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From design to implementation: lessons from large-scale rehabilitation trials in Botswana

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Abstract

At the 2024 Mine Closure Conference, a case study was presented on harmonising engineering and landform design to support sustainable closure at a diamond mine in Botswana. The original paper outlined a staged approach incorporating detailed material characterisation, erosion modelling, growth medium optimisation, stormwater management design and landform refinement to reduce long-term liability and align with the approved post-mining land use.

Since then, the project has transitioned from concept to full-scale physical implementation under the rehabilitation trials plan. This paper provides an update on the progression from design to execution and highlights the practical realities encountered during onsite implementation, monitoring and adaptive management.

Implementation has revealed challenges specific to the Botswana context that directly influence the constructability of the engineered landform design. These include constrained availability of specialised contractors and earthmoving equipment, precision requirements in stormwater paddock construction, early-stage erosion risks on reshaped slopes and the necessity for continuous technical assurance to preserve design integrity. A critical constraint identified is the limited availability of suitable indigenous rehabilitation seed. The volumes required for large-scale implementation are not commercially available within Botswana and had to be sourced from South Africa, where supply is also limited and inconsistent.

This supply limitation fundamentally shifts rehabilitation strategy. Large-scale closure cannot feasibly commence only at life of asset. Instead, concurrent rehabilitation during operations is essential to define procurement requirements across all rehabilitation phases in accordance with the prescribed workflow, distribute seed demand over time, reduce closure risk exposure, enable progressive ecosystem establishment and support liability reduction.

The trials further exposed a national capacity gap. Rehabilitation at this scale has not previously been undertaken in Botswana, resulting in limited local technical expertise. In response, a structured onsite training program was developed to transfer knowledge and build sustainable in-country implementation capacity.

The findings demonstrate that rehabilitation implementation depends not only on robust engineering design, but equally on supply chain realism, skills development and early, concurrent execution.

Keywords: *landform design; concurrent rehabilitation; mine closure rehabilitation trials; skills development and resource management; liability management*

1 Introduction

At the 2024 Mine Closure Conference, the paper 'Harmonising engineering and landform design for sustainable mining: a case study' presented a staged approach to reducing closure liability at a large diamond mine in Botswana. The study incorporated detailed material characterisation, erosion modelling, growth

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medium optimisation, stormwater management design and landform refinement to develop erosionally stable landforms aligned with the approved post-mining land use (Koekemoer & van Wyk 2024). The objective was to create sustainable landforms capable of supporting vegetation establishment under semi-arid climatic conditions.

Since publication, the project has transitioned from conceptual design and modelling into physical implementation under a structured rehabilitation trials plan. This progression provided an opportunity to evaluate how theoretically optimised landforms perform under real operational conditions. While erosion modelling and laboratory testing provided confidence in slope geometries, growth medium compositions and stormwater management configurations, implementation introduced additional operational, logistical, climatic and workforce-related variables not fully represented during the modelling phase.

The waste rock dump (WRD) remains a critical closure component. Ongoing open pit expansion and cutback activities continue to generate significant waste rock volumes, resulting in continued development of the facility under the current life of mine plan. Historic end-tipping practices created extended single-slope geometries, increasing erosion susceptibility, rehabilitation complexity and long-term closure liability. In response, a revised dumping strategy was introduced in 2021, transitioning towards controlled bench-based deposition to improve landform stability, reduce reshaping requirements and facilitate concurrent rehabilitation.

The present paper shifts the focus from design optimisation to implementation performance. It evaluates the practical challenges encountered during construction of stormwater structures, growth medium placement, ripping and seeding, and assesses how operational realities, including construction precision, climatic variability, and indigenous seed and ameliorant availability, influence rehabilitation outcomes. The paper further reflects on local capacity constraints and the importance of structured skills development to support large-scale rehabilitation implementation.

The transition from design to implementation provides important insight into the practical realities of mine closure in emerging mining jurisdictions and highlights the importance of integrating engineering, operations, ecology, logistics and workforce development into a unified closure framework. The study was undertaken at a diamond mining operation located in the Southern District of Botswana. Figure 1 illustrates the regional location of the mine within Botswana and its position relative to surrounding countries and major regional centres.

