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Harmonising engineering and landform design for integrated rehabilitation and closure planning: a case study

Leon Koekemoer [a], **Gerhard van Wyk** [a,*]

[a] *E-TEK Consulting, South Africa*

Abstract

As the global demand for minerals keeps rising, the mining industry plays a pivotal role in meeting these demands while adhering to the United Nations Sustainable Development Goals. This case study explores the intersection of engineering and landform design in terms of sustainable mining practices.

The case study pertains to the waste rock dump of a diamond mine in Botswana and was driven by the socio-economic needs of the local population. A reduction in the overall liability and promotion of a sustainable development was sought, in tandem with resource extraction that adhered to associated legislation and ensured a stable landform suitable for the proposed end land use. This was achieved by conducting a staged approach.

The first stage involved conducting soil erosion studies on the site-specific extricated mine residue materials. These studies involved two primary phases: chemical testing and erodibility testing. Chemical testing assesses parameters such as pH, electrical conductivity, nutrient levels, trace elements, organic carbon and particle size distribution. Erodibility testing involves simulated rainfall experiments to evaluate soil susceptibility to erosion. These datasets are used to calibrate erosion models like the water erosion prediction project and inform landform and cover designs.

The second stage consisted of utilising the results of the soil erosion studies, whereby these results guided a dumping strategy design including a range of batter geometry designs and shapes (uniform gradient, concave gradient), slope gradients and lengths, final cover designs and, ultimately, the final landform design.

The last stage involved ensuring outputs met regulations and stakeholder expectations while integrating environmental and socio-economics factors into the landform design for long-term sustainability and positive community relations.

In conclusion, the case study showcases how integrating engineering and landform design promotes sustainable mining practices. The project mitigated erosion risks, minimised earthworks during operations and closure, created opportunities for concurrent rehabilitation, and ultimately ensured a stable landform and a reduction in liability.

Keywords: *sustainable mining, socio-economic integration, environmental regulations, landform design, erosion*

1 Introduction

The presented case study focuses on the operational dynamics of a diamond mine situated in Botswana. The mine's residue facilities (MRDs) are in a state of continuous expansion, with projections indicating that the mine will remain operational until the year 2034, with the possibility of future underground mining and extension of the life of mine (LoM) well into the future. Central to the study is the waste rock dump (WRD): a critical component of the mine's onsite aspects to be considered for rehabilitation and closure planning. The WRD has reached a final height of 150 m with a LoM footprint covering a total area of

[*] Corresponding author. Email address: gvanwyk@etekconsulting.co.za

1,500 ha. The case study for this facility focuses on the current mine plan, which excludes future underground operations (Figure 1).

Figure 1 The waste rock dump of a Botswana diamond mine

An analysis of the current geometry of the WRD and prospective dumping strategies serves as the basis for delineating requisite actions for its closure planning. Two scenarios for closure are considered, namely premature closure and LoM closure, to ensure compliance with statutory and corporate-related requirements. The rehabilitation and closure planning documentation was developed in accordance with the Anglo American Toolbox (Version 3) standards, and included opportunities for concurrent rehabilitation and planning of the landform design phase with closure in mind (Anglo American 2019).

The closure plan outlines the physical actions and associated costs, termed as closure liability, necessary for the rehabilitation of the WRD. Factors such as bench designs, dumping methodologies and existing industry benchmarks were taken into account during the complete process. The calculated closure liability reveals a substantial financial burden attributed to various factors:

- The WRD has reached its maximum allowable elevation.
- Dumping activities have led to a long single slope bench geometry on the outer faces due to end tipping of material on a short-haul basis.
- The absence of a formal dumping strategy exacerbates the rehabilitation challenges, necessitating extensive earthworks and material handling efforts.

Interventions were proposed to mitigate the inflated closure liability. These included redesigning the WRD expansion and formulating a dumping strategy aligned with the closure objectives. The aim was to optimise the WRD's design to facilitate cost-effective closure criteria and the implementation of concurrent rehabilitation.

Moreover, the composition of the WRD facility is not only basalt but also calcrete, Kalahari sand and sandstone, which is a mixture of different materials with different characteristics. The proposal submitted to the client was to conduct a soil erosion study in association with Landloch, an Australian-based company. This study aimed to assess the different WRD materials and inform closure criteria determination, thereby ensuring effective rehabilitation strategies.

While models such as the revised universal soil loss equation and the water erosion prediction project (WEPP) are widely used for erosion prediction, it is important to recognise their limitations in the context of mine rehabilitation. These models often do not fully capture the complexities of natural drainage patterns and the dynamic processes that occur in disturbed mining environments. For example, designing drainage systems that align with natural downhill flow rather than across slopes is crucial for stability and sustainability. The evolving understanding of these limitations is driving a shift towards geomorphic reclamation and rehabilitation approaches which are increasingly being recognised for their effectiveness in creating landforms that are more stable and require less maintenance over the long-term (Sawatsky & Beckstead 1996; Toy & Chuse 2005; Sawatsky & Beersing 2014).

The primary objectives of this study encompassed several technical components aimed at enhancing the effectiveness of WRD management:

- conducting a comprehensive assessment of the growth potential and erodibility of WRD materials
- identifying and determining the most erosionally stable batter designs tailored for rehabilitation purposes
- refining the dumping strategy to facilitate the effective implementation of rehabilitation criteria
- revising the design of the WRD with closure considerations at the forefront, focusing on mitigating liabilities associated with closure obligations
- optimising WRD management practices to ensure sustainable and efficient closure outcomes.

