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Water Research Commission



THE EFFECT OF THE CHEMICAL PROPERTIES OF TAILINGS AND WATER APPLICATION ON THE ESTABLISHMENT OF A VEGETATIVE COVER ON GOLD TAILINGS DAMS

Report to the WATER RESEARCH COMMISSION

by

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THE EFFECT OF THE CHEMICAL PROPERTIES OF TAILINGS AND THE APPLICATION OF WATER ON THE ESTABLISHMENT OF A VEGETATION COVER ON GOLD TAILINGS DAMS

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EXECUTIVE SUMMARY

The core economy of South Africa has developed around the mining industry but the finite quantity of an ore body places a limit on the life of a mine. As the viability of mines begins to decline, mine closure becomes more and more a reality, as do the liabilities associated with mine closure. One of the liabilities is the rehabilitation of areas disturbed by mining or associated activities. Regulatory standards and guidelines for the rehabilitation of tailings dams are becoming increasingly prescriptive as regards procedural and technical requirements. Sustainability is a closure requirement, however, no guidelines for the assessment of the sustainability and/or rehabilitation success are provided by mining legislation in South Africa.

Although the successful rehabilitation of gold tailings dams goes back as far as the early 1960's there is still uncertainty with regards to the sustainability of the vegetation cover established using different rehabilitation methods. Uncertainty with regard to the sustainability of re-vegetated systems stems from:

- The concept of sustainability is as difficult to define as it is to put into practice
 and qualifiers for rehabilitation methods such as "ecological", "natural
 recovery", and "self-maintenance", are often used interchangeably with
 sustainability, causing even more confusion
- Over emphasis of certain vegetation attributes such as diversity of species, grazing potential etc. while ignoring the function that the vegetation cover has to full-fill (the main function of a vegetative cover on gold tailings is to reduce air pollution (dust) and to reduce water pollution (sediment and salt load).
- Lack of knowledge with regard to vegetation succession on gold tailings dams

Objectives of the study

The primary objective of this study was:

 To determine which commonly used rehabilitation methods for gold tailings produced the most sustainable vegetation cover at the end of the rehabilitation period

A secondary objective was:

To quantify the water needed for the different rehabilitation methods

Methodology

A literature survey had been conducted with regard to- the properties of gold tailings, the environmental impacts associated with tailings dams, rehabilitation methods, methods to evaluate rehabilitation projects, sustainability of vegetated areas and regulations regarding closure.

The following rehabilitation methods most commonly used in South Africa for revegetating tailings dams, were selected for evaluation:

- Leaching method
- · Revised leaching with lime filled trenches on contour
- Elementary amelioration
- · Minimum cultivation with topsoil, and

Chemical amelioration to eliminate the need for leaching.

For the chemical amelioration method three irrigation systems were also evaluated namely a micro-yet irrigation system, a drip irrigation system, and a sprinkler irrigation system.

Plots on the south-facing slope of the old President Steyn number 6 tailings dam at Welkom, were vegetated in accordance with the method applicable to a particular rehabilitation method. For each of the methods the following was recorded:

- · Quantity of irrigation water used
- · Type and amount of ameliorants
- · Type and amount of fertilisers
- Seed cocktail (species and amount of seed)

The following were monitored for each method over the period November 1998 to March 2002:

- Chemical attributes of the tailings
- · Species abundance, basal cover, and root development
- Soil microbial activity

To assess the "tailings quality" and the "vegetation quality" obtained in this study it was decided to compare them with the "tailings quality" and "vegetation quality" of tailings dams rehabilitated in the past, using different methods, which currently sustain a good vegetation cover.

The following tailings dams were selected representing the different methods of vegetation establishment on gold tailings dams:

- Leaching method (selected by Mr Cook and Mr Dawson)
 - 1L1 East Champ D'or (vegetated in the early 1960's)
 - 2L3 Consolidated Main Reef (Fleurhof- vegetated late 1960's)
 - 3L44 City Deep (Wemmer Pan-vegetated in the late 1970's)
 - 4L48 East Rand Proprietary Mines (ERPM Dam 1-vegetated in the mid 1990's)
 - 4L50 ERPM Dam 4-vegetated in the mid 1990's
 - 2L24 Durban Roodepoort Deep –mid 1990's
- Chemical amelioration (selected by Mr van Deventer)
 - Stilfontein no 5 –vegetated in the mid 1990's
 - Saaiplaas –vegetated in 1996
 - PS 5- vegetated in 1999
 - Oryx –vegetated in 1997
 - 2L24 DRD-vegetated 1999
- 3. Others
 - PS 3-vegetated 1996 (revised leaching)
 - Beatrix –vegetated mid 1990s (topsoil)

Discussion and conclusions

Criteria used to evaluate the sustainability of a vegetation cover include, diversity of species, dynamic stability, and productivity. The productivity of plants depends largely on climate and the fertility of the growing medium. Tailings fertility is related to:

- The physical properties of the tailings which influence the amount of water that can be held in the profile and the ease with which roots can penetrate, and
- 2. The tailings chemistry (pH, EC, and nutrients).

The dynamic nature of re-vegetated systems requires data not only on the initial conditions but also over time to monitor the system's evolution.