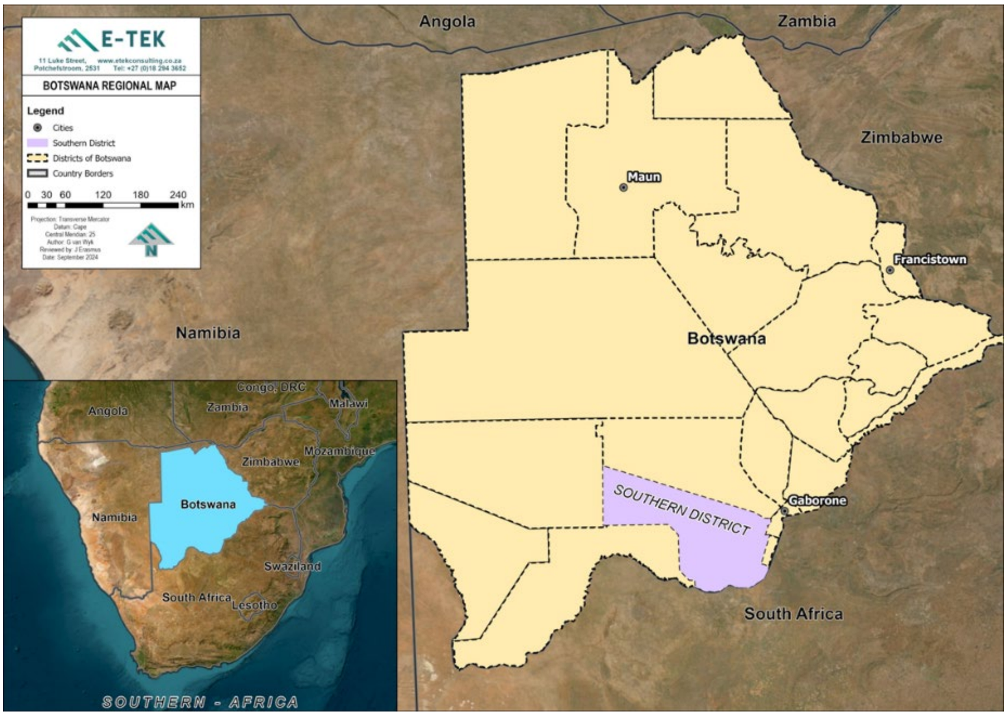

Figure 1 Regional location of the diamond mine

2 Implementation context and operational setting

The work presented in this paper is grounded in the rehabilitation of a large open pit diamond operation in south-central Botswana. The mine has been operational since the early 1980s and continues to generate significant volumes of waste rock material through ongoing open pit expansion and cutback activities. The WRD remains one of the largest mine residue facilities on site and constitutes a major component of long-term closure liability.

Under the current life of mine plan, the WRD has reached substantial vertical and lateral development. Historical end-tipping practices resulted in extensive single-slope geometries along the outer WRD faces. While operationally efficient during active deposition, these geometries increased closure complexity due to long slope lengths, elevated erosion susceptibility and significant reshaping requirements required to achieve closure-aligned landforms.

In response, a revised landform design and dumping strategy was introduced in 2021 to better align operational deposition with closure objectives. The revised design incorporated controlled bench-based deposition, maximum lift height limitations, inter-bench slope refinement, optimised dozing distances to improve operational constructability, and the integration of contour-aligned stormwater paddocks into the evolving WRD geometry.

The revised landform design was informed by erosion modelling, material characterisation, growth medium optimisation studies, stormwater management design and operational constructability assessments. Water Erosion Prediction Project (WEPP) erosion modelling and associated rehabilitation studies were undertaken to evaluate long-term erosion performance under semi-arid climatic conditions and identify geometries capable of supporting sustainable vegetation establishment while minimising long-term maintenance requirements and closure liability.

Importantly, the revised design aimed to not only improve long-term erosion stability but also facilitate concurrent rehabilitation during operations. By progressively reshaping and rehabilitating WRD sections during operations, the mine could reduce future closure earthworks, progressively reduce liability exposure, and evaluate rehabilitation performance under actual climatic and operational conditions.

The transition from conceptual design to physical implementation occurred within a specific operational and regional context. Large-scale rehabilitation implementation of this nature has historically not been undertaken within either the company group or the broader Botswana mining sector. As a result, practical constraints such as contractor experience, construction precision, equipment limitations, indigenous seed and ameliorant availability, seasonal climatic variability and workforce capability became significant factors influencing rehabilitation performance.

This operational setting provides the foundation for evaluating how theoretically optimised landform designs perform when translated into full-scale rehabilitation practice.

3 Transition from design to implementation

3.1 From modelling confidence to field execution

The 2024 study demonstrated, through laboratory testing and WEPP erosion modelling (Flanagan & Nearing 1995), that specific material mixtures, slope geometries and stormwater management configurations could achieve erosion rates within acceptable thresholds under defined climatic conditions. The modelling framework provided confidence in maximum lift heights, inter-bench slope gradients, berm configurations, growth medium compositions, and stormwater control measures required to support long-term erosion stability and vegetation establishment.