In summary, the case study underscores the importance of proactive planning and strategic interventions in managing the closure of mining facilities. By leveraging technical expertise, including landscape evolution modelling and geomorphic approaches to erosion modelling, and adhering to regulatory standards, mining companies and relevant stakeholders can navigate the complexities of mine closure while minimising the environmental impact and financial liabilities. Recognising the limitations of traditional models and adopting geomorphic reclamation principles can lead to more resilient landform designs and sustainable mine rehabilitation outcomes (Sawatsky et al. 2008; Bugosh & Epp 2019).

2 Case study context

A prominent diamond mine located in the Southern District of Botswana, illustrated in Figure 2, is considered one of the world's richest in terms of value per carat. Since its inception in 1982, this mine, operated through a partnership between the government of Botswana and a leading international diamond company, has been a critical contributor to Botswana's economy. The high-quality diamonds produced here have significantly impacted the global diamond market, further highlighting the mine's importance both locally and globally.

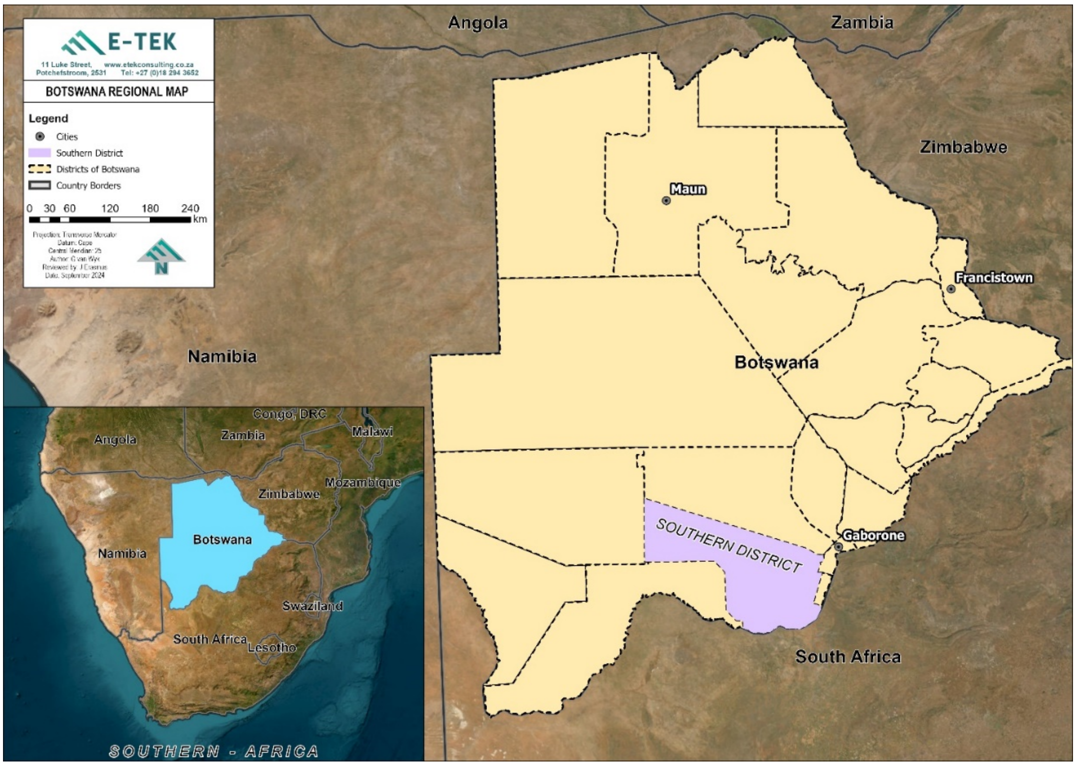

Figure 2 Botswana regional map

The mine utilises open pit mining techniques to extract diamonds from three kimberlite pipes. These operations generate substantial volumes of waste rock material, necessitating the development of an extensive WRD facility. Managing the dumping of the material of the WRD is a central focus of environmental management and rehabilitation efforts, especially as the mine approaches its planned closure.

This diamond mine has profoundly influenced the socio-economic landscape of its surrounding regions. It employs thousands of people, both directly and indirectly, and has spurred the development of infrastructure such as roads, schools and healthcare facilities. The nearby town has grown around the mine, thriving on the economic activities generated by the mining operations.

However, the mine's operations also present challenges. The local population depends on the mine for employment and economic stability, raising concerns about the future post-closure. Ensuring a sustainable transition for the local community involves addressing the socio-economics impacts of the mine's eventual closure and developing alternative economic opportunities.

Botswana's mining sector operates under a robust legislative framework designed to balance economic development with environmental conservation.

Specific to mine closure and rehabilitation, the regulations require mining companies to develop and implement detailed closure plans. These plans must outline measures for environmental restoration, land reclamation and post-closure monitoring. The objective is to minimise the long-term environmental impact of mining activities and ensure that the land can be repurposed for other uses once mining operations cease.

In the case of this diamond mine the closure plan follows international best practice guidelines, which provide a comprehensive framework for mine closure and rehabilitation. This includes guidelines for managing WRDs, controlling soil erosion, and ensuring that post-closure landforms are stable and sustainable.

3 Methodology

3.1 Introduction

In response to increasing environmental regulations and the need to ensure sustainable mining practices, the diamond mine in Botswana has initiated efforts to minimise its liability through the application of updated WRD design and land rehabilitation strategies. The mine's operations include the extraction of diamonds from kimberlite pipes, resulting in the production of significant volumes of waste rock material. To manage these materials responsibly and sustainably, the mine has undertaken a comprehensive study focusing on soil erosion and plant growth potential.

Landloch, in association with E-TEK Consulting (E-TEK), a leading environmental consultancy, was engaged to conduct a soil erosion study aimed at assessing the plant growth potential and erosion characteristics of various materials including calcrete, sandstone, basalt, and Kalahari sand. This study was crucial in informing updated design considerations for the WRD, closure strategies and the development of rehabilitation criteria.

