. Weighted scores, suitability classes, and dominant limiting factors

Zone	Slope Score	Material Score	Drainage Score	Final Score (Class)	Dominant Limiting Factor / Priority Action
A	90	84	88	87.2 (S1)	Minor constraints; direct reclamation and routine maintenance.
B	76	72	68	72.6 (S2)	Moderate drainage weakness; improve channels and maintain surface runoff control.
C	58	61	50	56.9 (S3)	Steeper slope and weaker material; regrading, surface stabilization, and drainage improvement required.
D	40	48	35	41.6 (N)	Severe multi-factor limitation; major redesign, stabilization, and drainage reconstruction before revegetation.

Zone A is the only classed S1 because it combines gentle slopes, comparatively dense material, low plasticity, and efficient drainage. Under such conditions, reclamation can proceed directly to surface preparation and revegetation with routine monitoring.

Zone B remains feasible for reclamation but only after limited corrective action. Its scores suggest that material and slope conditions are still manageable, while drainage is the main weakness. If channel continuity and outlet protection are improved, the zone can move toward more secure reclamation performance.

Zone C is only conditionally suitable because the limiting factors are cumulative rather than isolated. Slope steepness is already moderate to high, material quality is lower, and drainage performance is poor. Direct revegetation without prior engineering treatment would therefore risk erosion, ponding, and progressive surface degradation.

Zone D is unsuitable under present conditions. The combination of steep geometry, low density, higher plasticity, lower shear resistance, and very poor drainage means that the land should be redesigned before any claim of reclamation readiness is made. In a field setting, such

a zone would require more detailed geotechnical and hydrological investigation.

Discussion

The analysis indicates that reclamation suitability declines systematically as slope steepness increases, material quality deteriorates, and drainage performance worsens. This pattern is consistent with the broader geomorphic reclamation literature, which argues that stable slope form and hydrological functionality are prerequisites for durable ecosystem reconstruction (Hancock et al., 2020; Zapico et al., 2018; Tibbett, 2024). In practical terms, the framework confirms that reclamation readiness is first a physical systems question and only then a biological one.

A key advantage of the framework is its diagnostic specificity. Approaches based primarily on revegetation indicators, canopy cover, or post hoc remote sensing metrics are valuable for monitoring outcomes, but they can miss the engineering reasons why some reclaimed zones later fail or require repeated repair. In Indonesian post-mining contexts, vegetation recovery and land-cover improvement have been documented; however, such indicators do not automatically prove that slope geometry, drainage continuity, or spoil behavior are already adequate for long-term stability (Pambudi et al., 2025; Wang et al., 2023). By contrast, the present framework identifies the dominant limiting factor before large-scale planting decisions are made.

The framework also improves on generalized land suitability approaches by focusing on parameters most directly linked to erosion, ponding, and shallow instability. Broad multi-indicator evaluation models remain useful at a strategic scale, especially for comparing alternative land uses or ecological outcomes across districts (Tang et al., 2025; Wang et al., 2017). However, they often require a more operational pre-screening layer at the site scale. The present model fills that role by translating slope, material, and drainage observations into action-oriented classes that can be used by mine planners, field engineers, and regulators.

Another strength is the explicit coupling of slope and drainage. Previous work on geomorphic reclamation has shown that drainage networks and slope design cannot be treated independently, because concentrated flow progressively reshapes landforms and can destabilize even visually acceptable slopes (Zapico et al., 2020). The simulated results reflect that logic: Zone B remains moderately suitable because its main weakness is drainage performance, whereas Zone C becomes only conditionally suitable because drainage weakness interacts with steeper slopes and lower shear resistance. In other words, drainage is not a cosmetic add-on; it is a controlling process variable.

The model nevertheless has clear limitations. First, the paper demonstrates the framework using simulated, rather than site-specific, measured data. This choice is methodologically transparent but means the article should be read as a framework paper, not as a completed empirical site investigation. Second, the weighting system is analytically defensible; however, it still requires calibration through expert elicitation, historical reclamation performance, or multi-site validation. Third, the model is intentionally simple and therefore does not replace detailed geotechnical analysis, such as factor-of-safety calculations, rainfall-runoff modelling, seepage analysis, or deformation monitoring on high-risk slopes.

Its practical applicability therefore depends on mine context. For relatively low- to moderate-relief post-mining areas, spoil benches, or regraded dump surfaces, the framework can serve as an efficient first-stage screening tool. For steep highwalls, highly plastic spoils, acid-generating waste, or terrain with strong seasonal rainfall response, the model should be paired with more detailed geotechnical and hydrogeological investigations. Even with these limitations, the framework remains useful because it structures field judgment into a repeatable zoning logic and supports better budget targeting: direct reclamation for S1, light correction for S2, pre-treatment for S3, and redesign for N.

Conclusion

This study demonstrates that post-mining land can be evaluated for reclamation readiness through an integrated engineering geological assessment of slope condition, material properties, and drainage systems. Using a weighted scoring framework, the simulated demonstration classifies Zone A as very suitable, Zone B as moderately suitable, Zone C as conditionally suitable, and Zone D as unsuitable. The results show that gentle to moderate slopes, denser and less plastic materials, and effective drainage produce the highest reclamation readiness, whereas steep slopes, weaker materials, and poor runoff control sharply reduce suitability.

The main contribution of the study is methodological. It provides a transparent pre-revegetation diagnostic framework that identifies dominant limiting factors and translates them into practical reclamation actions, such as regrading, drainage rehabilitation, material improvement, staged revegetation, or complete redesign. In policy terms, the framework can support technically accountable reclamation planning by helping companies justify zoning decisions and by providing regulators with a clearer basis for reviewing reclamation-readiness claims.

Future work should move beyond simulated data by applying the model to multiple mine sites with contrasting lithology, spoil properties, rainfall regimes, and reclamation histories. The weighting system should be calibrated using expert judgment and empirical performance data, and the framework should be integrated with GIS-based zoning, factor-of-safety analysis, rainfall-runoff assessment, and vegetation monitoring. For real-world implementation, reclamation plans should explicitly require an engineering geological suitability check before large-scale planting, especially in zones with steep slopes, drainage discontinuities, or weak near-surface materials.

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Conflict of Interest

The authors declare that there are no financial, professional, or personal conflicts of interest that could have influenced the design, interpretation, or publication of this manuscript.

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