However, while erosion modelling defines theoretical stability under controlled assumptions, field implementation introduces variability that cannot be fully replicated within laboratory or simulation environments. Real-world rehabilitation implementation is influenced by operational, climatic, logistical and human factors that directly affect landform performance.

These implementation variables include:

- practical limitations in achieving precise design tolerances using large-scale earthmoving equipment
- variability in operator experience and construction sequencing
- temporary exposure of reshaped slopes prior to vegetation establishment
- climatic variability during implementation and establishment phases
- limited machinery availability and contractor scheduling constraints
- supply chain constraints associated with indigenous seed and ameliorant availability.

The transition from conceptual modelling to physical implementation therefore provided an opportunity to evaluate the practicality and robustness of the landform design under actual operational conditions.

3.2 Implementation framework under the rehabilitation trials plan

Implementation of the rehabilitation trials commenced during 2025 under a structured rehabilitation trials plan developed for both the WRD top surface and side slope environments (Figure 2) (E-TEK Consulting 2026a).

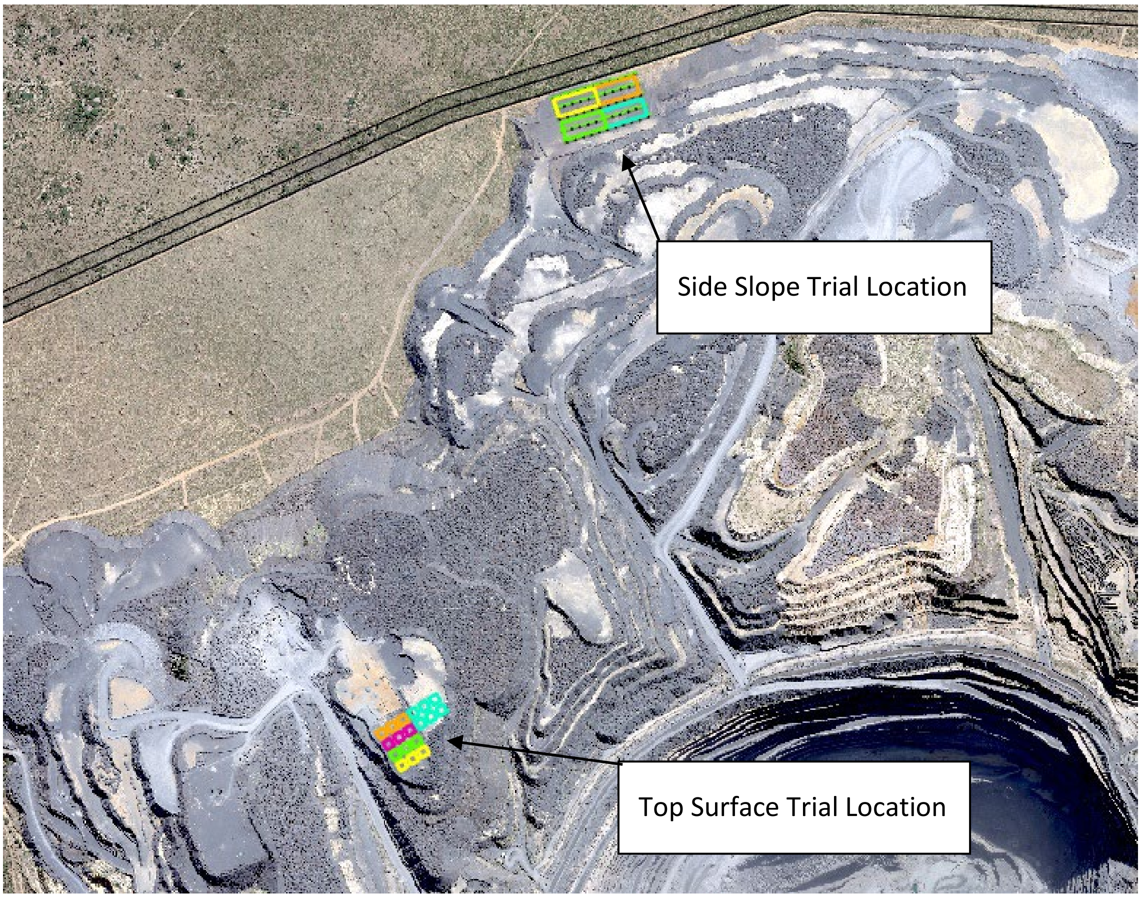

Figure 2 Trial site locations

The implementation phase included the development of implementation schedules; procurement of growth medium materials, compost, ameliorants and indigenous seed mixes; and training and assurance support for mine personnel and contractors involved in the rehabilitation works (E-TEK Consulting 2026b).