Tailings quality

The amelioration of tailings, in accordance to the different rehabilitation methods, has changed the following chemical attributes for the 0-30cm layer significantly, pH, K, Mg, Ca, Al, CEC, and P. Liming had the largest effect on the chemical attributes of the tailings as it caused an increase in pH, Ca, and Mg. The increase in pH in turn caused Al to precipitate and the CEC to increase. The measured active and reserve acidity (H⁺ + Al³⁺) before amelioration indicate that 3 tons lime per ha was needed to neutralise it. But the results obtained indicate that almost 13 tons of lime per hectare was needed to neutralise the active and reserve acidity. This large discrepancy can be explained by the presence of iron sulphate minerals in the tailings that also contribute to reserve acidity. The standard agricultural laboratory tests to determine reserve acidity must be modified for material containing iron sulphate minerals to be more applicable for rehabilitation purposes.

After amelioration, a comparison between the leaching methods indicates that none of the chemical attributes differs significantly, while a comparison between the chemical amelioration methods indicate that only the EC and K differ significantly. When the leaching methods are compared with the chemical amelioration methods the chemical attributes that differ significantly were pH, Al, and CEC. However, all methods had after amelioration produced a growing medium that is suitable to sustain a vegetation cover. Six weeks after amelioration none of the chemical attributes within the 30-60 cm layer had changed significantly for any of the rehabilitation methods.

The application of compost had increased the water holding capacity of the 0-30 cm layer significantly, and had an additional effect on the CEC. The compost had however, no effect on the EC of the tailings, which is in contradiction with laboratory studies. For this study it was found that the EC of the saturated paste was not a good indicator of the salt content of the tailings. This could be explained by the formation of the ion pair CaSO₄⁰, which is important in solutions containing more than 1000 mg/l sulphate, (on average more than 2000 mg/l sulphate for this specific tailings) as more than half the dissolved calcium could be present in the form of the CaSO₄⁰ ion pair. This neutral ion pair had no influence on the electrical conductivity of the saturated paste, and the net result of the ion pair is that electrical conductivity measurements underestimate the ion concentration and total dissolved solids.

The phosphorus status of the tailings after amelioration is on the high side if compared against the phosphorus level of the adjacent natural veld. Potassium did not increase in relation to applied fertilisers because it either was leached from the tailings or become fixed through the precipitation of jarosite.

The change in chemical attributes in the period after amelioration to the end of the study period was very similar between the different rehabilitation methods although the magnitude of change differed. At the end of the study period the only chemical attribute for the 0-30 cm layer that differed significantly between the leaching methods was Ca. Between the chemical amelioration methods the drip irrigation method differs in EC, Ca, and Cl from the other irrigation methods. This difference can be explained in terms of the amount of possible leaching that could take place, between the different irrigation systems. The chemical attributes that differ at the end of the study period between the leaching and chemical amelioration methods were mainly EC, Ca, and Cl. The chemical amelioration methods had at the end of the study period, on average, a higher salt content compared to the leaching methods.

The chemical constraints that the tailings of the experimental site imposed on vegetation establishment were not very severe because the elementary amelioration method that was neither a leaching method nor a chemical amelioration method was just as successful for establishing vegetation and there were no extreme differences in chemical attributes relative to the other rehabilitation methods.

A comparison between the chemical attributes of tailings dams rehabilitated in the past with that of this study indicate that the chemical conditions of the experimental site had at present a better overall fertility. The only negative elements were Na and Cl, which were higher for the experimental site. If the fertility can be maintained then all the rehabilitation methods were successful in turning the tailings into a suitable growing medium to sustain a good vegetation cover. However, it is foreseen that the tailings of the chemical amelioration plots will become more saline in future although the pH will remain more or less neutral. On the other hand the tailings of the leaching methods will become more acidic but the salinity would be relatively constant.

Cone penetration studies conducted during the study period indicate that plant roots can exploit the upper 60 cm of the tailings once the chemical constraints that limit root development were removed.

Vegetation quality

The initial seeding involved the sowing of a mixture of 16 species for the leaching methods and the sowing of a mixture of 8 species for the chemical amelioration methods (five species were common to both methods). At the end of the study period 8 of the sown species remained of a total number of 39 species that have been identified on the site at the end of the study period. However, the three dominant plant species, in order of dominance, at the end of the study period were Dactylis glomerata, Medicago sativa, and Eragrostis curvula for the leaching methods and Medicago sativa, Eragrostis curvula and Dactylis glomerata for the chemical amelioration methods.

The results obtained from tailings dams rehabilitated in the past reveals that in the early stages of succession (up to 5 years after re-vegetation) the plant community is dominated by Cloris gayana, at a later stage Eragrostis curvula become the dominant species, to be follow by a Hyparrhenia hirta dominated community which can be regarded as the secondary succession climax on tailings dams. In this study Chloris gayana dominate only in the first year after re-vegetation. The fast disappearance of Chloris gayana was attributed to the fact that the experimental site was located on the south facing slopes of the tailings dam (Chloris gayana still dominated the north facing perimeter wall of the experimental plots at the end of the study period). Although Eragrostis curvula was not the dominant specie at the end of the study period, this specie had steadily increased over the study period to be the subdominant specie for all chemical ameliorated methods. At the end of the study period the Hyparrhenia hirta occurring on the experimental plots were those established by hand planting.

It is anticipated that in the near future the vegetation will have to adapt to changes in the chemical conditions of the tailings, which is expected to become more saline for the chemical ameliorated plots while the leaching plots will become more acidic. The neutral pH and higher salinity conditions for the chemical amelioration plots is more compatible with chemical conditions occurring in soils of dry climates and therefore natural colonising of the plots by grass species from the surrounding veld is foreseen to be favoured towards the chemically amelioration plots.

At this stage (three years after rehabilitation) no conclusive statement can be made regarding the sustainability of the vegetation cover for any of the rehabilitation methods. However, results from tailings dams rehabilitated according to the different methods in the past indicate that stable plant communities can be obtained. The leaching method had the longest track record with stable *Hyperhenia hirta* communities in excess of 40 years old on certain tailings dams.