3.2 Determination of landform design

The determination of a suitable landform design included the assessment of plant growth potential and erodibility testing of material mixtures composed of basalt, calcrete and Kalahari sand. Specifically, the following tasks were completed:

1. assessment of plant growth potential
    a. characterisation of the plant growth potential of the four bulk samples provided
    b. analysis of soil properties including pH, electrical conductivity, exchangeable cations, nutrient availability, organic carbon content and particle size distribution
2. assessment of erodibility

   a. evaluation of the erodibility of seven surfaces representing different waste materials and mixtures thereof derived from the bulk samples
   b. testing was conducted to parameterise the WEPP erosion model
3. WEPP erosion modelling
   a. 2D WEPP erosion modelling to develop erosionally stable batter designs using specific material mixtures.

The findings from these assessments were used to determine the final slope geometry, maximum lift height of benches, stormwater control measures and the growth medium required for effective rehabilitation.

3.3 Growth media characterisation methods

Before testing erodibility, four materials from the mine in Botswana were analysed for properties related to plant growth potential and structural stability. Analyses were performed on both the fine fraction (< 2 mm particle size) and the coarse fraction (> 2 mm particle size) in the following sections.

3.3.1 Fine fraction analyses (< 2 mm particle size)

- pHK (pH in potassium chloride [KCl] solution) — used to estimate pHw (pH in water solution). Importance — influences nutrient availability and microbial activity
- electrical conductivity (EC1:5) — electrical conductivity of the saturation extract (ECse) was estimated from EC1:5. Importance — measures salinity, which affects water uptake and plant health
- exchangeable cations — calcium (Ca), magnesium (Mg), sodium (Na) and potassium (K). Importance — essential nutrients and indicators of soil fertility
- effective cation exchange capacity (ECEC) — Importance — reflects the soil's ability to hold and exchange nutrients
- exchangeable sodium percentage (ESP) — ESP is a measure of the sodium ion concentration relative to other cations in the soil. High ESP values can lead to clay dispersion and poor soil structure, increasing the risk of erosion. Importance — identifies soils that may be unstable and prone to dispersion and erosion under certain conditions
- total nitrogen (N) and phosphorus (P) — Importance — key nutrients for plant growth
- organic carbon (C) (Walkley Black) — Importance — reflects soil organic matter, which is crucial for structure and nutrient supply
- available nutrients — P and K (Olsen), sulphur (S) (NH4), copper (Cu), manganese (Mn) and zinc (Zn) (EDTA extractable). Importance — indicates availability of essential nutrients
- particle size distribution — including coarse sand (2.0–0.25 mm), fine sand (0.25–0.05 mm), silt (0.05–0.002 mm) and clay (< 0.002 mm). Importance — influences soil texture, permeability and erosion potential
- dispersion class — assessed using Emerson class. Importance — indicates soil stability and erosion susceptibility.

3.3.2 Coarse fraction analyses (> 2 mm particle size)

- Particle size distribution (PSD) — including coarse gravel (> 25 mm), medium gravel (25–4.75 mm), and fine gravel (4.75–2.0 mm). Importance — reflects the soil's structural support and erosion resistance.

3.3.3 pHK and pHw

To assess the pH impact on rehabilitation, basalt and calcrete pH values were compared to that of Kalahari sand which supports vegetation. Materials with similar pH to Kalahari sand were deemed suitable for plant growth. The Kalahari sand has a pHK of 7.7, translating to a pHw of 8.7 (moderately alkaline). Waste samples with pHK values between 7.0 and 8.0 were classified as suitable. Importantly, proper pH ensures nutrient availability and healthy plant growth.

3.3.4 Salinity (EC1:5 and ECse)

Salinity was measured using EC1:5, with ECse estimated using texture-based conversions. The Kalahari sand is non-saline (< 0.1 dS/m). Sandy/sandy loam waste materials with EC1:5 > 0.2 dS/m were considered sufficiently saline to impact vegetation. Importantly, high salinity can hinder plant water uptake and growth.

3.3.5 Structural stability (tunnel erosion potential)

Structural stability and tunnel erosion risk were evaluated based on chemical and physical properties:

- chemical properties
  - ESP — high ESP values indicate a greater potential for clay dispersion and erosion, making soils unstable. Importantly, it identifies soils that are likely to be susceptible to erosion
  - Emerson stability index (ESI) — a measure of soil aggregate stability, with values less than 0.05 indicating a high risk of dispersion if the clay content is above 10%. Importantly, low ESI suggests a higher risk of erosion, which is crucial for planning soil conservation efforts
  - Ca/Mg ratio — this ratio is calculated by comparing the concentrations of calcium to magnesium. A ratio ≤ 0.5 indicates a potential for soil dispersion. Importantly, imbalanced calcium-to-magnesium ratios lead to poor soil structure, as calcium plays a critical role in maintaining soil stability and aggregation.
- physical properties
  - materials with fine sand, silt and clay compositions ≥ 70% were considered at risk of instability. . Importantly, high fine content can lead to compaction and erosion
  - Emerson aggregate test — used as a general guide for dispersion potential. An Emerson class of 1–3 indicated risk of dispersion. Importantly, it indicates stability of soil aggregates.

Materials meeting the criteria for ESP, ESI, Ca ratio or PSD were classified as being at risk of tunnel erosion. This classification is important for identifying erosion risks and aids in soil conservation efforts.

3.3.6 Wind erosion potential

Wind erosion potential was assessed based on aggregated PSD, coarse fraction abundance and moisture content. Sandy soils (< 10% clay), especially those with fine sand, had high wind erosion potential. Importantly, high wind erosion potential can lead to loss of soil and nutrients.

