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Rehabilitation of highly erodible smectite bearing kimberlitic tailings facilities in South Africa: a case study

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Abstract

This paper presents a case study of rehabilitation status quo of kimberlite tailings facilities dating back more than 100 years. Since there was no specific environmental legislation, the tailings materials were deposited by means of downhill tipping and later by open-end pipe distribution on the toe of a foothill and semi-contained in a makeshift trench and paddock system. Erosive forces have since decimated the highly erodible tailings surfaces and evidence of downstream impacts on receiving water bodies have emerged which necessitate urgent and sustainable rehabilitation interventions. The study site presents a realistic case for caution for the broader rehabilitation and closure risks for the mine's much larger tailings operations.

Literature studies revealed that the kimberlitic tailings present a cocktail of challenging properties for conventional rehabilitation methods – to the extent that it is practically uncontainable without serious civil interventions. The smectite clay mineral in the kimberlite rock present the tailings with unique secondary type pedo-physical and geochemical properties. Extreme Exchangeable Sodium Percentage (ESP) presents soil surface stability challenges through chemical dispersiveness, hard crust formation, lack of water infiltration, extreme erodibility and limiting soil moisture as well as potassium metabolism in plants and soil organisms. Furthermore, the tailings have extreme alkaline pH values (9.7–10.2) which present unsuitable conditions for vegetation establishment for various reasons whilst high Cation Exchange Capacity (CEC) values present substantial buffer capacity against pH, inhibiting soil amelioration potential. Considering the compounding effect of steep tailings geometry, harsh climate and intense rainfall events, direct revegetation cannot be regarded as a sustainable cover for closure.

The Revised and Modified Universal Soil Loss Equation (RUSLE/MUSLE) was used to evaluate various geometrical and cover combinations for the kimberlitic substrates, considering the existing contamination status, availability of cover materials (topsoil, rock and geofabrics) and space around the facilities. The modelling incorporated long-term erosion loss, as well as single event recurring erosion loss for 2-, 5-, 10-, 20-, 50- and 100-year rainfall data. The results showed that the only scenario to achieve less than 10-tonne/ha/annum erosion loss would be complete rock encapsulation. The only topsoil store-and-release cover system that would restrict high erosion rates would be for a geometry of 25 m and 14° and a minimum of 350 mm thick cover for the specific sandy cover material available in the region. However, considering the coarse nature of the cover soils available, cover failure can be expected from sub-surface chemical sealing that will interface with low shear strength of the cover on the topsoil/tailings interface. Tunnel erosion and slope failure will desiccate the cover during high intensity rain events leading to seepage and consistent gully and donga erosion irrespective of any geometric design, rendering complete (imported) rock encapsulation the only sustainable cover option. This case study revealed that smectite bearing kimberlite tailings closure require an urgent re-evaluation and an alternative view on design, costing and operation is required to meet closure commitments.

Keywords: *kimberlite, erosion, tailings, smectite clay, closure design, covers, rock cladding*

1 Introduction

Diamond mining dates to the late-1800s in South Africa and has created substantial wealth as a major contributor to the South African economy to this day. However, the vast amounts of deposited kimberlite tailings derived from milling processes remain largely unrehabilitated with closure only a vivid future objective (van Deventer et al. 2008). Designing tailings landscapes for closure has become integrally part of the tailings engineering thought process and design principles today. Tailings structures need to stand the test of time against natural erosive forces and water erosion is usually well accounted for in closure design (Hattingh et al. 2002). Closure practice in South Africa is still largely following international guidance and although legislation now requires that tailings storage facilities (TSFs) be capped in accordance with specified risk based criteria and waste classification categories (South Africa, 2008), ever-changing regulations and standards (South Africa, 1998a; South Africa, 1998b; South Africa, 2006) as well as ownership changes and changing cost scenarios result in decision delays (also considering no guarantees of a closure certificate).

Final rehabilitation considerations of TSFs have historically (prior to the 1990s) not formed part of formal legislative mine design requirements. Since all kimberlite TSFs in South Africa are uncapped from a closure perspective, environmental and geotechnical risk pose long-term spill and water pollution potential. The combination of erosive forces of wind and water will compromise the integrity of uncovered facilities threatening environmental sustainability for future generations around these mine communities. A permanent rehabilitation solution and a closure methodology are therefore urgently needed for sustainable closure of kimberlitic TSFs. From the literature review, it was evident that there is a substantial lack of information pertaining to the characteristics of kimberlite tailings and case studies of rehabilitation (van Deventer et al. 2008) and closure of these facilities are few and far between. This study will therefore contribute to a better understanding of the challenges towards sustainable closure of kimberlitic tailings.

The post-closure surface stability of TSFs depends both on the long-term rehabilitation effectiveness of the side slope and retaining the integrity of the beach catchment area (Small & Clark 1982). The design of a final cover should consider either a water shedding or water retaining system whereby calculated outcomes of the rainfall, as well as the soil physical, chemical, and biological properties of the cover materials are incorporated (Hattingh & van Deventer 2003). The store-and-release cover approach is nowadays considered as a preferred option as it allows for gradual release of rainwater thereby reducing seepage and associated potential toxic leachate from TSFs (Defferrard et al. 2016). A selected cover system should also consider how to counteract the upward migration of solutes into the vegetation rooting zone and how the vegetation cover can be optimised to evapo-transpirate excess moisture from the cover system. Furthermore, all these parameters should the incorporated into a design that will create a landscape that is in harmony with the long-term sustainability requirements of the system which must achieve physical surface stability, landscape functionality, and a productive land-use potential. Factors which play a major role in the final quality and characteristics of such a post-closure landscape are amongst others the physico-chemical effects of the tailings on the cover, the durability of any constructed cover against erosive processes (rock cladding, etc.), the geochemical and pedo-physical properties of the growth medium in case of vegetation cover, and hydraulic properties of the tailings and the selected cover system with special reference to surface stability (Hattingh et al. 2002; Weiersbye & Witkowski 1998).

The study objectives therefore aim to provide insights into how these sustainable rehabilitation and closure objectives can be achieved on kimberlitic tailings by evaluating principles from a case study of a kimberlite tailings landscape and surrounds that has been interacting for the past 100 years. The study objectives are:

- To describe the mineralogical, soil and tailings characteristics of kimberlite tailings materials.
- To evaluate the erodibility of kimberlitic tailings and its implications for rehabilitation scenarios.
- Consideration of the potential contamination status of the revegetated kimberlitic tailings material and the downstream surface water system below the kimberlite tailings landscape.

- To evaluate design interventions by means of the Universal Soil Loss Equation (USLE) informing permanent cover scenarios for sustainable closure.

The learnings from this study would aid rehabilitation and closure planning, costing and implementation methodologies of kimberlite tailings materials of similar characteristics.

2 Study background

2.1 Characteristics of kimberlite tailings: a literature review

Kimberlite is one of only very few rocks with a prominent smectite clay mineralogy component. This mineral presents tailings with unique secondary type of pedo-physical and geochemical properties with extreme exchangeable sodium percentage (ESP) (24–65%), which may explain the associated soil surface stability challenges. Kimberlite presents abundant Na cations on the exchange complex of the colloidal fraction in a weathered state and therefore the ESP value in relation to the Cation Exchange Capacity (CEC) is high (Levy & van der Watt 1988; Smith 1990). Additional Na is added to the tailings stream to disperse ore particles as part of the flocculation process in the mine's process plant and adding the fine milling of kimberlite, the weathering process is accelerated (high Na and excessive ESP), and the inherent chemical dispersiveness results in extreme erodibility of the tailings (Dixon 1989; Stern 1990; van Deventer 2000). Mg cations are also found to be very high which exacerbates the erodibility of kimberlite tailings, as the combination of soil Na and Mg disperses soil colloids (Young & Mutchler 1977; Shainberg & Singer 1988). Figure 1 shows typical erodibility of kimberlite tailings (Figure 1 left) and the swelling cracks of the clay minerals (Figure 1 right).