Water needed for the different rehabilitation methods

Water is used in rehabilitation methods to establish vegetation and in the leaching methods also for reclamation (leaching salts and acids out of the root zone). In this study the water inputs in terms of rainfall and water applied through irrigation were recorded. The exact amounts of water that leached through the root zone could only be estimated roughly.

Where a micro-jet irrigation system was used, about twice as much water was used in the leaching method compared to the chemical amelioration method. The amount of water applied for a chemical amelioration method, under sprinkler irrigation, was about the same as that of a leaching method under a micro-jet irrigation system. The least amount of water was applied under a drip irrigation system, i.e. three times less than for a leaching method under micro-jet irrigation.

The experimental site was unfortunately on a tailings dam where the conditions were favourable for the establishment of vegetation. Furthermore the experimental site was on a south-facing slope, which is wetter than a north, west, or east, facing slope. The beneficial role of water in terms of vegetation establishment or as a reclamation agent was therefore not highlighted in this study.

Further studies and recommendations

During this study some of the problems that become apparent were:

- The sustainability of re-vegetated tailings dams, even with a proven stable plant community in excess of 40 years, are questioned, only due to a lack of diversity in the plant community
- The degradation of vegetated tailings dams is driven by a combination of forces such as lack of funds, low biological productivity, lack of knowledge, lack in ability or desire to maintain the biological productivity, and poorly defined or inadequate tenure systems. Unfortunately, any vegetation failure, irrespective of the reason for failure, is used as an example to point out that revegetation efforts are unsustainable.

The problem experienced over the years is that once vegetation has been established the mining companies viewed it as a walk away solution and see little value in maintenance and monitoring as part of the rehabilitation process. Hopefully this attitude will change, as the application for closure of a tailings dam has to be substantiated with data to prove that the rehabilitation measures taken are effective.

Future research needs to address biological productivity/diversity, and tenure systems. Tenure systems (land management) should be evaluated and tested against the five pillars of sustainability, namely, productivity/services, security/resilience/risk, protection, viability, and acceptability.

Recommendations with regard to future research are:

- 1) Models: If the ACRU-model and the Salmine-model, or any other water balance and geochemical model, can be modified and integrated then it can become an important tool in the rehabilitation of tailings dams for:
- Estimate the water needs for leaching and vegetation establishment
- Estimate the amount of erosion (sediment yield) under different plant covers and or erosion control measures
- Estimate the effect of different rainfall scenarios on vegetation performance
- Estimate the runoff from vegetated tailings for determining the size of paddock structures and return water structures
- Estimate the chemical attributes of the tailings for different rehabilitation methods and climatic scenarios
- Evaluating "what if " -scenarios, and
- Risk assessments.
- 2) Monitoring: Monitoring is an important aspect but is a relative new endeavour (at least for tailings material) and the necessary indicators, minimum data sets, procedures, thresholds, and standards have still to be developed.

Re-vegetation monitoring on the other hand comes a long way but the exact vegetation parameters and goals (ecological condition assessment, pro-active management systems, evaluation of the rehabilitation process, etc) have yet to be defined.

Monitoring of environmental impacts should also be addressed.

3) Other research:

- Methods to effectively build up potassium to favourable levels in tailings should be investigated
- Soil organic matter dynamics in tailings and their relationship with other chemical/physical attributes should be investigated
- Methods to address the physical limitations of tailings need urgent attention
- The fate of additional lime to counteract potential acidity should be investigated over a long period
- Vegetation succession or state and transition models for rehabilitated gold tailings dams have to be developed because such models are essential for land management of re-vegetated systems and to make more conclusive statements regarding sustainability of the vegetation cover, when application for closure is made.
- A thorough understanding of the chemistry and mineralogy of iron-bearing minerals such as pyrite, jarosite, schwermannite, ferrihydrite, and goethite, is essential to understand the chemical behaviour of gold tailings.
- Certain standard methods of soil chemical analysis should be modified to ensure that the results are more applicable for the chemical amelioration of gold tailings.
- A search for other plant species adaptable to gold tailings conditions is required to ensure a higher plant diversity

Recommendations

- Every rehabilitation project should be monitored, preferable by tertiary and research institutions, to ensure that a better understanding of re-vegetated ecosystems can be gained, so that a closure application can be substantiated with relevant data
- Environmental scientists, researchers, rehabilitation specialists, the mining industry and the regulators should work together to develop a framework for assessing sustainability as well as for the sustainable management of revegetated tailings dams.

THE EFFECT OF THE CHEMICAL PROPERTIES OF TAILINGS AND WATER APPLICATION ON THE ESTABLISHMENT OF A VEGETATION COVER ON GOLD TAILINGS DAMS

Chapter 1

Introduction

According to the historian H.G. Wells "the history of humanity has always been a race between learning and disaster". The threat of disaster is always with us, only its form changes. Major past disasters were famine and pestilence and presently we experience various threats of environmental damage, degradation of land and water resources, destruction of natural vegetation, a change in global climate, etc. The development of agriculture and medical sciences as well as technology has alleviated famine and pestilence to a certain degree but the question is whether the conventional practice of science (simplifying the complexity of nature, and lack of interdisciplinary cooperation) can alleviate environmental damages? Man by changing their abode through modifying plant communities, and manipulating the soil and the water regime, have caused severe environmental damage (Hillel, 1993). The objective of this study is to determine whether rehabilitation methods by manipulating (ameliorating) the tailings, manipulating (controlling) the water regime of the tailings dam and introducing a modified plant community on the dam, can alleviate environmental hazards associated with tailings dams.