3.3.7 Fertility

Materials requiring nutrient addition for vegetation establishment were identified based on fertility values. Ensuring adequate nutrient levels is crucial for successful vegetation establishment and growth.

- Total N: Kalahari sand had 40 mg/kg total N, indicating low nitrogen availability for vegetation. Sufficient nitrogen is essential for plant growth.
- Organic C: Assessed with total N values. High C:N ratios (> 20–30) indicated nitrogen lockup and poor structure. Organic carbon is crucial for soil structure and nutrient cycling.

- Total P: Kalahari sand had 20 mg/kg total P, indicating low phosphorus availability. Phosphorus is vital for root development and overall plant health.
- Available nutrients:
  - P: ~1 mg/kg
  - K: ~150 mg/kg
  - S: ~2 mg/kg
  - Cu: ~10 mg/kg
  - Mn: ~30 mg/kg
  - Zn: ~2 mg/kg

These nutrients are essential for various physiological functions in plants, impacting growth and productivity.

3.4 Material mixtures created for the testing of erodibility

The following seven surfaces were created from the four bulk samples supplied and were assessed for erodibility:

- basalt sample 1 (unmixed)
- basalt sample 2 (unmixed)
- Kalahari sand (unmixed)
  - 1:2 mixture of calcrete and basalt sample 1
  - 1:2 mixture of calcrete and basalt sample 2
  - 1:2 mixture of Kalahari sand and basalt sample 1
  - 1:2 mixture of Kalahari sand and basalt sample 2.

3.5 Laboratory-based erodibility testing

Laboratory-based erodibility testing was conducted on the seven mixtures listed in Section 3.4. This erodibility testing enabled the parameterisation of the WEPP runoff/erosion model. Key material input parameters for the WEPP include:

- interrill erodibility (Ki)
- rill erodibility (KR)
- critical shear for rill initiation (τc)
- effective hydraulic conductivity (Ke)
- sediment particle size and density distributions.

Interrill erodibility (Ki) describes the detachment and movement of particles by the combined action of raindrops and shallow overland flows. Rill erodibility (KR) describes the detachment of particles by shear stresses caused by concentrated flows. Critical shear for rill initiation (τc) is the shear stress applied by concentrated flows to the surface above which particle detachment and transport by flow rapidly increase and rills form. Effective Ke defines the rate of water movement through a defined soil profile in response to wetting by rainfall and is derived through analysis of a material's steady infiltration and runoff rates.

The calibrated WEPP erodibility specifications for these parameters were derived from experimental methods involving the application of:

- simulated rain and the measurement of runoff rate and sediment loads in the runoff to obtain estimates of Ki and Ke
- concentrated surface water flows and measurement of flow characteristics and sediment loads to obtain estimates of KR and τc.

Predictions of erosion rates are sensitive to the particle size and density distributions of the eroded sediment. The version of the WEPP model available for general use has been coded to estimate sediment properties based on input soil PSD data. However, Landloch has a specialised version of WEPP that allows input of material-specific sediment particle size and density distributions. This version of WEPP has been used because it can more accurately predict erosion.

Samples of the rain-impacted surface from all materials were taken using the methods described by Loch (1994). These samples were placed into automated settling columns that provide equivalent sand size distributions for the generated sediment (Loch 2001). Equivalent sand size distributions integrate both particle size and density distributions into a single distribution that is representative of the sediment and that can be readily input to the WEPP.

3.6 Water erosion prediction project modelling

The WEPP model was developed by the United States Department of Agriculture to predict runoff, erosion and deposition for hillslopes. WEPP is a simulation model with a daily input time step, although shorter time steps are used by internal calculations on days when rainfall occurs. Plant and soil characteristics important to erosion processes are updated every day. When rainfall occurs, those plant and soil characteristics are considered in determining the likelihood of runoff. If runoff is predicted to occur, the model computes sediment detachment, transport and deposition at points along the slope profile.

The erosion component of the WEPP model uses a steady-state sediment continuity equation as the basis for the erosion computations. Soil detachment in interrill areas is calculated as a function of the effective rainfall.

4 Results and discussion

As mentioned previously, E-TEK, in collaboration with Landloch, jointly worked on this project, with each organisation responsible for different stages. E-TEK was responsible for performing the initial soil analysis and soil erosion studies. Once the raw data was acquired, Landloch utilised this data to run various erosion models, including the WEPP model, for different scenarios and mixtures. These results then further informed the limitations and best options for designing an economically and socio-economically viable landform. The results obtained from Landloch's modelling are discussed and displayed in the following section.

4.1 Water erosion prediction project modelling results

4.1.1 Water erosion prediction project erodibility and sediment properties

The effective Ke values, representing the bare (0% cover) and 40% vegetated surfaces, are summarised in Table 1. Materials containing Kalahari sand exhibited lower Ke values (12–26 mm/hr), indicating reduced water permeability compared to those without sand content. Interrill erodibility values were notably higher for surfaces with Kalahari sand, indicating increased susceptibility to detachment by raindrop impact. Similarly, rill erodibility values for Kalahari sand were significantly higher than those of waste rock and rock mixtures, suggesting a reduced potential for rill formation when basalt is added. Critical shear values followed a similar trend, with Kalahari sand requiring lower shear forces for erosion initiation compared to rocky surfaces.

Table 1 Water erosion prediction project effective hydraulic conductivity parameters derived from laboratory testing for bare materials (0% cover) and 40% surface cover (obtained from Landloch)

Mixture	Effective hydraulic conductivity, K_e (mm/hr^{-1})	
	0% cover	40% cover
Basalt sample 1	51	75
Basalt sample 2	50	75
Kalahari sand	12	35
1:2 calcrete: basalt sample 1	40	64
1:2 calcrete: basalt sample 2	46	71
1:2 Kalahari sand: basalt sample 1	23	50
1:2 Kalahari sand: basalt sample 2	26	51

The sediment size distributions depicted in Figure 3 reveal that materials with larger equivalent sand particle sizes tend to settle closer to the slope toe or within runoff control structures. Kalahari sand surfaces displayed slightly higher sediment mobility compared to calcrete and basalt, indicating potential challenges in sediment settling. However, the majority of sediment from all materials is likely to deposit near the slope toe or within control structures.