The implementation sequence included:

- bulk reshaping of WRD side slopes to the required geometries
- construction of growth medium mixing pads
- placement and spreading of growth medium materials
- construction of crest berms, contour paddocks and stormwater control structures
- ripping parallel to contours
- premixing and application of ameliorants and indigenous seed mixes
- seeding of slope and top surface trial areas
- ongoing monitoring, assurance and maintenance activities.

The implementation activities undertaken during the rehabilitation trials, including growth medium placement, construction of stormwater control structures, ripping and seeding, are illustrated in Figures 3 and 4.

Figure 3 Implementation of trials (growth medium placement and stormwater structure construction)

Figure 4 Implementation of trials (ripping and seeding)

Implementation was undertaken in phases linked to critical construction milestones requiring technical assurance. Multiple site visits were conducted throughout implementation to provide training, assess compliance with the trials plan, identify risks, and provide corrective guidance to contractors and operational personnel (E-TEK Consulting 2025a, 2025b, 2026a, 2026b).

The implementation phase highlighted the importance of sequencing and construction timing. Several activities were delayed due to limited machinery availability, contractor scheduling constraints and operational delays associated with earthmoving equipment (E-TEK Consulting 2025b). During certain assurance visits, activities such as growth medium spreading, crest berm construction and top surface preparation could not be fully assessed due to the absence of required machinery or delays in load and haul activities (E-TEK Consulting 2026a).

Growth medium placement and spreading generally achieved acceptable compliance with the design intent; however, isolated areas of exposed calcrete and inconsistent material coverage required corrective lateral dozing and redistribution of material. Stormwater control structures also required continuous oversight during construction. Minor deviations in crest berm geometry, contour paddock alignment and cross-wall construction highlighted the difficulty of achieving precise construction tolerances under operational conditions (E-TEK Consulting 2026b).

3.3 Rehabilitation trial configurations and growth medium treatments

The rehabilitation trials plan incorporated multiple rehabilitation treatments across both the WRD side slopes and top surface areas to evaluate the performance of different growth medium mixtures, ameliorant applications and revegetation approaches under operational field conditions. The trials were developed to assess the suitability of various material combinations for supporting vegetation establishment, reducing erosion susceptibility and improving long-term landform stability under semi-arid climatic conditions.

The trial configurations included combinations of available site-derived materials, together with imported growth medium components, imported compost and imported ameliorants, applied at varying ratios and thicknesses across the different treatment areas. The objective was to evaluate the practicality of implementation, material constructability, erosion response and vegetation establishment performance for each treatment under actual operational conditions.

Separate trial areas were established on both the WRD top surface and side slope environments to assess the influence of slope geometry, run-off behaviour and surface water management on rehabilitation performance. The side slope trials incorporated contour-aligned stormwater paddocks, crest berms, ripping and seeding treatments to evaluate erosion control performance and vegetation establishment on rehabilitated slopes.

Growth medium mixing pads were established operationally to facilitate the blending and preparation of various rehabilitation mixtures prior to placement. The implementation phase included the load and haul of growth medium materials, spreading it to specified thicknesses, premixing of ameliorants and seed mixtures, and subsequent ripping and seeding activities (E-TEK Consulting 2026a, 2026b).

Figures 5 and 6 illustrate the layout of the rehabilitation trial areas and associated treatment configurations implemented across the WRD top surface and side slope environments. The figure further indicates the various growth medium mixtures evaluated as part of the rehabilitation trials program.

The implementation of multiple treatment configurations provided an opportunity to compare rehabilitation performance under varying material compositions and operational conditions. This approach also enabled ongoing refinement of growth medium specifications, ameliorant application methodologies and revegetation strategies for future large-scale rehabilitation implementation.