1.1 Disturbances and environmental hazards associated with tailings dams

During the construction and commissioning phase of a tailings dam the major impacts of tailings deposition are related to 1) changes in actual surface elevations and hence landform, and 2) the composition of the tailings, particularly, sulphide minerals, radioactive minerals, and processing chemicals. The main environmental hazards associated with gold tailings dams are; air pollution (dust generation and radon emission), water pollution (acids, salts, heavy metals, radionucleotides, cyanides and sediment load), erosion and the stability of the tailings impoundment. After decommissioning of the tailings dam, the stability of the tailings dam generally improves (as the phreatic water surface decline) but all other environmental hazards become more pronounced if necessary precautionary and preventative measures are not taken. Waste rehabilitation efforts are heavily influenced by statutory and regulatory compliance. Regulatory standards and guidelines are becoming increasingly prescriptive as regards procedural and technical requirements.

1.2 Legislation and rehabilitation

Current legislation requires all mining companies to produce Environmental Management Programme Reports (EMPR's). Legislation placed responsibility for the mining industry to protect and conserve the environment on the owner of a mine until such time as the owner has been issued with a certificate releasing him from such responsibility (section 12 of the Minerals Act, 1991). Wates et al. (1997) and Mol & Mbalo (2001) discussed the legal aspects dealing with tailings dams and mining and therefore only national environmental management principles and Acts pertain to

mine residue deposits will be listed. The National Environmental Management Act (NEMA) 107 of 1998 lays down a set of national environmental management principles. These principles support the concepts of the precautionary principle, the preventative principle and polluter pays principle.

- The precautionary principle advocates for a risk averse and cautious approach considering the limits of current knowledge and is promoted in;
 - NEMA 107 of 1998
 - Mining and Minerals policy for South Africa
 - Mines and Works Act regulations 1970
- The preventative principle is reflected in;
 - The constitution
 - Mining and minerals policy for South Africa
 - Minerals Act 50 of 1991
 - Mines and Work Act regulations 1970
 - NEMA 1998
 - National Parks Act 1976
 - National Heritage Resources Act 1999
- The polluter pays principle is reflected in;
 - National Water Act 36 of 1998

The following Acts have principles or requirements that may influence tailings dams:

- Environmental Conservation Act (1989)
- Nuclear Energy Act (1993)
- Hazardous Substance Act (1973)
- Health Act (1977)
- Conservation of Agricultural Resources Act (1983)
- Physical Planning Act (1991).

The Mines Health and Safety Act 1996 (MHSA) imposes on the mine manager the responsibility to identify hazards, to mitigate the hazards so as to: eliminate the risk, control the risk at source, minimise the risk, and in so far as the risk remains to institute a programme to monitor the risk. Guidance for implementation of this requirement of the MHSA for residue deposits are given in the Department of Mineral and Energy Affairs (DME) document for the compilation of a mandatory Code of Practice on Mine Residue Deposits (DME, 2001).

Rehabilitation measures must be carried out either in accordance of the EMP, or at the same time as the mining operations, or within the context of closure, or to the satisfaction of the Regional Director (section 38 of the Minerals Act, 1991). From the mines point of view the sooner a closure certificate is obtained, the better. Rehabilitation, within the context of a Closure Plan, must be based on the same principles as for an EMP, but the emphasis must be on closure. The Department of Mineral and Energy Affairs (1995 & 2002) had set general requirements/standards to be met for the closure of tailings dams.

A systematic approach is usually followed to rehabilitate a tailings dam, consisting off:

- Identifying the hazards
- Assessment of the hazards in terms of likelihood of harm and the consequences of harm (risk analyses)

- Defining rehabilitation objectives in terms of the risk assessment and statutory and regulatory requirements
- 4) Rehabilitation plan hazards that are most likely and that have the greatest potential consequences are targeted for remedial work as well as all requirements to met statutory and regulatory compliance, and
- 5) Monitoring and management plan a management and monitoring plan is put in place to facilitate and measure the effectiveness of the remedial work Monitoring should focus 1) on the assessments of impacts and verification of information, and 2) on compliance with objectives and standards, regulatory requirements, control methods etc. (DME, 1998 & 2002).

The establishment of vegetation on gold tailings can suppress or control some of the environmental hazards (air and water pollution) associated with tailings. Revegetation of tailings dams had become almost the norm for the rehabilitation of gold tailings dams. However, no guidelines for the assessment of the sustainability or rehabilitation success are provided by mining legislation in South Africa.

1.3 Rehabilitation success and sustainability

According to Tomlinson (1984), rehabilitation is the restoration of a disturbed area to a landform and productivity, which are in unison with the landform, and productivity of the locality before the disturbance took place. It is further intended that the plant community, which is established, should develop to a stable and self-sustaining plant community that will adapt to the vegetation or land usage of the area. Thus, more attention is given to the quality of the result of re-vegetation. This quality is measured in terms of productivity, landscape, diversity, and resemblance to the plant community of that area.

Richter (1991) defined rehabilitation as rehabilitating disturbed land to a stable physical state with vegetation which is naturally surviving and propagating or made suitable for a predetermined use; to provide a proper water management system to prevent erosion and the pollution of surface and sub-terranean water, and effectively treat any polluted water; and to prevent any form of atmospheric pollution by dust, smoke or fumes. Preventive and mitigating measures shall be permanent, self-supporting and maintenance free.