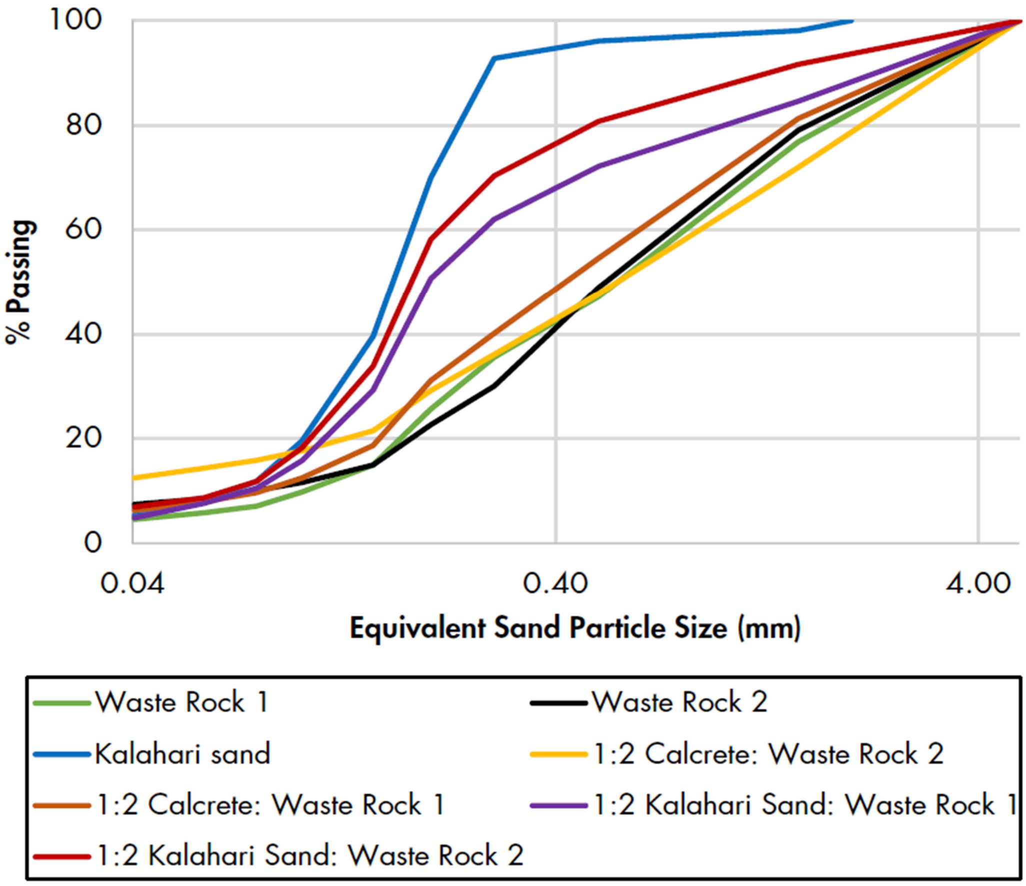

Figure 3 Average equivalent sand sediment size distribution for the five materials tested (obtained from Landloch)

4.1.2 Temporal variation in erosion

Erosion rates varied annually due to fluctuations in rainfall and runoff. Model simulations using the 100-year CLIGEN climate sequence demonstrated this variability, with some years experiencing minimal erosion while others showed high erosion potential. Vegetation establishment was identified as crucial for stability, particularly on Kalahari sand surfaces, where erosion rates were predicted to be high without vegetation cover.

4.1.3 Erosion pattern along a uniform slope

Erosion did not occur uniformly along the slope length, and depended on material erodibility, climate and slope geometry. Model predictions illustrated the relative erosion resistance of different material mixtures, with waste rock-based mixtures exhibiting higher erosion resistance compared to Kalahari sand.

4.1.4 Erosion of a uniform gradient slope

4.1.4.1 Uniform 18° batter shape with and without vegetation

Table 2 presents predicted erosion rates for various material mixes and vegetation cover levels on a 20 m-high, 18° uniform batter. Results indicated that basalt addition effectively reduced erosion to acceptable levels, even without vegetation. Moreover, achieving 40% grass cover further reduced erosion rates.

Table 2 Water erosion prediction project predicted erosion rates for seven mixtures and varying cover levels on a 20 m-high uniform batter with a gradient of 18° (obtained from Landloch)

Material	Surface cover (%)	WEPP-predicted average annual erosion (t/ha/y)	
		Mean	Peak
Basalt sample 1	0	< 0.1	0.2
	40	< 0.1	< 0.1
Basalt sample 2	0	< 0.1	0.3
	40	< 0.1	< 0.1
Kalahari sand	0	276	353
	40	24	36
1:2 calcrete: basalt sample 1	0	0.4	1.5
	40	< 0.1	< 0.1
1:2 calcrete: basalt sample 2	0	0.1	0.4
	40	< 0.1	< 0.1
1:2 Kalahari sand: basalt sample 1	0	1.3	4.6
	40	< 0.1	0.2
1:2 Kalahari sand: basalt sample 2	0	0.8	2.8
	40	< 0.1	0.1

Cells shaded darker green represent batter geometry and cover combinations that produce acceptable erosion rates. Cells shaded orange represent batter geometry and cover combinations that produce unacceptable erosion rates.