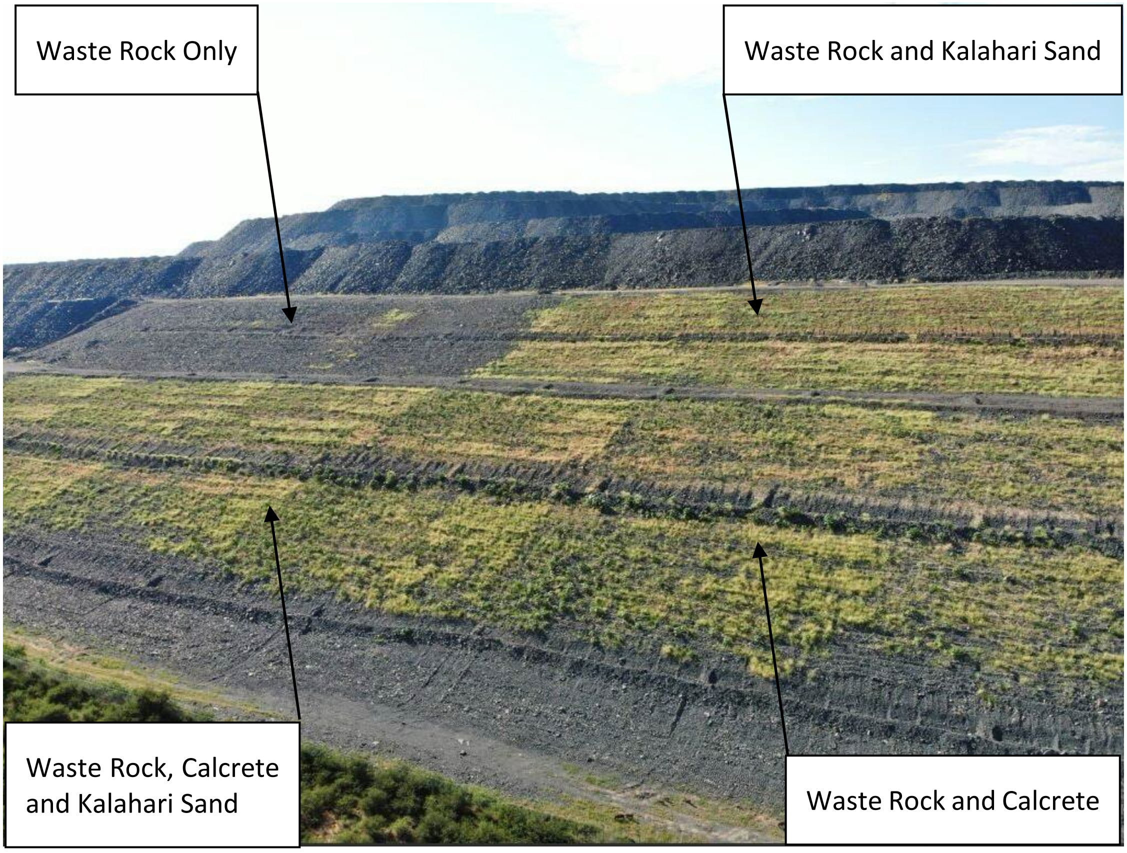

Figure 5 Side slope trial mixtures

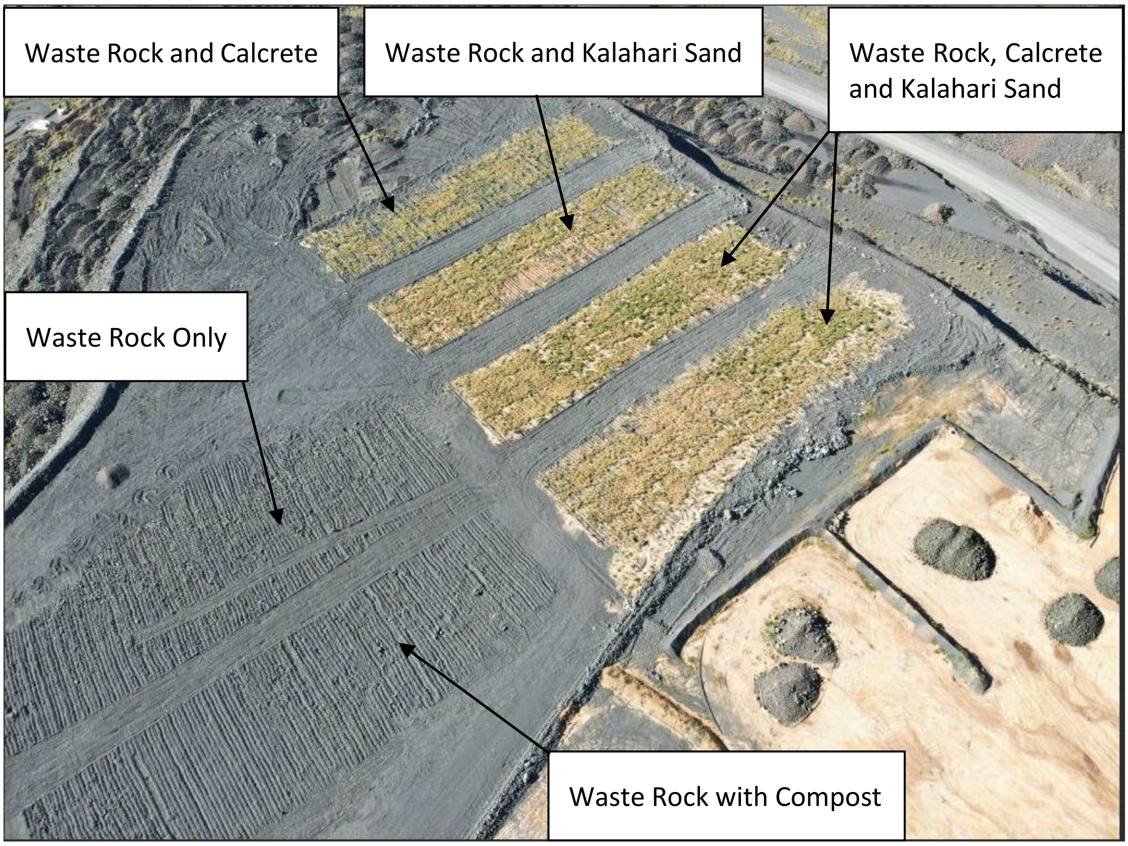

Figure 6 Top surface trial mixtures

3.4 Operational limitations and constraints during implementation

Following reshaping and seeding activities, monitoring identified several early-stage rehabilitation performance trends requiring adaptive management and ongoing technical oversight (Figures 7 and 8).

Observed trends included:

- localised sheet, rill and gully erosion on reshaped side slopes
- siltation within contour paddocks, with some sections reaching significant sediment accumulation levels
- localised overtopping risk associated with silted stormwater structures
- areas of inconsistent growth medium thickness resulting from operational spreading variability
- erosion associated with insufficient ripping depth
- differential vegetation establishment linked to micro-topography and soil variability
- localised voids and instability around stormwater cross-wall structures.

While none of these observations represented systemic design failure, they highlighted the difference between theoretically optimised rehabilitation designs and exposure to real climatic and operational conditions during implementation.

The implementation phase demonstrated that the period between reshaping and successful vegetation establishment represents one of the most vulnerable stages of rehabilitation. During this transition period, reshaped slopes remain highly susceptible to erosion until sufficient vegetative cover and root establishment occur. Monitoring indicated that early-stage erosion on the rehabilitated side slopes (Figure 7) contributed directly to siltation of contour paddocks and reduced stormwater holding capacity, increasing the risk of overtopping and structural failure during future storm events (Figure 8)(E-TEK Consulting 2026c).

Corrective actions identified during implementation included desilting of stormwater paddocks, repair of localised erosion features on side slopes, improvement of ripping practices and equipment selection, filling of voids within berm cross-wall structures, procurement of additional seed and ameliorants, and implementation of ongoing vegetation and invasive species management programs. It was identified that certain erosion areas were not related to deficiencies in the rehabilitation landform design