The most commonly employed method for assessment of rehabilitation success is the comparison of the vegetation composition between reconstructed communities and the original community (Ewel, 1987). Other criteria been proposed to measure rehabilitation success include:

- Are the environmental problems/hazards effectively been eliminated and is the rehabilitation effort sustainable in the long term? (van der Nest and van Deventer, 1997).
- Is the economic value of the new resource equal to the value of the resource that was destroyed during development? (Barnard, 1995)
- Is the established vegetation on disturbed mine land similar to vegetation on disturbed land not influencing by mining (e.g. road verges) and will it converge to a similar climax vegetation state? (Mentis and Ellery, 1994).

Weiersbye and Witkowski (1998) after studying 56 vegetated tailings dams in the Carltonville, Klerksdorp and Welkom areas came to the conclusion that:

- The existing vegetation strategies (leaching, high lime, fertiliser and water inputs) and the existing suite of species used are unsustainable, and environmentally and economically unsound.
- The current tailings amendment regime (leaching, high lime, fertiliser and water inputs) will inhibit, rather than promote the growth of tailings tolerant species.

They proposed that more restrained amendment practices, which encourage the development, rather than the inhibition, of tailings-tolerant flora, must be utilized.

It seems from their conclusions that existing re-vegetation methods are unsustainable and that natural vegetation recovery should be enhanced. Failure of established vegetation on gold tailings cannot be attributed only too rehabilitations methods *per se*, other reasons for failure include:

- Lack of tenure systems (care and maintenance and land management)
- · Lack of understanding the dynamics of re-vegetated systems,
- Lack of funds.
- · Lack in ability or desirability to maintain the biological productivity, and
- Adverse climatic conditions (drought) or disturbances (fire, water logging, offroad recreation, etc).

Although a number of plant species seems to colonise on untreated gold tailings, the complete re-vegetation of a gold tailings dams through natural vegetation recovery do not exist in South Africa. The current state of grassing/rehabilitation of tailings dams is such that a walk away situation after grassing can as yet not be obtained. Some degree of after-care is therefore necessary. The amount and intensity of after-care with regard to the vegetation will vary from site to site and from locality to locality on sites. The main objective should be to maintain a good healthy grass cover with preferably no bare spots on the tailings dam to prevent erosion and dust pollution (DME, 1995b). This research project was initiated to determine the quality of the vegetation cover established through different rehabilitation methods currently used on gold tailings. A key question is, which standard should be used to measure the quality of rehabilitation methods, sustainability, or BATNEEC (Best Available/Proven Technology not Entailing Excessive Cost)?

1.4 Objectives of the study

To address the question of the quality of rehabilitation methods this project was initiated with two aims in mind:

- To determine which rehabilitation method produced the most sustainable vegetation cover at the end of the rehabilitation period, and
- To quantify the amount of water applied for the different rehabilitation methods

The aims of the project were addressed as follows:

Five rehabilitation methods that are commonly used in the industry were evaluated in terms of their water need and the sustainability of the vegetation cover, after a period of three years. The methods selected were:

- Leaching method
- Revised leaching with lime-filled trenches on contour
- Elementary amelioration
- · Minimum cultivation with topsoil, and
- Chemical amelioration to eliminate the need for leaching.

Plots on the south-facing slope of President Steyn number 6 tailings dam (Welkom) were vegetated in accordance with the method applicable to a particular rehabilitation method. Chemical analyses were conducted on the tailings before amelioration, after amelioration and at the end of the project to assess the beneficial effect of amelioration and the chemical quality of the tailings at the end of the project. The species composition, species abundance, basal cover, and root development were monitored over the study period for assessing vegetation quality.

To assist with the interpretation of results obtained, a reconnaissance investigation of sites rehabilitated in the past according to the different methods used for this study will be done, to serve as benchmarks.

The view of the project team is that the outcome of a good rehabilitation method should ensure that the tailings do not become re-acidified over time, and that the ameliorated tailings will be able to function as a "normal" soil in terms of nutrient cycling, thus allowing the perpetuation of a self-sustaining vegetation community.

1.5 Report structure

Following the introductory Chapter 1 in which the background and research objectives are provided, Chapter 2 provides a literature overview of the properties of tailings, environmental impacts of tailings dams, rehabilitation methods, and sustainability. Chapter 3 describes the trial treatments, including, the surface preparation, the amelioration of tailings, seed mixtures, the changes in the chemical attributes of the tailings, and the amounts of water applied over the study period, for the different rehabilitation methods. Chapter 4 describes the assessment of tailings quality, including the processing of data, the changes in chemical attributes over the study period and the comparison of the chemical attributes of the tailings from the experimental site with the chemical attributes of tailings from tailings dams rehabilitated in the past. Chapter 5 describes the assessment of vegetation quality, including, the changes in vegetation composition and diversity over the study period and an assessment of the sustainability of the vegetative cover at the end of the study period. Chapter 6 is a synopsis of the study as well as recommendations for further studies.

Chapter 2

Literature Review

In this chapter a literature overview will be given of:

- The properties of tailings
- The role of water in certain processes active on the tailings surface or within the tailings
- Environmental hazards associated with gold tailings dams
- Water balance for a tailings dam
- · The water balance of a re-vegetation system
- · Methods used for re-vegetation gold tailings dams
- The sustainability of re-vegetation systems
- Sustainable land management, and
- Monitoring of rehabilitated tailings dams

2.1 The role of water in the disposal of tailings and in the physical processes, which the tailings undergo

The following is a synopsis from the Chamber of Mines (1983 &1996) and Williams (2000) of the disposal of metalliferous tailings.