Figure 1 Typical Kimberlitic tailings substrate. Note the extreme erosion gullies originating from extreme dispersive properties of the smectite bearing material (left) and the lack of root development (right)

Kimberlite tailings have high alkaline pH values (pH H_2O) ranging between 9.7 and 10.2, which are not suitable for sustainable vegetation persistence due to unavailable macro and micro elements. Although ameliorative techniques exist to counteract high pH conditions (gypsum application to counteract high ESP), direct revegetation trials reported by van Deventer et al. (2008) revealed diminishing vegetation cover since the high CEC values of the kimberlite tailings (>10 $cmol_+ kg^{-1}$) presents substantial buffering capacity against pH change, and the gypsum application increases the electrical conductivity above acceptable norms. The smectite mineral also inhibits soil moisture availability resulting in water stress conditions; the presence of high Na and Mg in the smectite mineral counteracts the essential functions of potassium in the metabolism of plant and soil organisms (Levy & van der Watt 1988; Smith 1990; van Deventer & Hattingh 2003). These material properties leave any direct revegetation intervention flawed, which is a major concern since vegetation covers are committed to for the mine's final closure.

2.2 Kimberlite characteristics and cover design

Most rehabilitation designs consider the use of quality soils and rock materials available around mines and consider the variation of slope angles, cover options and amelioration techniques. This design philosophy can be extrapolated to kimberlite tailings slopes with a reasonable factor of accuracy. However, in the case of legacy kimberlite TSFs, hindsight design and the knowledge from improved modelling and technology can be applied to sites where rehabilitation considerations were historically absent.

2.2.1 Kimberlite tailings materials as cover system (Smit 2008; van Deventer et al. 2008)

From the literature it is evident that kimberlite material properties will present accelerated soil loss with increase in slope steepness and slope length, as well as severe chemical erosion factors (high ESP), which can be expected for periods of a thousand years and more. The cumulative effect of slope angle, high ESP, clay mineralogy and follow-up rain events on the hydraulic properties of the kimberlite tailings will have the following negative pedo-physical effects:

- No infiltration can take place in any soil-like material with an ESP > 20% (Kimberlite range from 24% to 65%). At an ESP of 65% it is not possible for water to infiltrate into the medium except along desiccation cracks, joints, or large pedo-physical structures, i.e. rock fragments or roots.
- The theoretical infiltration capacity of the tailings material is -121 mm/h after wetting for 15 or more events and no infiltration can take place. Total surface run-off increases within six rain events and from 25% to 55% of event run-off can be expected. As soon as surface run-off dominates, the soil particles are dislocated (total cohesion is eliminated) and sediment transport (erosion) ensues.
- Chemical sealing will then present limited soil moisture field capacity and the fine tailings have larger reaction surface-to-volume ratios with salts rapidly mobilised once exposed to water and oxygen.
- It is highly unlikely that direct revegetation of kimberlite tailings will develop into sustainable vegetation due to the high Sodium Adsorption Ratio (SAR), high ESP, alkaline pH and associated unavailability of nutrients. Hard crust formation, low water infiltration capacity, high surface run-off and extreme erodibility will also impede vegetation survival.

2.2.2 Topsoil on kimberlite as cover system (Smith 2008; van Deventer et al. 2008)

The affordable alternative to direct revegetation would be to cover the tailings materials with available soil material. Soils with specific traits are required for topsoil to be hydraulically and biologically suitable. Availability of soil volumes in proximity and with suitable capping characteristics must first be considered and the following tailings-soil interaction will influence the success of a functional cover on kimberlitic tailings:

- The overall matric potential and water retention for topsoil in proximity to the mine, in this instance, is lower than that for the tailings due to the texture and porosity. Therefore, soil (sandy structureless sandy soil in this case) as a cover might not be able to retain all the water after a rain event as it will rapidly infiltrate onto the tailings compounding long-term cover instability (pending cover thickness).
- The extreme dispersive nature of the tailings (which results in a chemical surface seal on the tailings) will cause an interface with low shear strength and subsequently tunnel erosion on the topsoil/tailings interface and will be a common phenomenon after rain events. Tunnel erosion will follow, which normally develops into gully erosion and eventually into donga erosion. As soon as the interface between the two media is exposed, severe donga erosion will develop, eroding all topsoil.
- Taking the porosity, permeability, matric potential of topsoil into account, it is evident from literature that total water holding capacity will not be enough to sustain a vigorous and healthy plant life when sandy soils are placed as a cover. Such plant systems will continuously be inhibited

to develop from a pioneer to a climax system over the short term. Hence a sparse plant population with the minimum cover ability and subsequent bare soil surfaces will be extremely prone to continual soil erosion.

- A shallow root system can be expected because of soil water deficiency and sodic subsoil. Further limitations to root zone development are presented by chemical sealing and physical crusting.
- Combining topsoil and rock mixture is regarded as less than ideal from a cost-effectiveness perspective since fines from the topsoil will illuviate into the large pores of coarse waste rock over time, especially if waste rock is placed below the topsoil. This will decrease the total water holding capacity of the active root zone even more, hence lower or underdeveloped above ground biomass and poor vegetation quality. The advantage of illuviation of fines into the waste rock is the increase in physical surface stability and strength and potential improvement of infiltration and less run-off.

2.2.3 Rock armour on kimberlite as rehabilitation cover system (van Deventer et al. 2002; Hattingh & van Deventer 2003)

Although expensive as a hindsight solution, complete encapsulation of the topsoil with waste rock may be regarded as a sustainable cover option depending on the volume required and operational feasibility:

- Rock volumes within the area and with the required engineering characteristics for capping need to be confirmed before this can be regarded as a viable option.
- Inert waste rock and overburden with specific traits regarding coarse-to-fine ratios and compactability are required for a suitable cover and the rock material should not be acid-bearing.
- Expensive civil works and storm-water management systems and infrastructure would be required for this cover to be implemented. Complete clean-up of all spill material around and below the facility would be required before this solution can be deployed as all rainwater from this water shedding system will report to the downstream area.

2.2.4 Geotechnical considerations for a kimberlite cover system (Hattingh et al. 2002)

The geotechnical slope stability and risk of future slope failure is largely dependent on the properties of the clay mineralogy and erodibility of the selected cover system.

- The materials selected and proposed slope angle of the final designed cover could have a major influence on future landscape’s integrity as slippage of topsoil on smectite dominated materials are to be expected. If the erosion from the side slopes is not eliminated, the TSF will remain a source of tailings pollution for many years to come and eroded slopes may create geotechnical weaknesses.
- Water infiltration through the cover into the tailings is not ideal from a geotechnical perspective.
- Sub-surface failures due to moisture build-up on the cover/tailings interface may result in geotechnical slope failure considering the sealing properties of the tailings and the unconsolidated nature of topsoil usually available for cover systems.
- The eroded material will end up in the landscape around and below the TSF and eventually ‘sterilise’ the remainder of the downstream soil whilst silting up the receiving water courses over time, finding its way to the lower order drainage rivers and affecting livelihoods and the ecosystem health.

2.3 Mine background

The mine is in operation for more than 120 years and was owned and operated by numerous corporations, under various political dispensations. It has been subjected to various legal and governance frameworks. The footprint of the mining area is vast, and many legacy sites are to be expected. The mine still has more than

25 years life-of mine able to plan responsible mine closure, albeit several environmental issues have arisen that were not directly a result of the existing owner's operation. Legacy tailings deposits of 100 ha produced and deposited more than 100 years ago (almost a spill area) must be dealt with. The largely natural rehabilitation process is now a work in progress of 70 years. The tailings materials were deposited by means of downhill tipping and later by open-end pipe distribution on the toe of a foothill, initially without containment and later in a trench and paddock system. Severe thunderstorms caused substantial erosive damage to the tailings deposits and four make-shift tailings containment structures were constructed. The area is now contoured and reinforced with imported topsoil berms to contain the spread of tailings to the nearby river, but the tailings layers covering the area largely cover the catchment below the area of concern. The harsh winter and summer temperatures of the semi-arid ecosystem present challenging survival conditions for natural colonisation and dry-land vegetation establishment. The geometry of the tailings facilities and the receding vegetation cover now presents renewed pressure on the mine to intervene and, therefore, permanent rehabilitation solutions are sought after urgently.