but rather to the use of inadequate ripping machinery during construction. The equipment utilised was unable to consistently achieve the specified 500 mm ripping depth within the waste rock and growth medium profile, resulting in shallower ripping, insufficient material mixing, reduced infiltration capacity and increased susceptibility to erosion in certain areas. Long-term monitoring programs for climatic conditions, erosion performance, stormwater stability and vegetation establishment were also identified as critical components of the rehabilitation strategy (E-TEK Consulting 2026a).

The implementation phase ultimately reinforced that successful rehabilitation depends not only on robust engineering design but equally on construction precision, operational execution, maintenance responsiveness, monitoring and adaptive management under real operational conditions.

Figure 7 Trials assurance findings – side slope erosion

Figure 8 Trials assurance findings – siltation of stormwater structures

3.5 Re-evaluating closure strategy through implementation

The implementation phase also revealed that closure strategy cannot be separated from operational sequencing and supply logistics. The ability to conduct concurrent rehabilitation depends not only on geometric design but also on:

- experienced and skilled operators/contractors capable of achieving required tolerances
- the availability of suitable earthmoving equipment and machinery
- the availability of suitable growth medium materials
- access to sufficient volumes of indigenous seeds and ameliorants
- the aftercare and maintenance of trials and/or full-scale implement of rehabilitation after implementation
- implementation of a monitoring program post rehabilitation.

These practical constraints prompted a broader re-evaluation of closure timing assumptions. Specifically, the assumption that large-scale rehabilitation could be deferred to mine end of life was challenged by the limited availability of indigenous seeds and ameliorants at required volumes and by the need for progressive skills development within the local workforce.

The transition from design to implementation therefore expanded the closure framework beyond erosion stability alone, incorporating supply chain realism, workforce capability and adaptive management as integral components of long-term landform sustainability.