Most tailing storages are constructed above ground by the downstream, upstream or centreline methods (Figure 2.1):

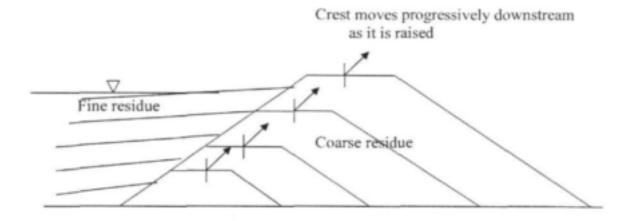
- The down stream construction method in which the centre-line of the embankment moves progressively downstream requires the greatest volume of fill and is therefore the most stable but unfortunately the most expensive method.
- The upstream construction method in which the centre-line of the embankment moves progressively upstream resulted in a rather insubstantial outer shell for the impoundment. The upstream method requires about half the volume of fill of the downstream method and is the cheapest but the least stable method. The upstream method is no longer used in other parts of the world, although it is the method traditionally and still most commonly used in South Africa.
- The centre-line construction method in which the centre-line of the embankment remains in the same position through out construction is intermediate between the other two methods.

Upstream construction imposes significant operational constraints in that; an adequate starter structure is required, the rate of rise must be controlled, and consolidation must be maximised to improve stability. Some of the problems associated with sub-aerial deposition of tailings are: poor water recovery, excessive reliance on evaporation, low bulk density and strength, high piping and liquefaction potential, acid mine drainage, and uncertainty with regard to the long-term stability of the impoundment. However, under South African climatic conditions the upstream method of placement is perfectly safe if manage correctly (Chamber of Mines, 1983).

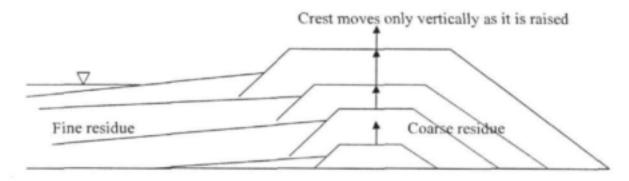
Tailings are typically angular, silt-sized (0.06 to 0.002mm) particles that are disposed of as slurry, with a solid concentration of between 30% and 50% by mass. The median size (D₅₀) of gold tailings ranges between 0.02 mm to 0.1 mm, and the

material, according to the Unified Soil Classification System, classified typically as ML/CL/SM, silty materials, with a low plasticity.

DOWN STREAM METHOD



CENTRE-LINE METHOD



UPSTREAM METHOD

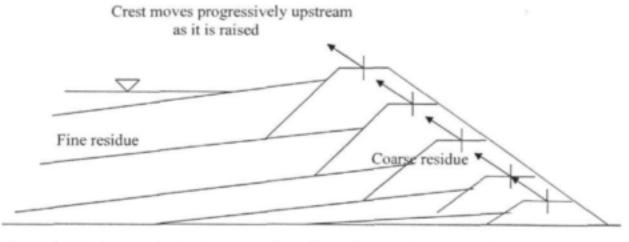


Figure 2.1. Various methods of constructing tailings dams or dykes (Chamber of Mines of South Africa, 1983).

The physical processes that tailings undergo on sub-aerial disposal include beaching, hydraulic particle sorting, sedimentation, self-weight consolidation, desiccation, and loading. On discharge, the tailings settle and consolidate over time to a largely water-filled porosity of 0.45 to 0.55. The dry density of settled and consolidated tailings is typically in the order of 1.3-1.8 Mg.m⁻³. The dry density increases with depth due to the effect of self-weight loading. Tailings comprising of angular particles settle into an open (loose) packing which may collapse on loading. Cementation may also occur as a result of precipitation of iron oxi-hydroxides.

Beaching and hydraulic particle sorting occur as the tailings slurry stream meanders across the beach and dominate on the exposed upper part of a tailings beach. Coarse and any high specific gravity particles deposit rapidly while finer and/or lighter particles are carried further down the beach toward the decant pond. A tailings profile consists typically of relatively thin layers (10 to 20mm thick) that are differentiated by their particle size and specific gravity. The particle sorting down a tailings beach is well characterised by the river transport model (Blatt et al. 1972) which is an exponential expression:

$$D_x = D_o \exp[-a(x-b)] \tag{2.1}$$

Where D_x is the particle size at a distance x downstream, D_0 is size at x is 0 (point of discharge) and a, b, are constants for a given tailings beach, related to the particle size, and specific gravity of the tailings, and the initial solids concentration.

Sedimentation occurs in the upper, more recently deposited part of the tailings column, with consolidation occurring simultaneously at the base of the column. Self-weight consolidation of tailings, determines its ultimate density profile, and the coefficient of consolidation (c_v) determines the time rate of consolidation. Sedimentation and consolidation coupled with hydraulic sorting causes tailings to be an anisotropic material. The hydraulic conductivity of tailings is highly anisotropic, with the horizontal hydraulic conductivity 3 to 4 times higher than the vertical hydraulic conductivity (Mrost and Lloyd, 1970), although it can be 50 times higher for residue containing a wide range of particle sizes (Chamber of Mines, 1983) due to the change in void ratio that the tailings undergo as it consolidate. The vertical hydraulic conductivity is best described by:

$$K=a.e^{-b}$$
 (2.2)

Where K is the hydraulic conductivity (L/T), a, and b are constants determined from consolidation data.

Water within the tailings impoundment may flow downwards, driven by gravity, towards the foundation or containment structure, resulting in seepage. The water may also flow upwards driven by evaporation, capillarity, and possibly also due to transpiration by vegetation. The direction and magnitude of water flow in tailings are determined by the matric suction profile and hydraulic conductivity of the tailings. The quantity and rate of seepage is controlled by the geohydrological conditions of the foundation, hydraulic conductivity of the tailings material, hydraulic conductivity of the foundation, and the design, construction, and operation of the impoundment (Wagener et al. 1997).