This study cautions the broader rehabilitation implications and closure costing of all TSFs of the mine (what to be expected from the natural erosive processes that desiccated the tailings facilities investigated) and best-cost clean-up and improved rehabilitation recommendations drafted from this study may inform the planning and mining operation for the larger affected area. The effects of the tailings erosion into the downstream water habitat have advanced the urgency of rehabilitation way-forward for the mine.

2.4 Study area description

2.4.1 Locality and topography and hydrology

The study area is located 50 km east of Pretoria, in the Northern-Gauteng Region of South Africa. The mine is situated on the eastern foothills of the Magaliesberg range and located at an altitude of ~1,440 m AMSL. The surrounding area is typically rolling hills with undulations of ~100 m between local hill rises and valleys. In the immediate vicinity of the mine, the topography is relatively gentle, sloping down to large tailings facility areas and to the southeast of the tailings areas, relief rises sharply to a height of 1,484 m AMSL. The natural topography has been significantly altered by open cast mining and rock dumps whilst tailings cover an area of 320 ha. This study evaluates four impoundments (Old Tailings) covering approximately 100 ha (Figure 2).

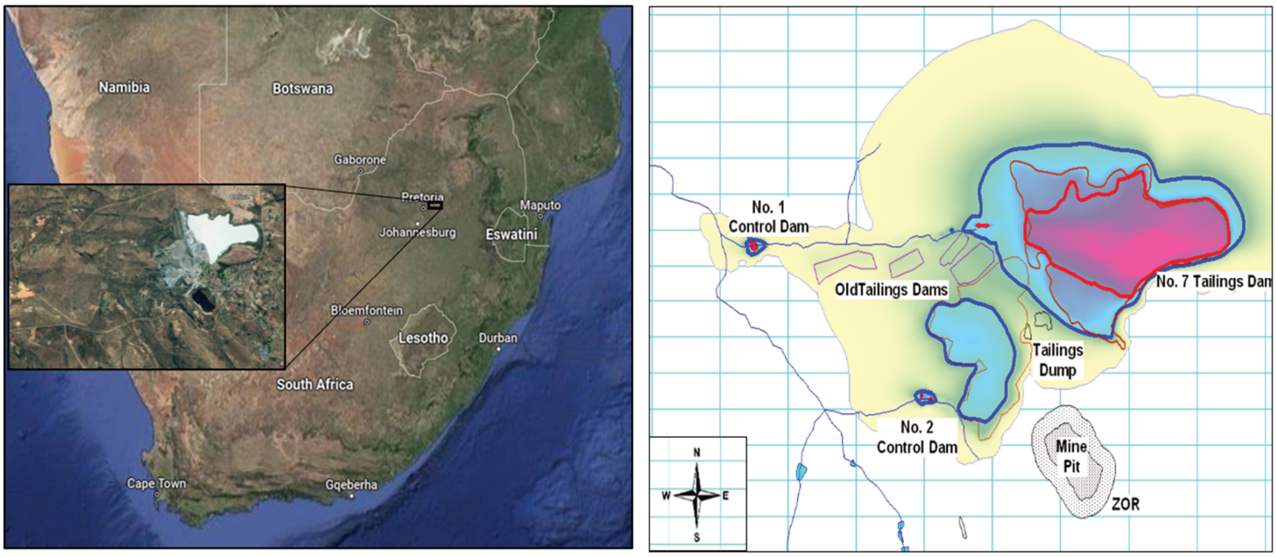

Figure 2 Study area location and mine layout. Note the four 'Old Tailings Dams' as the study focus

From a hydrological perspective, the mine is in the upper region of the upper Pienaars River catchment. The effect of the four TSFs on the water quality of the receiving water bodies is of concern and include a seasonal stream, a wetland system, and a return water control dam). Van der Merwe (2007) reported independently that the four tailings containment structures directly affect the surface water quality of the downstream water bodies, and the suspended solids, fluoride, sodium and sulphates were of concern. The elemental minimum and maximum range measured in the water throughout a five-year study were:

Suspended solids (10–300 mg/l); chlorides (19–84 mg/l); fluoride (2–8.5 mg/l); sulphate (71–484 mg/l); sodium (46–381 mg/l); manganese (0.1–0.95 mg/l); EC (74–155 mS/m); and pH (7.9–8.5).

The report found that the highly turbid waters in the water system have a significant impact on the aquatic ecological integrity of the systems and that the in-stream riparian ecology has been compromised with limited macro-vertebrate and plant diversity. The aquatic habitat is considered unsuitable for supporting a sustainable and diverse aquatic macro-invertebrate community and the basic ecosystem function is severely impaired by the choking effect of a lack of flow volumes and substrate variation stemming from frequent deposition of fine silt from the kimberlite tailings dams. These annual spills alter the habitat from a hard substrate to soft, unstable fine sedimentary layer resulting in deep sediment deposits. The proliferation of *Phragmites australis* restricts water flow throughout the three systems resulting in an anticipated regression in water quality over time (van der Merwe 2007).

2.4.2 Climate

The mine experiences a typical Highveld climate. January is generally the warmest month of the year with a mean temperature of 22.1°C and June is generally the coldest month of the year with a mean temperature of 11.3°C. Mean annual rainfall amounts to ~686 mm.a^{-1}. The 24-hour maximum on record is 187 mm received in January 1978. The average annual rain days are 85.9 days, with most of the rainfall in the summer months between October and March, winter months are dry and frosty without snow. However, thunderstorm events are frequent in summer. The highest evaporation levels generally occur between September and January 180 mm per month, and the lowest evaporation levels occur in March to August, averaging 120 mm per month. From the wind data the mine experiences 36.1% of calm conditions; predominant winds are from east–north-easterly direction and average wind speed between 0.5 and 2.5 km.h^{-1} (wind speeds rarely above 3.5 km h^{-1}).

2.4.3 Geology and soils

The mine occurs within the main zone of the Bushveld Complex comprising large masses of Waterberg Conglomerate with a diamond bearing Kimberlite volcanic pipe as the ore source of the mine. The country rock often embedded in the kimberlites are felsite; gabbro; norite; metasediment and lower norite. The different types of kimberlite found in the pipe (and predominant tailings composition) include: brown kimberlite; grey kimberlite; hypabyssal kimberlite; black kimberlite; and weak kimberlite. The grey kimberlite forms most of the volcanic pipe and is relatively stable. The Brown kimberlite decomposes when exposed to moisture and is extremely susceptible to erosion as it has high clay content which swells and breaks down the rock structure when wetted. The weak kimberlite is a poor-quality kimberlite on the boundary between brown and grey kimberlites. The hypabyssal (Black and Piebald) kimberlite is very hard and has no, or low, susceptibility to weathering (van Deventer et al. 2008).

From a soil perspective, the mining area is located within the Highveld Plinthic Catena (Ba6a land type, McVicar 1986) and the soils comprises primarily of red, brown and yellow apedal soil forms - generally fit for cover purposes. The soil pattern identified beneath and adjacent to the study area around the four TSFs are sandy and structureless with characteristic red B-horizon and known to be deep and well-drained. These soils are extensively damaged and modified by kimberlite sediment (light grey sediment) (van Deventer 1997) due to seepage and erosion of tailings sediment (Smith 2008). The soils are thus characterised by orthic A-horizon overlaying a human-made (anthropogenic) B-horizon. Only 5% of the apedal soils are uncontaminated and within economical proximity as a potential cover option.