4 Seed and ameliorant supply constraints and the strategic necessity of concurrent rehabilitation

4.1 Indigenous seed and ameliorant availability as a limiting factor

One of the most significant constraints identified during implementation was not geotechnical but biological and logistical; specifically, the availability of suitable indigenous rehabilitation seed and ameliorants at the scale required for large-scale WRD rehabilitation (Figure 9).

Figure 9 Seeds and ameliorants sourced for the trials project

The rehabilitation design assumed establishment of vegetation using indigenous grass and shrub species aligned with the approved post-mining land use. In addition, successful vegetation establishment depended on the availability of suitable ameliorants required to improve growth medium fertility, structure and moisture retention capacity. However, during procurement it became evident that commercial volumes of indigenous seed and rehabilitation ameliorants required for large-scale implementation are not readily available within Botswana. Local suppliers are constrained in both species diversity and bulk production capacity.

Seed procurement therefore required sourcing from South Africa. However, even within a more mature agricultural and rehabilitation supply market, available volumes remain constrained, seasonal and dependent on supplier production capacity. Similarly, the procurement of suitable ameliorants and organic material at the required scale remains logistically challenging and subject to regional supply variability (Figure 9).

Large-scale procurement for rapid end of life rehabilitation would therefore not be feasible without long-term forward planning and progressive implementation approaches.

This finding fundamentally altered the strategic closure outlook.

4.2 Implications for end of life rehabilitation assumptions

Traditional closure planning models often assume that large-scale rehabilitation can be executed over a condensed time frame following the cessation of operations. This assumption presupposes:

- immediate access to bulk growth medium
- sufficient contractor and equipment availability
- access to large volumes of indigenous seed and ameliorants
- rapid vegetation establishment under favourable climatic conditions.

The implementation experience demonstrated that these assumptions are unrealistic within the Botswana context. Seed and ameliorant supply chains cannot support compressed rehabilitation schedules at the required scale. Attempting to procure full WRD rehabilitation volumes within a single procurement cycle would exceed supplier capacity and introduce unacceptable establishment risk.

Furthermore, vegetation establishment within semi-arid climates is strongly influenced by seasonal rainfall variability. A compressed rehabilitation schedule therefore increases exposure to establishment failure during unfavourable climatic periods.

The implementation phase also highlighted that procurement timelines for rehabilitation materials are often significantly longer than anticipated during conceptual planning phases. The sourcing, transport, blending and application of growth medium materials, compost, ameliorants and seed mixes required extensive coordination between suppliers, contractors and operational teams throughout implementation.

4.3 Concurrent rehabilitation as a strategic risk mitigation measure

The seed and ameliorant supply constraint therefore reinforces concurrent rehabilitation not simply as a best-practice preference but as a strategic operational and closure risk mitigation requirement.

Progressive rehabilitation during operations provides several advantages:

- Seed and ameliorant demand is distributed over multiple seasons, aligning with supplier capacity.
- Natural seed banking and self-propagation processes are initiated earlier.
- Rehabilitation performance can be monitored and refined incrementally.
- Closure liability reduces progressively rather than remaining static.
- Local workforce skills develop gradually through repeated implementation cycles.

By aligning operational dumping strategies with progressive reshaping and revegetation, the mine reduces both ecological and financial risk exposure.

Concurrent rehabilitation also provides opportunities to refine species mixes, growth medium recipes and stormwater management designs under actual climatic and operational conditions before large-scale closure implementation is required.

4.4 Integration of seed strategy into closure planning

The implementation phase highlighted the need to formally integrate seed and ameliorant procurement strategies into closure planning documentation. This includes:

- multi-year forward procurement agreements
- investigation of local seed harvesting and propagation initiatives
- potential establishment of onsite nursery or greenhouse facilities
- development of species resilience testing under local climatic conditions
- alignment of rehabilitation scheduling with seasonal rainfall patterns.

Closure planning must therefore extend beyond engineering geometry and erosion modelling to include biological supply chains, procurement planning and ecological establishment timelines.

The lessons from implementation indicate that sustainable closure in emerging mining jurisdictions requires integrated planning across engineering, ecology, procurement and operations rather than isolated technical optimisation.

5 Capacity gap and structured skills development

5.1 Rehabilitation as a specialised technical discipline

The transition from modelling and design to full-scale execution revealed that large-scale mine rehabilitation is significantly more technically demanding than conventional operational earthworks. While dozer operators and contractors are highly competent in bulk material movement, rehabilitation works require geometric precision and sequencing control beyond typical production activities.