4.1.4.2 *Unvegetated uniform batter geometries*

Table 3 provides the maximum permissible lift heights for different material mixes and gradient levels. Lift heights were restricted to maintain acceptable erosion rates and limit slope lengths. If greater heights are required, concave slope options or berms could be considered.

These findings underscore the importance of material selection, vegetation establishment and slope geometry in erosion control. Further refinement of rehabilitation strategies should consider these factors to ensure long-term stability and environmental sustainability.

Table 3 Water erosion prediction project predicted erosion rates for six mixtures and varying batter geometries, assuming a 0% cover level (obtained from Landloch)

Material	Lift gradient (°)	Max. permissible lift height (m)	Berm width for the given max. permissible lift height (m)
Basalt sample 1	10	30	13
	14	35	11
	18	40	10
Basalt sample 2	10	30	13
	14	35	13
	18	40	12
1:2 calcrete: basalt sample 1	10	30	15
	14	35	15
	18	40	16
1:2 calcrete: basalt sample 2	10	30	14
	14	35	11
	18	40	10
1:2 Kalahari sand: basalt sample 1	10	30	19
	14	35	21
	18	35	18
1:2 Kalahari sand: basalt sample 2	10	30	18
	14	35	19
	18	40	17

4.2 Discussion

The results of the WEPP modelling provide valuable insights into the erosion potential of different material mixtures used in the study. The effective Ke values and erodibility parameters show that Kalahari sand, partly due to its low Ke values, has significantly higher erodibility compared to the basalt and calcrete mixtures. This indicates a higher susceptibility to erosion by raindrop impact and runoff, necessitating careful management and potentially higher vegetation cover to mitigate erosion risks.

The temporal variation in erosion rates demonstrates the influence of climate variability on erosion potential, underscoring the importance of vegetation establishment for stabilising surfaces. This is particularly crucial on Kalahari sand surfaces, where erosion rates are predicted to be high without adequate vegetation cover.

The erosion pattern along a uniform slope reveals varying erosion rates based on material mixtures and their sediment size distributions. The ranking of materials by erosion resistance suggests that waste rock and calcrete mixtures are more effective in reducing erosion compared to Kalahari sand.

Recommendations for slope rehabilitation include consideration of batter geometries and vegetation cover levels to achieve acceptable erosion rates. The results suggest that the addition of basalt into Kalahari sand and calcrete mixtures significantly reduces erosion to acceptable levels, even without vegetation. However, higher vegetation cover is predicted to further reduce long-term erosion rates.

5 Design and implementation

The initial phase of the study involved the meticulous determination of a suitable landform design through a comprehensive assessment of plant growth potential and erodibility testing. This assessment encompassed the examination of material mixtures comprising basalt, calcrete and Kalahari sand. Specifically, the following tasks were undertaken:

- assessment of plant growth potential
    - characterisation of four bulk samples
    - analysis of soil properties such as pH, electrical conductivity, nutrient availability and organic carbon content.

Evaluation of erodibility across seven surfaces representing various waste materials and mixtures derived from the bulk samples:

- testing conducted to parameterise the WEPP erosion model.

2D WEPP erosion modelling:

- development of erosionally stable batter designs using specific material mixtures.

These assessments provided crucial insights into determining the final slope geometry, maximum lift height of benches, stormwater control measures and the growth medium required for effective rehabilitation.

Initially the mine began deposition on the WRD by means of end-tipping material from the final height of the dump. This resulted in an immense closure liability, with constraints on rehabilitation methods and opportunities. To address this, a new dumping design and strategy was developed that led to a uniform design whereby material is placed from the outer perimeter in benches moving inwards. This approach reduces the liability annually through smart dumping by alleviating the long single slopes on the outer faces and facilitates concurrent rehabilitation while the facility is still operational.

Figure 4 illustrates the year-by-year development of the new dumping strategy, showing how waste rock is systematically deposited to optimise space for reshaping and rehabilitation while managing closure liabilities effectively.