2.4.4 Habitat and vegetation type

Considering vegetation selection for rehabilitation purposes, the surrounding vegetation assemblages can provide information on potential species selection as well as the anticipated interaction of the restored system and the native ecology. The mine occurs on the transition zone of the savannah and grassland biome. (Low and Rebelo 1996). The savannah biome is characterised by a grassy ground layer and a distinct upper layer of woody plants. The grassland biome is found mainly on the high central plateau of South Africa and is characterised by an absence of trees. The amount of cover for both the biomes depends on rainfall, grazing, and fire (Acocks 1988). Grasses that occur in both the biomes include *Digitaria eriantha*, *Eragrostis lehmanniana*, *Heteropogon contortus*, *Melinis repens*, *Cynodon dactylon*, *Eragrostis chloromelas*, and *Imperata cylindrica*. Trees found along the stream below the TSFs include *Acacia karroo, Sericea leptodictya, Sericiea lancea, Sericiea pyroides*, *Ziziphus mucronata* and *Jacaranda mimosifolia.* Areas disturbed by mining activities and vast tailings surfaces are covered by pioneer species where clayey soils dominate. Of 53 plant species found in this area, 41 are classified as exotic plants with the dominant tree species being *Eucalyptus grandis* (exotic) and *Acacia karoo* (pioneer). The most common grass species *Hyparrhenia hirta* dominate most of the disturbed land on the mine. On tailings facilities, *Phragmites australis* are mostly occurring with other exotic invader plant species such as *Pennisetum setaceum, Schinus molle and Acacia melanoxylon*.

3 Study and design methodology

3.1 Field evaluation of the TSF area

Field recognisance was carried out to determine the scale and extent of the tailings spread (spill) across the landscape. The field evaluation informed the sampling locations along a downhill transect that would provide the information to achieve the study objectives. Soil (tailings) samples were collected by means of a soil auger at 250 mm depth and nine representative composite samples, as well as a sediment sample from the return water dam were sent for analysis. The soil physical and chemical properties that would inform the soil erosion models, as well as soil toxicity, were analysed for at an AGRILASA (SANS) accredited laboratory.

The soil physical analysis was conducted by means of the pipette technique and particle sizes were determined as a primary requirement for the modelled parameters in the prediction of the erosive properties of the materials. Soil chemical analysis of a saturated water paste extract was submitted for inductive plasma mass spectrometry (ICPMS) to determine the immediate availability of water-soluble macro- and micro-nutrients and to reveal the potential soil chemical properties that may explain the erodibility of the tailings substrate.

From the literature it was evident that kimberlitic materials may present swelling clays known to inhibit water infiltration and associated extreme run-off through presented by its sealing properties. Since moisture infiltration and sub-surface flow is inhibited in both lateral and horizontal planes in smectite bearing substrates, high erodibility is expected from the weathered form of kimberlite and it is therefore of design importance to pre-characterise the clay mineral content. Mineralogical analysis was carried out by means of X-Ray diffraction to understand the presence and abundance of clay minerals.

3.2 Erosion assessment and cover design criteria

The primary function of a rehabilitation solution for a TSF is to ensure that the surface area is permanently stabilised against the erosive forces of wind and water over the long term. Secondly, the chosen rehabilitation measures should eliminate the possibility of any pollution from the site, whether it is land contamination, air pollution or surface- and groundwater pollution. Therefore, the final geometry and cover selected to protect the facility should be custom-designed to resist the natural erosive forces. Calculating the long-term average soil loss per unit area, or A_{sy}-factor, the relative erosion risk from any surface area can be better understood and inform erosion risk and the effect of management interventions. The Revised Universal Soil Loss Equation (RUSLE) is used by specialists to assess the magnitude of rill erosion, to pinpoint where erosion is serious, and to guide development of plans to control soil erosion (USDA-ARS National Sedimentation Laboratory).

The equation is applicable wherever factor values are available to determine long-term annual soil loss and combines interrelated physical and management parameters such as soil type, rainfall pattern, and topography that influence the rate of erosion (Renard et al. 1991). These parameters are represented through RUSLE's five factors whose site-specific values can be expressed mathematically as:

$$A_{sy} = R\ K\ LS\ C\ P \tag{1}$$

where:

A_{sy} = long-term average soil loss per unit area ($\text{tonne}\cdot\text{ha}^{-1}\cdot\text{annum}^{-1}$).

R = index of annual rainfall erosivity ($\text{MJ}\cdot\text{mm}\cdot\text{ha}^{-1}\cdot\text{h}^{-1}\cdot\text{annum}^{-1}$).

K = soil erodibility factor ($\text{tonne}\cdot\text{hour}\cdot\text{MJ}^{-1}\cdot\text{mm}^{-1}$).

LS = slope length and gradient factor (dimensionless).

C = cover and management factor (dimensionless).

P = support practice factor (dimensionless).

However, the mass portion of eroded soil leaving the site – or the sediment yield – accumulating in paddocks and return water facilities, is as important for erosion estimation. A separate term, the delivery ratio, was added by Williams (1975) by replacing the rainfall erosivity factor with a stormflow factor which allows for direct prediction of sediment yield. This modification, termed the Modified Universal Soil Loss Equation or MUSLE, is applicable for individual storm events and the Q and q_p factors must be determined. The MUSLE is expressed as:

$$Y_{sd} = \alpha(Q\ q_p)^{\beta} K\cdot LS\cdot C\cdot P \tag{2}$$

where:

Y_{sd} = sediment yield from an individual event (tonne).

Q = stormflow volume for the event (m^3).

q_p = peak discharge for the event ($m^3\cdot s^{-1}$).

K = soil erodibility factor ($\text{tonne}\cdot\text{hour}\cdot\text{N}^{-1}\cdot\text{ha}^{-1}$).

α, β = specific coefficients ($\alpha = 8.934$ and $\beta = 0.56$).

The factors Q, q_p, are determined from the MUSLE, estimating stormflow depths and volumes while K, LS, C and P are determined from RUSLE empirical equations. The techniques and equations are used to derive values for the different erosion factors as outlined in this paper.

The aim of various rehabilitation scenarios is to determine which rehabilitation solution will result in the lowest exposure to the effects of erosion. The scenarios include varying slope lengths, slope angles and covers, including topsoil, vegetation, rock cladding and rock armouring. These estimations give a relative indication of soil loss or sediment yield for different treatments and should not be seen as actual values. Much more studies and verification work are necessary on mine spoil to assess the suitability of the algorithms of these models for mine spoil, however, this work provides a basis for decision-support for the mine. The evaluated rehabilitation scenarios for the TSFs are presented in Table 1.

Table 1 Cover scenarios for the rehabilitation and closure of the four kimberlite TSFs

	Material	Slope length (m)	Slope (degrees)	Cover
Scenario 1	In situ material	10	33	Vegetation (4%)
Scenario 2	Topsoil (350 mm)	10	33	Vegetation (4–6%)
Scenario 3	Rock (350 mm)	10	33	Rock – Partially vegetated
Scenario 4	In situ material	25	18	Vegetation (4%)
Scenario 5	Topsoil (350 mm)	25	18	Vegetation (5–8%)
Scenario 6	30% soil mix	25	18	Vegetation (4–6%)
Scenario 7	In situ material	25	14	Vegetation (4%)
Scenario 8	Topsoil (350 mm)	25	14	Vegetation (6–8%)
Scenario 9	30% soil mix	25	14	Vegetation (4–6%)
Scenario 10	Rock amour (350 mm)	10	33	Rock amour only

4 Results and discussion

4.1 Factors influencing soil erosion (Renard et al. 1991)

4.1.1 Rainfall erosivity factor (R-Factor)

Erosivity is the ability of rainfall to cause soil detachment through drop impact and through runoff entrainment resulting in sediment transport at micro- and macro scales. Rainfall erosivity indices, such as the widely used EI30 index, were developed to correlate rainfall with potential soil loss. EI30 is a product of the total kinetic energy (E) of the storm multiplied by its maximum 30-minute intensity (I30). Some areas in South Africa are occasionally characterised by high intensity rainstorms. Short-lived intense storms, where the infiltration capacity of the soil is exceeded, are usually responsible for the bulk of seasonal soil loss. The mine is situated in an area where EI30 range between a low value of 200 and a high value of 370.