The preceding discussion can be summarized through a framework of structure formation. The structure of tailings is composed of a fabric and inter-particle force system that reflect, to some degree, all facets of the tailings composition and history. Structure-determining factors and processes in tailings are summarised in figure 2.2 (Hattingh, 2001).

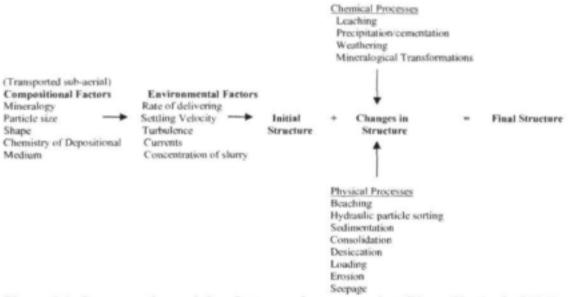


Figure 2.2. Structure-determining factors and processes in tailings (Hattingh, 2001) as modified from the framework of Mitchell (1976) for structure formation of residual and transported soils.

2.2 The action of water within or on a tailings dam

Water is essential for all biological, chemical, and physical, transformation processes (weathering, neoformation of minerals, decomposition, humification, aggregate formation, ion exchange, redox processes etc.) within tailings. The actions of water can be grouped into four categories (percolating, ascending, runoff and stagnated), each of these categories controlling different processes on and within the tailings dam.

2.2.1 Role of water as a weathering agent

The decomposition of gold tailings by solution, hydrolysis, acidolysis, and oxidation is the response of minerals in the tailings to water, oxygen, carbon dioxide, and H⁺ ions. Considering the prevalence of redox and hydrolysis reactions in the weathering zone, the activities of the electron and of the proton have a special significance. Thus, the most generally useful master variables of the weathering environment will be the redox potential (Eh) and pH. The spread of Eh-pH conditions that can be expected in the weathering environment (within the stability field of water) is approximately as shown in figure 2.3 (Chesworth, 1992). This figure shows three salients, which correspond to three lines of evolution in weathering materials.

The trends are directly related to the behaviour of water. The acid and alkaline trends are in the oxidising or water-unsaturated zone of weathering. The acid trend requires an acid sulphate mineral. The alkaline trend is found in fresh or un-oxidized tailings.

The reduced trend is found in water-saturated conditions in the weathering profile of the tailings. In a tailings dam all three trends exist, each imposing different problems with regard to re-vegetation. In the upper layer of the tailings, the oxidation of pyrite dominates which is accompanied by the formation of sulphate salts (gypsum, melanterite, and rozenite), iron sulphate minerals, (jarosite and schwertmannite), and iron hydroxides (lepidocrocite, ferrihydrite, and goethite) (Singh et al., 1997).

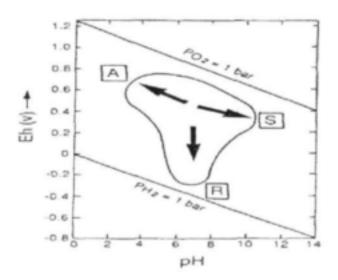


Figure 2.3. The Eh-pH framework of alteration under Earth-Surface conditions (A= acid trend, S= alkaline trend and R = reduced trend, Chesworth, 1992)

2.2.1.1 Oxidation of pyrite

The most important transformation reaction in gold tailings is the weathering of pyrite. The quantitative determination of iron sulphide weathering is a complex problem because pyrite oxidation can involve both geochemical and biochemical components. The geochemical oxidation of pyrite may be characterized by the reactions reported by Stumm and Morgan (1981):

$$FeS_2 + 7/2 O_2 + H_2O = Fe^{2+} + 2SO_4 + 2H^+$$

$$Fe^{2+} + 1/4O_2 + H^+ = Fe^{3+} + 1/2H_2O$$

$$Fe^{3+} + 3H_2O = Fe(OH)_3 + 3H^+$$

$$FeS_2 + 14Fe^{3+} + 8H_2O = 15Fe^{2+} 2SO_4^{2-} + 16H^+$$
(2.3)
(2.4)
(2.5)

The sequence occurs as follows; pyrite oxidation proceeds by both air oxidation and direct bacterial attack with equal amounts of acidity produced by the oxidation of sulphide to sulphate and the oxidation of ferrous iron to ferric iron (Kleinmann and Erickson, 1982). *Thiobacillus ferrooxidans* grows on elemental sulphur at pH values between 1 and 7, and will oxidize elemental sulphur to sulphuric acid (Ehrlich, 1981).

The rate-determining step involves the specific oxidation of ferrous iron (Eq. 2.4). The rate of oxidation of ferrous iron is very slow under chemical conditions analogous to those found in mine water, indeed considerable slower than the

oxidation of pyrite by ferric iron (Eq. 2.6). At pH 3, the half time for the oxidation of Fe²⁺ is of the order of 1,000 days, whereas in the case of pyrite oxidation by Fe³⁺, a half time of the order of 20 to 1,000 minutes is observed (Stumm and Morgan, 1981). Pyrite oxidation gradually lowers the pH in the pyrite microenvironment until at pH of about 4.5 *T. ferrooxidans* takes on an additional role by accelerating iron oxidation (Kleinman and Erickson, 1982). The hydrolysis of ferric iron (Eq. 2.5) causes further lowering of the pH in the microenvironment. When the pH adjacent to the pyrite approaches 2.5, the kinetics of iron hydrolysis slow so that ferric iron remains in solution. Ferric oxidation of pyrite then occurs (Eq. 2.6). As mentioned the ferric oxidation of pyrite is a fast reaction and results in an exponential increase in acid production, which is dependent upon the bacterial oxidation of ferrous iron.