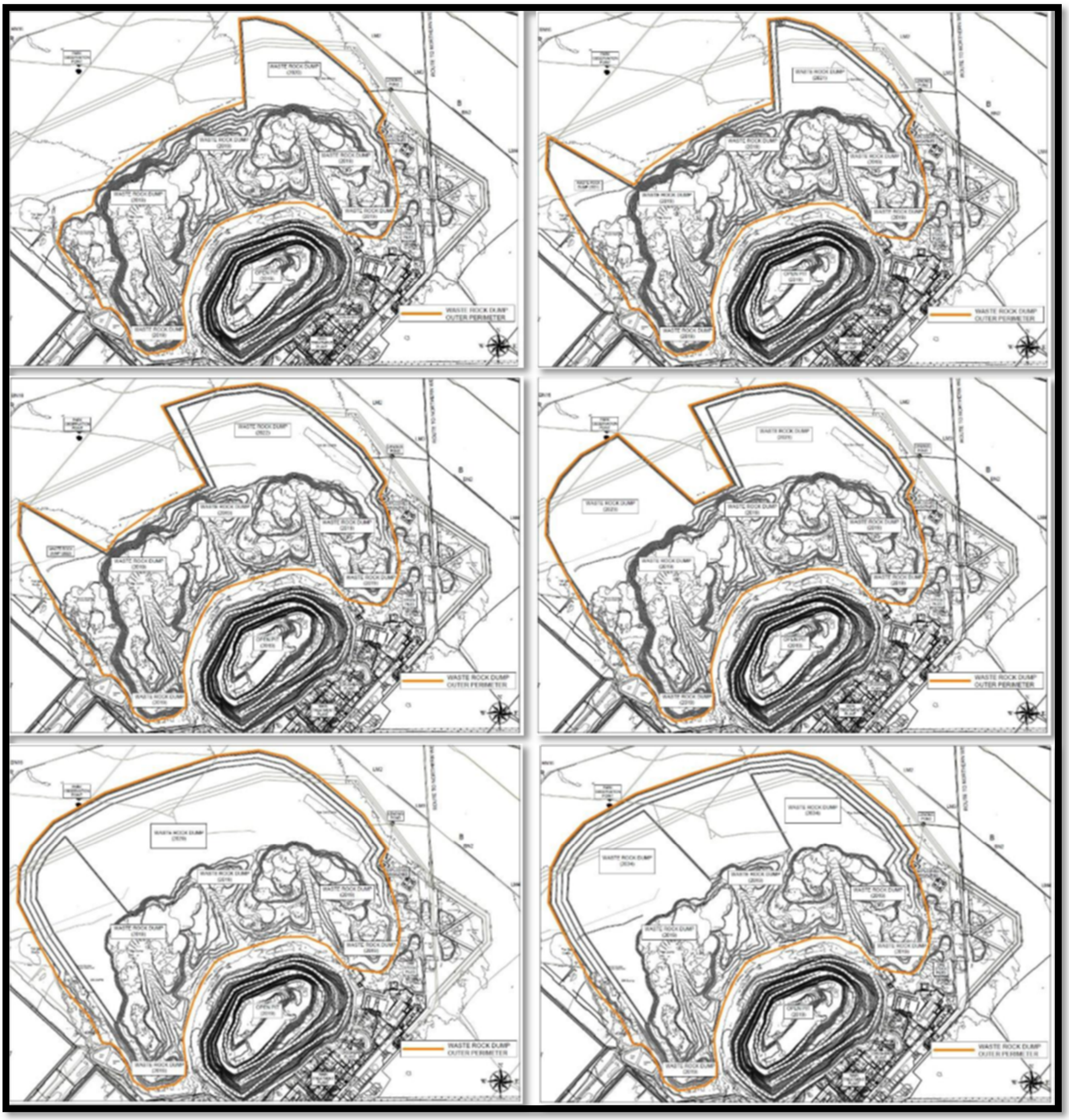

Figure 4 Waste rock dumping strategy up to the life of mine

In contrast to Figure 1, which illustrates the initial end-tipping approach, Figure 5 shows how the mine has adopted a new dumping strategy that integrates closure planning from the outset. This method involves creating adequate space for reshaping the facility by stripping growth medium from the footprint area and strategically placing waste material to allow for concurrent rehabilitation options.

These actions also enable socio-economic benefits and the potential for job creation and skills development for the local community, including those related to corporate social investment projects. With further planning and the influence of the social performance team and corporate affairs, projects such as seed harvesting may be influential to the socio-economics environment (Figure 5).

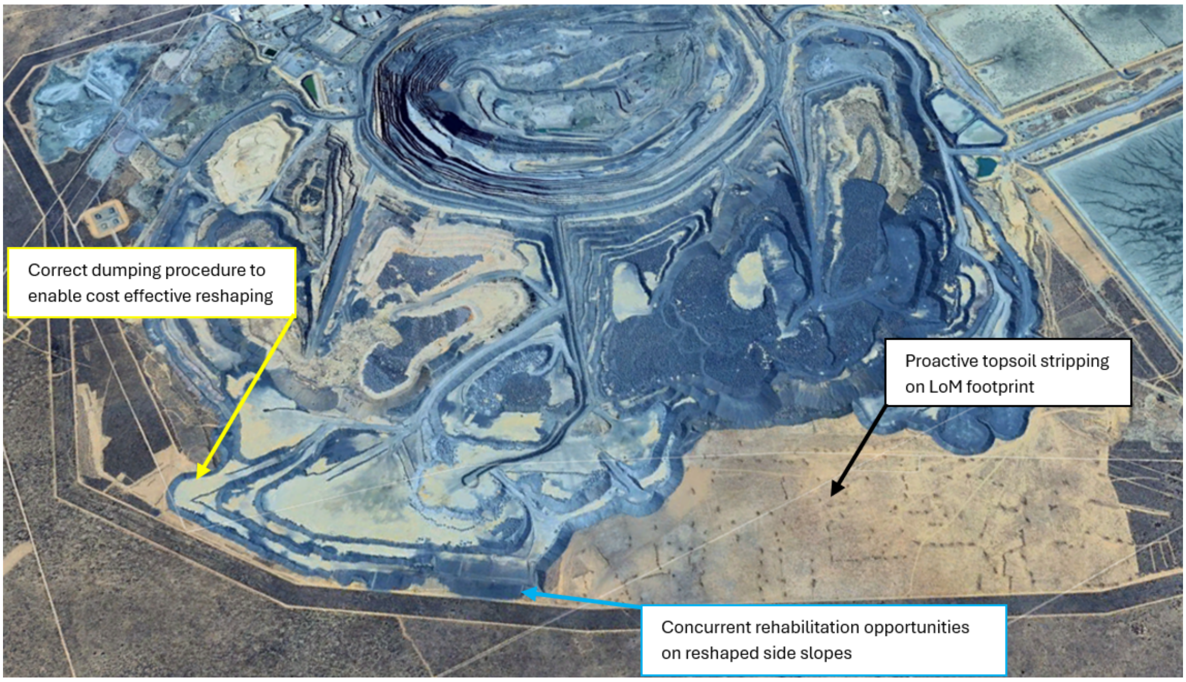

Figure 5 The waste rock dump of a Botswana diamond mine showcasing a formalized dumping strategy, developed based on key outcomes. These outcomes were instrumental in formulating an optimized dumping approach, influencing the structural configuration of the dump and shaping the rehabilitation criteria, while also enabling socio-economic benefits such as job creation, skills development, and corporate social investment initiatives.