The distribution of the rainfall data used for the modelling is summarised in Table 2 and the variation of rainfall around the average annual rainfall over this period is shown in Figure 3. The information is crucial to understand the variability of on-site conditions that must be considered for sustainable rehabilitation design. The lowest recorded annual rainfall is 432.7 mm and the highest 1,215 mm (Table 2). The information presented in Figure 3 clearly demonstrate the variability in annual rainfall that must be considered in the calculation of the Energy and Intensity values.

Table 2 90-year rainfall summary for the mine (ARC Weather Station)

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
Avg.	70.1	107.7	117.8	122.3	92.8	85.2	43.9	20.5	6.5	6.0	7.8	18.2	700.7
Std dev.	46.7	62.5	48.5	71.6	55.2	55.8	35.4	26.3	13.9	15.6	15.7	20.6	161.7
Max.	215.5	339.0	230.8	447.0	295.0	287.1	153.8	135.9	73.5	89.2	82.4	90.0	1215.0
Min.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	432.7

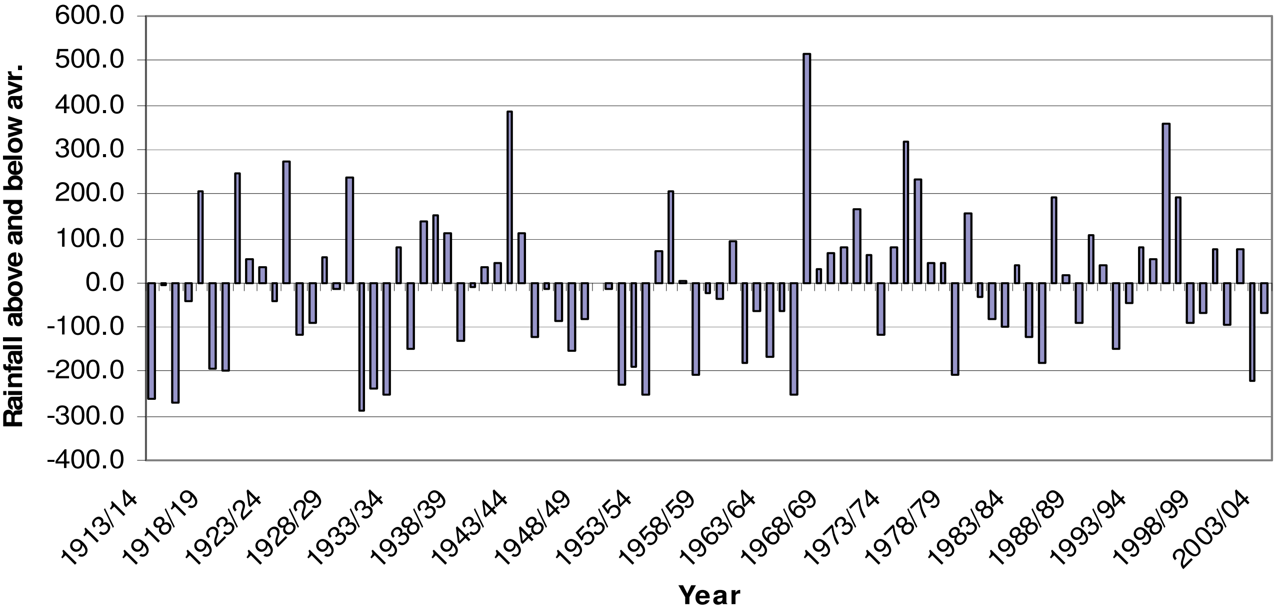

Figure 3 Variation of rainfall around the average rainfall at the mine (ARC Weather Station)

The rainfall erosivity for each year was calculated from the annual rainfall using the following equation:

$$R = 0.41*P - 38.51 \text{ (map area I)} \tag{3}$$

Most of the previous rainfall erosivity work done in South Africa made use of the R and K values of the USLE rather than the RUSLE as the latter can overstate erosivity by a factor of 17. Therefore, the P value in the equation (annual rainfall) was calculated as 700.7 mm and the long-term R-factor value for the site is 249.

4.1.2 *Runoff and peak discharge factor (Q-Factor)*

The amount of runoff, Q, resulting from a storm rainfall, P, on a catchment with catchment characteristics, c and S, can be estimated with the Soil Conservation Service (SCS) runoff equation (McPhee et al. 1983) expressed as:

$$Q = (P-cS)^2/[P+(1-c)S] \tag{4}$$

S is the maximum retention of the soil (mm), or moisture deficit, and *c* is the coefficient of initial abstraction. The potential maximum retention of the soil, *S*, is related to the soil type and cover conditions and the moisture status of the catchment. The practical upper and lower limits of S are approached at the permanent wilting point and porosity of the soil in the catchment. To keep this catchment characteristic inside workable limits, S has been transformed to a catchment response index to rainfall, called the runoff Curve Number, CN. This transformation is expressed (for S in mm) as:

$$CN = 25\,400/(S+254) \tag{5}$$

Peak discharge is estimated using the unit hydrograph of the SCS for a single triangular hydrograph (37.5% of the total runoff volume under the rising limb) and the equation for peak discharge, q_p, is expressed:

$$q_p = 0.2083 \cdot A \cdot Q/(D/2 + L) \tag{6}$$

where:

q_p = peak discharge ($m^3 \cdot s^{-1}$).

Q = runoff depth (mm).

A = catchment area (km^2).

L = catchment lag time (h).

D = effective storm duration.

For more realistic runoff hydrographs, incremental single unit hydrographs in specified time steps are superimposed to obtain a composite hydrograph. The peak discharge equation for an increment of runoff is

$$\Delta q_p = 0.2083A.\Delta Q/(\Delta D/2 + L)\ (m^3 \cdot s^{-1}) \quad (7)$$

where:

Δq_p = peak discharge of the hydrograph.

ΔQ = increment of runoff.

ΔD = incremental duration of effective rainfall (h).

Fifteen incremental hydrographs were used and the time to peak was chosen to be:

$$Tp = 6.\Delta D = \Delta D/2 + L \text{ which means that } \Delta D = L/5.5 \quad (8)$$

The amount of runoff and the peak discharge was calculated for maximum one day rainfall events with a recurrence interval of 2, 5, 10, 20, 50 and 100 years. The maximum one-day rainfall events for the mine (Weather Bureau Station number 514010) are summarised in Table 3:

Table 3 Maximum one-day rainfall events for the mine

Recurrence intervals (years)	2	5	10	20	50	100
Rainfall (mm)	60	82	99	118	145	168

The stormflow volume and peak discharge for these rain events for topsoil, topsoil mixed with in situ material and for the in-situ material for the different slope lengths are summarised in Table 7.