Stormwater paddocks must be constructed to defined crest elevations and cross-fall tolerances. Inter-bench slopes must meet specified gradients to maintain run-off control and erosion performance. Growth medium thickness must be consistent to support uniform vegetation establishment. Ripping must be undertaken parallel to contours and at the required depth to prevent preferential flow paths. Minor deviations in these parameters can have disproportionate hydrological consequences.

The implementation phase demonstrated that achieving these tolerances consistently requires specialised training and a clear understanding of the closure intent behind each specification.

5.2 National implementation context

Large-scale rehabilitation of this nature has not historically been undertaken in Botswana or within the mining group. Although the regulatory framework is robust and closure planning documentation is comprehensive, practical field implementation experience within the country remains limited.

This capacity gap manifested in the following several ways during early implementation:

- variability in achieving the required WRD reshaping geometries under operational conditions
- inconsistent growth medium placement thickness and material distribution
- variability in the construction accuracy of crest berms, contour paddocks and stormwater control structures
- variability in ripping depth and ripping orientation parallel to contours
- challenges associated with the procurement, handling and application of ameliorants and indigenous seed mixes
- limited familiarity with indigenous species seeding protocols and vegetation establishment requirements
- limited understanding of erosion processes during early establishment phases
- maintenance response delays following erosion and siltation events.

None of these observations indicate lack of competency; rather, they reflect the absence of prior exposure to rehabilitation at this scale.

5.3 Development of a structured training framework

In response to the identified implementation challenges, a structured rehabilitation training and assurance program was developed to support mine personnel, supervisors and contractors involved in the rehabilitation trials implementation process.

The training program focused not only on implementation procedures but also on the technical rationale behind each rehabilitation component. This included:

- principles of mine closure and long-term liability reduction
- interpretation of landform geometry and stormwater management designs

- construction tolerances and quality control requirements
- growth medium preparation and ameliorant application methodologies
- ripping orientation and erosion control principles
- seeding methodologies and vegetation establishment requirements
- monitoring and maintenance procedures
- identification and management of early-stage erosion risks.

Training was supported through ongoing site-based assurance visits conducted during critical implementation phases. These visits provided practical guidance during construction activities, identification of implementation risks and corrective recommendations where deviations from design intent were identified.

The implementation phase demonstrated that practical field-based training and continuous technical support were critical to improving construction quality, reducing implementation variability and supporting long-term rehabilitation success.

5.4 Skills development as a closure risk mitigation tool

The rehabilitation trials demonstrated that workforce capability and implementation quality are directly linked to long-term closure performance. Skills development should therefore not be viewed solely as a social or corporate responsibility initiative but rather as a critical closure risk mitigation measure.

Improved operator understanding and construction quality directly influence:

- stormwater management performance
- erosion susceptibility
- vegetation establishment success
- monitoring effectiveness
- long-term landform stability.

The implementation phase further demonstrated that progressive rehabilitation provides opportunities for gradual workforce development through repeated implementation cycles and ongoing operational exposure.

Developing in-country rehabilitation expertise also strengthens long-term closure sustainability by reducing dependence on external specialists and improving the mine’s capacity to implement large-scale rehabilitation progressively throughout operations rather than during compressed end of life closure periods.

The rehabilitation trials therefore demonstrated that sustainable mine closure depends not only on technically optimised landform designs but equally on the development of practical implementation capability, technical understanding and long-term operational ownership of rehabilitation activities.

6 Conclusion

The progression from conceptual landform design to full-scale rehabilitation implementation at a large diamond operation in Botswana has provided critical insight into the realities of mine closure execution in emerging mining jurisdictions.

The 2021 work demonstrated that erosion modelling, material characterisation and refined dumping strategies can significantly reduce projected closure liability and improve long-term landform stability. However, the transition to implementation revealed that theoretical optimisation alone is insufficient to guarantee sustainable outcomes.

Field execution exposed practical constraints related to construction precision, early-stage erosion vulnerability, indigenous seed and ameliorant availability, and local workforce capacity. Among these, seed supply limitations proved particularly influential; fundamentally reinforcing the necessity of concurrent rehabilitation. Progressive rehabilitation during operations distributes biological demand, reduces risk exposure, enables adaptive refinement and supports incremental liability reduction.

The implementation phase further demonstrated that skills development and structured training are not peripheral activities but central components of closure risk mitigation. Construction accuracy, stormwater integrity, vegetation establishment success and long-term stability are directly linked to operator understanding and capability.

The lessons presented extend beyond a single operation. Sustainable mine closure in semi-arid and developing jurisdictions requires integration across engineering design, ecological planning, operational sequencing, supply chain realism and human capital development.

Ultimately, successful closure depends not only on designing stable landforms but on building the systems, skills and strategies required to implement them progressively and effectively.

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