Incorporating the most economically viable dozing distances founded on the slope length and gradient facilitated the determination of optimal bench heights. The interplay between bench lengths and the associated lift heights is crucial, as evidenced by the study's findings. For instance, while a 20 m bench height may meet certain acceptability criteria it significantly increases dozing distances, subsequently increasing the liability associated with rehabilitation efforts.

The reduction of bench heights yields multiple benefits, foremost among them being the reduction of liability owing to reduced cut-and-fill volumes. Additionally, the reduction of bench heights results in shorter inter-bench slope lengths, thereby reducing the runoff distances for stormwater discharge. Consequently, there is a proportionate decrease in the requisite capacity of stormwater management structures on the slopes.

The development of the dumping strategy is vital to ensuring the avoidance of overlapping benches during the dozing-down phase of rehabilitation. This strategic approach prevents the formation of elongated single slopes, thus enhancing the efficiency and effectiveness of the rehabilitation process.

The dumping strategy and final landform design parameters to ensure the most optimal rehabilitation and success criteria (shown in Figure 1) are:

- dumping strategy design parameters
  - lift heights not exceeding 20 m
  - bench width (lift step back) > 50 m
- final landform design parameters
  - inter-bench slopes < 18°
  - bench width after reshaping > 10 m
  - bench back slope 1(v):5(h)
  - inter-bench slope length ±65 m

- stormwater
  - stormwater structures' capacity decreased from 4 m^3/m capacity to 2.5 m^3/m
- growth medium
  - spread > 100 mm ameliorated growth medium on all surfaces
  - ameliorated growth medium to be revegetated.

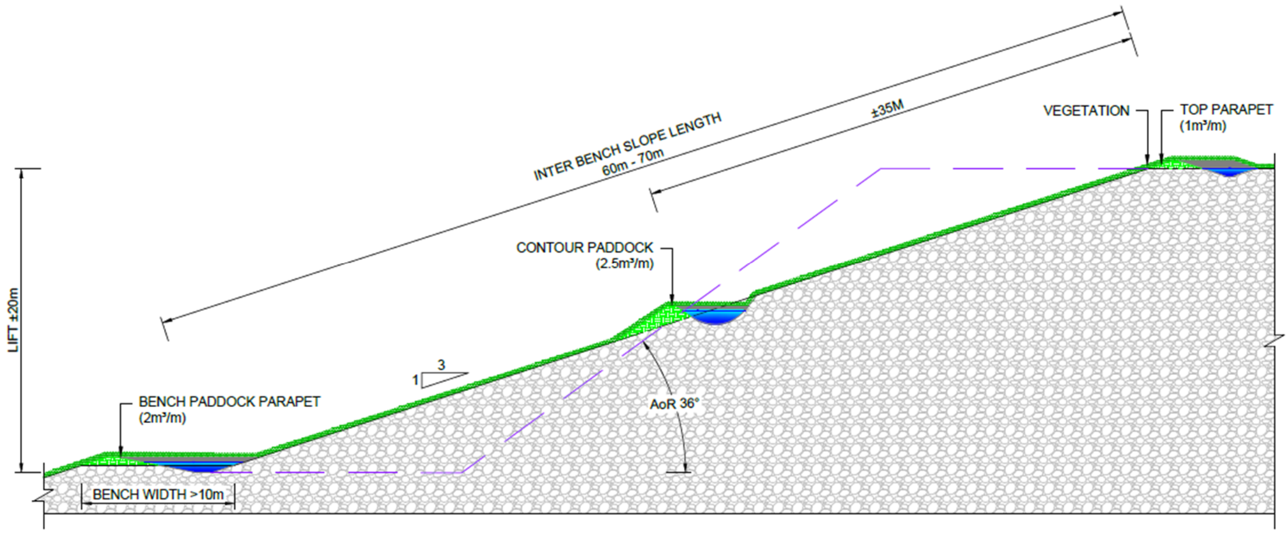

Figure 1 Section of rehabilitation criteria for the waste rock dump

6 Conclusion

Soil erosion studies have been instrumental in refining the disposal of waste rock material, closure strategies and rehabilitation criteria. By evaluating erosion characteristics and plant growth potential in materials such as calcrete, sandstone, basalt and Kalahari sand, these studies inform environmentally compliant and sustainable mining practices. This research optimises WRD facility management, enables the design of erosionally stable landforms, predicts erosion rates and guides effective erosion control measures. Overall, these studies are essential for promoting sustainable mining, protecting the environment and ensuring successful rehabilitation efforts.

In conclusion, the study's findings offer valuable insights into optimising WRD rehabilitation strategies. Recommendations for slope rehabilitation emphasise the importance of considering batter geometries and vegetation cover levels to achieve acceptable erosion rates. The results indicate that incorporating basalt into Kalahari sand and calcrete mixtures substantially reduces erosion to acceptable levels, with higher vegetation cover predicted to mitigate long-term erosion rates further.

Furthermore, the development of a new dumping strategy not only enables a continuous decrease in liability over each financial year but also unlocks opportunities for concurrent rehabilitation on the WRD, which were previously unattainable. Initially, the mine began deposition on the WRD by means of end-tipping material from the final height of the dump, which resulted in an immense closure liability and constraints caused by this method on rehabilitation processes. To address this, a new dumping design was developed that led to a uniform design by which material is placed from the outer perimeter in benches moving inwards. This approach reduces the liability annually through smart dumping by alleviating the long, single slopes on the outer faces and facilitates concurrent rehabilitation while the facility is still operational. These actions also enable socio-economics benefits.

By implementing these recommendations and leveraging the findings to inform design parameters and dumping strategies, mining operations can efficiently navigate the complexities of WRD facility closure while mitigating operational and closure risks while also managing financial liabilities.

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