4.1.3 Soil erodibility factor (K-Factor)

Soil erodibility (K) accounts for the resistance of soil to the impacting forces of rainfall and runoff, and through its influence on runoff initiation and the amount of runoff. Therefore, soil erodibility is a measure of the susceptibility of a given soil to particle detachment and transport. The physical as well as chemical soil properties and their interactions that affect K-values are many and varied. However, K depends primarily on the structural stability of the soil and on its ability to absorb rainfall (i.e. its infiltration capacity). Several studies demonstrate that dispersibility is a fundamental soil property to be considered in erodibility analysis. Dispersion processes supply fine particles to overland flow for transportation, as well as shifting dispersed particles into pores, decreasing infiltration and accelerating runoff. Stoniness may also be significant, though its effect varies according to soil physical variability. Stones may protect the soil from rain-splash, but once runoff is initiated, the stones may cause turbulence and thereby accelerate rilling. Soil depth is also important since deep soils typically have a higher water holding capacity, and thus can absorb larger rainfall amounts before overland flow is generated. The erodibility (K) was calculated, for the rock cover (uniform size) and mixed rock cover (well graded material), from the geometric mean particle size, Dg, using the following relationships:

$$K = 10\{0.0034 + 0.0405\exp[-((\log D_g + 1.659)/0.701)^2]\} \quad (9)$$

where:

$$D_g(mm) = \exp[0.01\Sigma(f_i.\ln(m_i))] \quad (10)$$

where:

$f_{i,}$ = primary particle size fraction in per cent.

m_i = arithmetic mean of the particle size limits of that size.

Furnas (1931) found that the porosity of rock cover systems depends on the ratio of the particle sizes and their relative proportions and therefore different packings must be incorporated into covers if only uniform spheres are available or geofabrics must be considered. Minimum porosity of higher-order systems can be obtained by adding finer and finer particles into the voids between the larger particles, while maintaining the latter's original packing.

The final porosity of the available rock cover was calculated as 0.09 or 9% and the size ratio of the example mixture is 0.02/75 = 0.00027. The proportions of each by volume, are 1 m^3 75 mm rock + 0.45 m^3 coarse sand and 0.18 m^3 silt, or approximately 11: 5: 2. Therefore, the K-factor for this specific mixture of materials available is 0.0344, which is only 1% higher than that of the uniform rock material. A geofabric layer would therefore not be required as the available rock mixture would provide adequate erosion protection.

The erodibility of the tailings (K-factor), can be calculated from the following relationship:

$$K = 1.317(-0.204 + 0.385X_1 - 0.013\,X_2 + 0.247\rho + 0.003\,SS_{\%} - 0.005\,X_3) \tag{11}$$

where:

X_1 = aggregation index, being the ratio of the mass of the 2–9 mm aggregates to all the rest.

X_2 = per cent montmorillonite in the soil.

X_3 = dispersion ratio, typically between 8 and 20.

$SS_{\%}$ = per cent silt plus very fine sand (0.002–0.1 mm size fraction).

The erodibility factors for the tailings, topsoil and soil mix were calculated from soil physical and soil chemical data presented in Tables 4 and 5 respectively.

Table 4 Soil physical results for the study samples along a downhill transect across the tailings landscape

	C-sand %	M-sand %	F-sand %	VF-sand %	C-silt %	F-silt %	Clay %	Texture %
Sample								
1	1.13	1.02	2.46	2.46	8.39	38.08	45.09	SiCl
2	0.84	5.33	20.69	15.99	14.32	16.51	24.19	Lm
3	0.32	0.11	0.11	0.43	1.13	20.01	75.84	Cl
4	4.52	23.12	30.94	11.31	6.83	7.76	13.16	SaLm
5	2.17	13.25	27.95	12.32	12.16	12.42	18.63	SaLm
6	4.29	18.22	30.65	11.15	7.98	11.58	14.26	SaLm
7	1.46	2.81	5.2	3.54	11.55	42.4	30.07	SiClLm
8	3.87	12.87	36.19	14.44	7.17	8.84	14.85	SaLm
9	***4.79***	***18.75***	***40***	***13.85***	***7.08***	***5.42***	***7.92***	***LmSa***
10	2.35	19.86	37.46	9.62	4.15	6.81	17.45	SaLm

The data for soil sample 9 (red sandy soil) were evaluated for the cover and erodibility (K) of these soils was calculated as 0.25 (medium erodibility). A weighted average value of K = 0.36 was used where the in situ material was mixed with 30% topsoil. Sample 10 represents the material properties for the sample that was washed into the downstream waterbodies (no modelling required).

Table 5 Soil chemical results of the tailings considering the required parameters for the erodibility study

	Ca		Mg		Na		SAR	EC	Sat
Sample	mg/kg^{-1}	cmol (+)/kg	mg/kg^{-1}	cmol (+)/kg	mg/kg^{-1}	cmol (+)/kg		mS/m^{-1}	%
1	83.6	0.417	31.76	0.261	8.41	0.037	0.212	82	88.92
2	48.36	0.241	17.73	0.146	254.5	1.107	9.9	246	65.32
3	23.43	0.117	17.33	0.143	287.53	1.251	10.328	165	113.94
4	20.26	0.101	7.24	0.06	2.61	0.011	0.178	40	51.4
5	169.72	0.847	45.16	0.371	6.67	0.029	0.129	151	84.09
6	51.53	0.257	15.49	0.127	3.73	0.016	0.14	68	71.14
7	85.64	0.427	31.7	0.261	4.4	0.019	0.104	80	99.3
8	9.38	0.047	8.14	0.067	1.7	0.007	0.122	32	65.3
9	15.42	0.077	8.92	0.073	1.38	0.006	0.09	37	59.13
10	70.43	0.351	81.53	0.671	286.7	1.247	7.391	356	56.04

Figure 4 presents the results from the mineral X-ray diffraction, and it is evident that all the composite samples, except for samples 8 and 9, contained more than 30% smectite on average, outlining the kimberlite spread across the catena transect sampled. Samples 2 and 3 indicate the characteristics of the pure tailings samples and, considering the occurrence of smectite bearing soils across the study site, erodibility will remain a constant threat for the downstream area. From the soil chemical results presented in Table 5 it is evident that the tailings samples contained elevated levels of Na, and the EC and SAR for these samples will present high erodibility as well as challenging survival conditions for vegetation (Foy et al. 1978; US Department of Energy 1997).

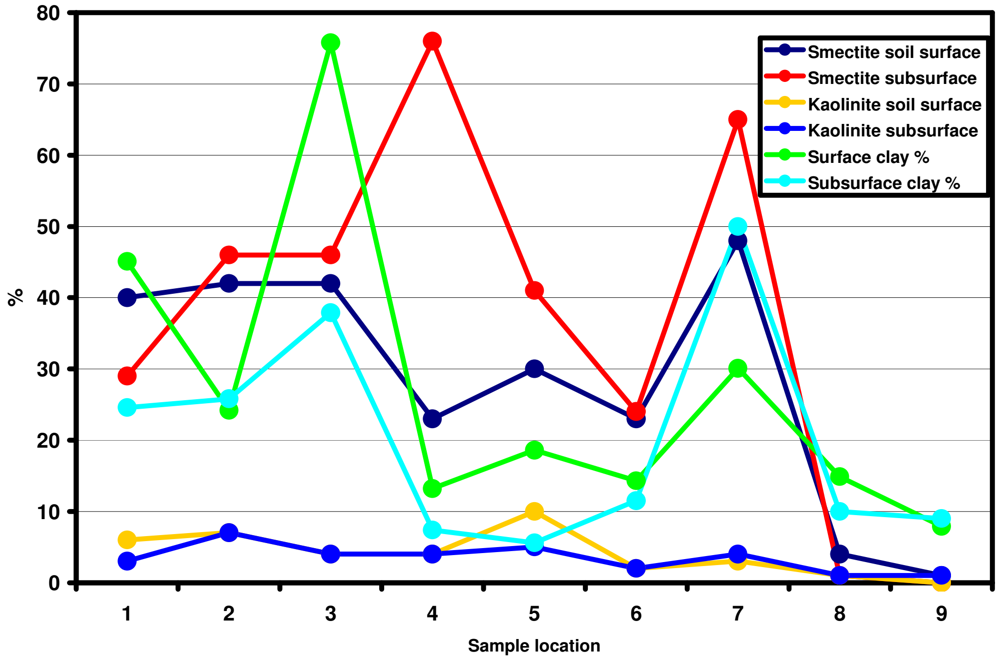

Figure 4 Clay percentage and clay mineralogy of the nine composite tailings samples

The risk of potential elemental toxicity exposure from the tailings to habitat was also considered. From the data presented in Table 6 it is evident that there is no soil elemental toxicity of concern and the high pH of the tailings material (9.7–10.2) will also limit elemental mobility for plant uptake (Foy et al. 1978; US Department of Energy 1997). It is evident from the soil chemical data that sampling point 10 – the sludge sample in the downstream water bodies resemble the same chemical characteristics as the tailings materials.

Table 6 Soil chemical results depicting elemental toxicity of concern across the samples area

Sample	Li mg/kg^{-1}	Ti mg/kg^{-1}	V mg/kg^{-1}	Cu mg/kg^{-1}	As mg/kg^{-1}	Br mg/kg^{-1}	Rb mg/kg^{-1}	Sr mg/kg^{-1}	Mo mg/kg^{-1}	Ba mg/kg^{-1}	U mg/kg^{-1}
1	0.142	0.008	0	0	0.015	0.088	0.035	0.795	0.012	0.247	0.001
2	0.144	0.008	0.015	0.088	0.035	0.274	0.065	0.751	0.784	0.048	0.005
3	0.24	0.009	0.107	0.29	0.055	0.101	0.088	0.311	1.323	0.013	0.052
4	0.141	0.004	0.001	0	0.014	0.017	0.02	0.162	0.034	0.04	0
5	0.142	0.014	0.002	0.03	0.016	0.213	0.135	1.778	0.006	0.389	0
6	0.141	0.01	0	0	0.014	0.057	0.061	0.52	0.013	0.114	0
7	0.141	0.014	0	0	0.017	0.032	0.092	0.984	0.037	0.179	0.001
8	0.14	0.008	0	0	0.011	0.015	0.016	0.036	0	0.006	0
9	0.141	0.008	0	0	0.011	0.014	0.012	0.055	0	0.015	0
10	0.142	0.005	0.062	0	0.031	0.546	0.107	0.859	0.358	0.056	0.006

4.1.4 Slope gradient and length factor (LS Factor)

The effects of topography on erosion are partitioned in the effects of slope steepness and slope length. On a sloping surface, rain splashes more soil particles downslope resulting in a net downslope movement of material. As the slope steepens, the proportion of downslope movement increases because of respective increases in velocity and volume of surface runoff. Gentle slopes erode less, because there is more surface ponding and slower overland flow which protect the surface against the impact of rain. Typically, erosion only becomes acute when slope angle exceeds a critical steepness, and then increases logarithmically thereafter. Runoff and erosion also tend to increase with increasing slope length. Slope length, together with the slope form, determines the severity of erosion through the type of erosion that will dominate, and the probability for downslope deposition. The slope length factor, L, incorporates the variation of the average erosion due to different slope lengths, λ_l (m), a

$$L = [\lambda_l/22.1]^m \tag{12}$$

where:

22.1 = RUSLE unit plot length (m).

M = variable slope length, related to the ratio, β, of ril (caused by flow) to inter-rill erosion (caused principally by rainfall impact) by $m = \beta/(1 + \beta)$.

The value of β is dependent on the susceptibility of the slope to be eroded by either rill or inter-rill erosion. Where the soil is moderately susceptible to both rill and inter-rill erosion, β can be computed from

$$\beta = (\sin S_{deg}/(0.0896[3.0(\sin S_{deg})^{0.8} + 0.56]) \tag{13}$$

where S_{deg} is slope angle in degrees.

When the storm water flows, the soil cover and management conditions simulated indicate that the soil is highly susceptible to rill erosion, such as on steep, freshly prepared slopes, the value of β should be doubled before it is used in the equation to calculate m. Conversely, when the conditions favour reduced rill erosion relative to inter-rill erosion, such as for gently sloping grasslands, the value of β is halved. Soil loss increase more rapidly with slope steepness than it does with slope length. The slope steepness factor, S, is given as:

$$S = 10.8 \sin S_{deg} + 0.03 \qquad \text{for } S_{\%} < 9\% \tag{14}$$

$$S = 16.8 \sin S_{deg} - 0.5 \qquad \text{for } S_{\%} \geq 9\% \tag{15}$$

The factor LS in the RUSLE model is the product of the length, L, and steepness, S, factors described above. For this study two slope lengths (10 and 25 m) and three slope angles (14, 18, and 33) were used. The LS factors for the different combinations are summarised in Table 7.

4.1.5 Surface covers and land management factor (C-Factor)

The cover management code or land use is the most important soil erosion factor and can change frequently due to land management practices. Plant cover is dominant over the effect of rainfall, slope, and the soil profile on erosion probability. The cover management factor is mainly a function of the canopy cover and residual effect. However, the canopy is not always protective against erosion. The effect of the canopy cover on soil loss depends on both density and height. If the canopy height is too high (>3 m), the fall velocity of the drip is higher than un-intercepted rain. Surface cover including mulch and gravel are more effective than equivalent percentages of canopy cover. Surface cover, such as the rocks and residue composition, is considered as one of the most sensitive factors controlling erosion.

The C value is not only a function of plant cover, but also a function of the distribution of erosivity. To arrive at an average annual C factor, the growth pattern must be estimated over the season. Therefore, C factor values are described as weighted averages of soil loss ratios that relate the soil loss at a given condition at a given time. The soil loss ratio (SLR) is an estimate of the ratio of soil loss under actual conditions to losses experienced under clean-tilled continuous fallow conditions. Therefore, soil loss ratios vary during the year as climate, soil and cover conditions change. The RUSLE uses a sub factor method to compute the SLRs for frequently disturbed soils. For tailings dams the C factor is computed as:

$$C = CC.\ SC \tag{16}$$

where:

CC = canopy cover (vegetation).

SC = surface cover (vegetation, mulch, rock etc.).

It was found that in the case of the influence of groundcover, SC, on erosion, the shape of the RUSLE empirical function matches the observed database information, but parameter values of the function vary over a wide range. This empirical relationship is:

$$SC = \exp(-b.\ M_{gc\%}) \tag{17}$$

where:

SC = ratio of erosion with groundcover to that without cover.

$M_{gc\%}$ percentage groundcover.

The parameter b varies over a wide range from about 0.017 to 0.1. To estimate erosion requires knowing the relation of b to measurable field conditions. Values for b are a function of the ratio of rill to inter-rill erosion. For the topsoil material, b was taken as 0.025 – a value typical for inter-rill erosion. The SC factor for the rock cover (100% rock) is 0.082 and that of the optimum mixture (61% rock) is 0.22. The amount of mulch on the ground were assumed to be three times the basal cover and the SC factor for 4%, 6% and 8% basal cover are 0.74, 0.64 and 0.55 respectively. The canopy component, CC, of C can be calculated as:

$$CC = 1 - FC\ [\exp(-0.328H_f)] \tag{18}$$

where:

FC = fraction of land cover by canopy.

H_f = distance raindrops fall after striking the canopy (m).

The canopy factor would depend largely on the rainfall during the growing season. For this study, only the basal cover was defined, and canopy cover was assumed to be ten times the basal cover. The distance that raindrops fall after striking the canopy was assumed to be 0.4 m. The CC factor for the 4%, 6% and 8% basal cover are therefore 0.65, 0.47 and 0.3 respectively. The cover factor results for the different scenarios are summarised in the data summary Table 7.

4.1.6 Summary of modelled erosion results

From the data presented in Table 7 and Figure 5, it is evident that the in-situ material on all accounts presented the highest long-term erosion rates and the modelled changes in slope angle, slope length and degree of cover proved to substantially reduce the erosion risk. It is evident from the study that the in situ rehabilitation of the kimberlite material presents more than 20 tonne ha^{-1} event^{-1} sediment yield which requires urgent intervention to permanently stabilise the material. The lack of natural vegetative colonisation and the existing geometry of the landscape – in combination with the physio-chemical soil conditions spell disaster of the long-term integrity of the TSFs and the receiving landscape. Since topsoil and rock mix materials must be imported for all other scenarios as well, this cost would be a constant and, therefore, the erosion loss reduction success per ha cost-ratio becomes the deciding factor for final implementation.

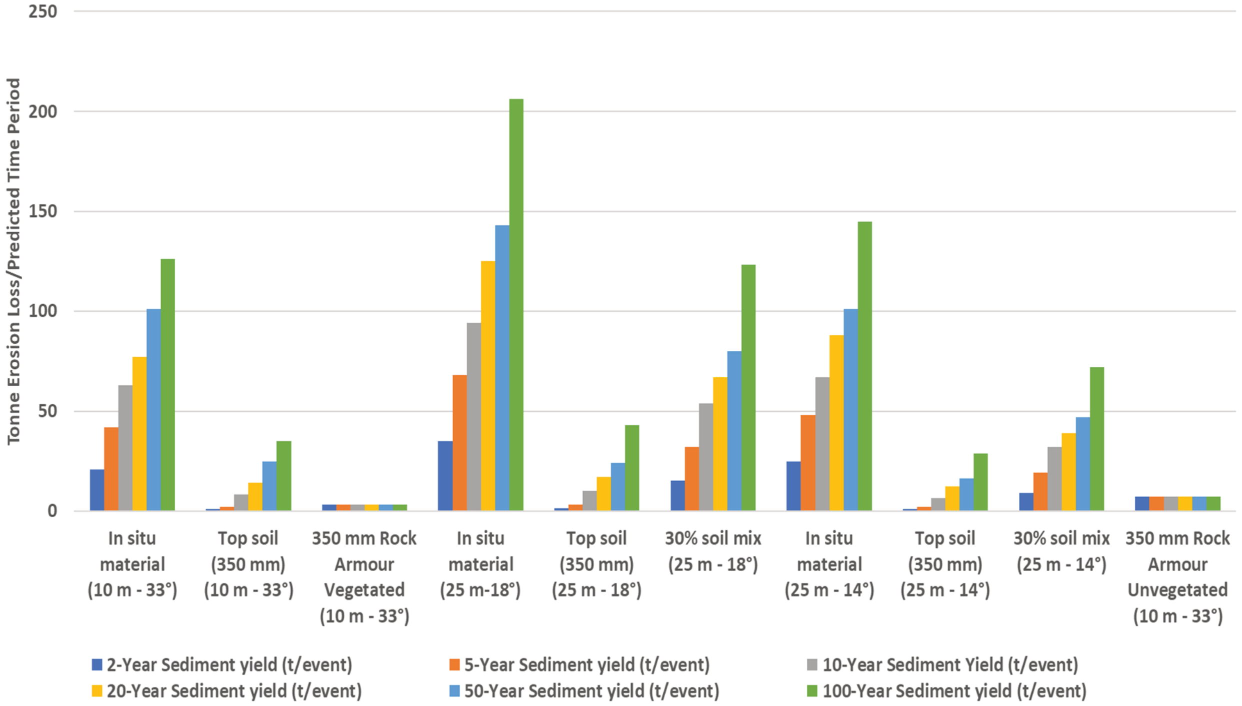

Figure 5 Erosion yield derived from the MUSLE equation for various modelled closure scenarios

Since the mine has ample rock crush available within affordable haulage distance, this scenario would entail a feasible cover operation whilst any topsoil related scenario would require borrowing cost and larger scale rehabilitation cost. Also of note is that the single event erosion rates for both topsoil and topsoil mix scenarios exceeded 10 tonnes ha^{-1}, especially on the longer and steeper slopes modelled. The sandy topsoils also have low water holding capacity that will influence the long-term vegetation cover negatively in the persistent semi-arid conditions. The interaction of moisture with tailings below any soil cover will also lead to severe geotechnical challenges over time, including slippage, sub-surface donga formation and eventually the desiccation of the cover. This would require high future maintenance cost and final closure risk. It is also evident from the data that shorter, flatter, and covered slopes are preferred to longer slope scenarios and it is also clear that a minimum cover of 350 mm topsoil or rock armour is paramount to the long-term closure success of this site.

Table 7 Data summary table for the calculated parameters (Renard et al. 1991). The data in this table outline all models for the 10 rehabilitation scenarios and compare erosion rates based on the various interventions proposed for the RUSLE model (long-term average anticipated erosion loss per tonne ha^{-1} year^{-1}) and the MUSLE model (sediment yield per years in tonne per event)

		RUSLE parameters									Sediment yield (recurring events per years in tonne per event)					
Closure scenarios	**Cover option**	**R**	**K**	**L**	**S**	**LS**	**SFc**	**CCr**	**C**	**L-term erosion (t/ha^{-1}/a^{-1})**	**2**	**5**	**10**	**20**	**50**	**100**
1	In situ material (10 m–33°)	249	0.41	0.58	8.65	5.02	0.74	0.65	0.48	246	21	42	63	77	101	126
2	Topsoil (350 mm) (10 m–33°)	249	0.25	0.5	8.65	4.33	0.68	0.57	0.39	105	1	2	8	14	25	35
3	350 mm rock armour vegetated (10 m–33°)	249	0.034	0.44	8.65	3.81	0.082	1	0.082	3	3*	3*	3*	3*	3*	3*
4	In situ material (25 m–18°)	249	0.41	1.06	4.69	4.92	0.74	0.65	0.48	241	1.3	3	10	17	24	43
5	Topsoil (350 mm) (25 m–18°)	249	0.25	1.04	4.69	4.87	0.61	0.43	0.26	79	35	68	94	125	143	206
6	30% soil mix (25 m–18°)	249	0.36	1.05	4.69	4.97	0.68	0.57	0.39	174	15	32	54	67	80	123
7	In situ material (25 m–14°)	249	0.41	1.08	3.57	3.86	0.71	0.6	0.43	169	0.9	2	6.4	12	16	29
8	Top soil (350 mm) (25 m–14°)	249	0.25	1.04	3.57	3.71	0.59	0.39	0.23	53	25	48	67	88	101	145
9	30% soil mix (25 m–14°)	249	0.36	1.06	3.57	3.78	0.64	0.47	0.3	102	9	19	32	39	47	72
10	350 mm rock armour unvegetated (10 m–33°)	249	0.0344	0.44	8.65	3.81	0.22	1	0.22	7	7*	7*	7*	7*	7*	7*

* Denotes repetitive value of RUSLE calculation for long-term erosion as MUSLE cannot be applied for rock armour erosion rates.

5 Conclusion

This paper presents a case study of the evaluation of rehabilitation interventions for smectite bearing kimberlitic material for a legacy tailings disposal complex. The literature review concerning kimberlitic tailings presented challenges for any anticipated rehabilitation interventions since the unique characteristics of a highly dispersive Na-rich tail, which has sealing properties when exposed to rainfall, need to be sustainably contended with. Adding the on-site conditions of large tailings volumes that has been deposited on the mid-slope of a foothill, the years of severe thunderstorm driven erosion has spread the tailings to a now much larger area, and the receiving water body is described as dysfunctional from siltation. Environmental toxicity was not found to be a concern although turbidity presents ecological challenges.

Sustainable rehabilitation and closure interventions were proposed and modelled to assist the mine with feasible and realistically implementable scenarios. The simulations indicate that the most effective way to reduce the long-term average soil loss and the single event sediment yield events is the construction of physical topsoil covers, soil-rock mixtures, and rock cladding. Even with geometrical interventions, in situ rehabilitation combined with the existing grazing end-land use planned for cannot be regarded as a sustainable closure scenario since the erosion from the TSFs range between 20 and 200 tonnes/ha/year. From the modelled options, cost and minimising additional borrowing impacts, either complete rock encapsulation or relocation of the tailings would achieve indefinite closure Lastly, the RUSLE and MUSLE methodologies were effectively applied as a rapid decision-support methodology for urgent scenario planning.

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