Iron hydroxide (ferrihydrate) precipitates in weakly acid to alkaline conditions and has a rusty brown colour. The ageing of iron hydroxide results in the precipitation of either goethite when the oxidation of ferrous iron is slow (yellowish to brown in colour) or lepidocrocite when the oxidation of ferrous iron is fast (brown to orange in colour). The ageing of iron hydroxide at high temperatures results in the precipitation of hematite (bright red in colour). The transformation of pyrite into ferric hydroxides and oxides causes acidification and colouring of the slimes. The intensity of colour is a good guide to the extent of pyrite transformation (weathering) (Fitzpatrick & Self, 1997). Jarosite and schwertmannite precipitate when the pH < 4 and SO₄ levels > 1000 mg/l, whereas at higher pH and lower SO₄ levels crystallisation of lepidocrocite, ferrihydrite and goethite is favoured (Singh et al., 1997).

2.2.1.2 Redox reaction in tailings

The fundamental characteristic of the reduced trend of weathering is the presence of an excess of water so that the weathering profile is completely or partially submerged. This saturation leads to the lowering of the partial pressure of oxygen in the system to the degree that anaerobic conditions develop. Consequently iron is present in a reduced state, a state in which it is readily mobilised (Dixon and Weed, 1977). This mobilisation is in direct contrast to its behaviour in oxidising environments. The iron leaving the profile causes particles to lose their dark colours and acquires lighter colours tending towards grey, a process referred to as gleying. What happens next depends upon other features of the chemical environment. For example if the environment contains sulphate ions and sulphate-reducing bacteria are present, pyrite may form, or if carbonate ions dominate, siderite may form (Chesworth, 1992).

The direct effect of a lack of O₂ is that organisms relying on this gas for their metabolism can no longer survive. Thus soil fauna move away from areas that are flooded for prolonged periods, the nature of the plant community changes in favour of those tolerant to anaerobic conditions, and the microbial population changes towards those species which can survive or which prefer these conditions (Rowell, 1994). The changed microbial population is less able to decompose organic matter, and build-up of plant residues on the tailing surface begins (most notable where tailings is "leached"). Plant and microbial ecology are linked with aeration.

The microbial populations becoming active in anaerobic tailings have to respire without using O₂, a process known as anaerobic respiration. Micro-organisms can reduce organic and inorganic compounds as a means of obtaining energy, and they

make use of either organic compounds or CO₂ as a source of carbon. Central to these processes is the transfer of electrons and protons from a compound, which is being oxidized to one that is being reduced. In aerobic respiration the electrons and protons are transferred from carbohydrate to O₂ to form water, whereas in anaerobic respiration they are transferred to either organic or inorganic compounds producing a wide range of reduced materials. Oxygen is the compound most easily reduced, and in its presence anaerobic respiration does not occur. When O₂ is not present, compounds are reduced in sequence depending on their ease of reduction with more severely reduced conditions developing as time proceeds (Rowell, 1994). The severity of reduction is measured by the redox potential of the tailings.

Reduction causes important changes in tailings properties. Almost immediately after becoming anaerobic denitrification occurs with negative effects on plant growth. At about the same time various organic compounds are produced including ethylene gas and acetic acid, which can interfere with plant growth. As the tailings become more severely reduced, iron and manganese oxides and hydroxides are reduced. Reduced iron can be transported in water and precipitated as an iron cemented layer or iron pan. Eventually in very severely reduced conditions sulphate is reduced to sulphide gas, H₂S, and some precipitated as pyrite.

The overall aerobic and anaerobic respiration and reduction reactions can be summarized by the following equations (Singer and Munns, 1992, Rowell, 1994):

a) Aerobic respiration

$$C_6H_{12}O_6 + 6O_2 = 6CO_2 + 6H_2O + energy$$
 (2.7)

The transfer of electrons and protons which occurs in the overall process can be shown in two stages:

$$C_6H_{12}O_6 + 6H_2O = 6CO_2 + 24H^+ + 24e^-$$
 (2.8)

$$24H^{+} + 24e^{-} + 6O_{2} = 12 H_{2}O + \text{energy}$$
 (2.9)

The electrons are donated by glucose and accepted by O2.

b) Anaerobic respiration

Carbohydrate can only be partially oxidized in the absence of O₂. The process can be illustrated by the oxidation of glucose to pyruvic acid:

$$C_6H_{12}O_6 = 2CH_3COCOOH + 4H^+ + 4e^-$$

Only anaerobic microorganisms can link this oxidation to substances, which can be reduced.

c) The following reductions are important in tailings: Denitrification

$$2NO_3^- + 12H^+ + 10e^- = N_2 + 6H_2O$$
 (2.10)

Fermentation

$$CH_3CHO + 2H^+ + 2e^- = CH_3CH_2OH$$
 (2.11)

Iron reduction

$$Fe(OH)_3 + 3H^+ + e^- = Fe^{2+} + 3H_2O$$
 (2.12)

Manganese reduction

$$MnO_2 + 4H^+ + 2e^- = Mn^{2+} + 2H_2O$$
 (2.13)

Sulphur reduction

$$SO_4^{2-} + 8H^+ + 6e^- = S + 4H_2O$$
 (2.14)

Methane production

$$CO_2 + 8H^+ + 8e^- = CH_4 + 2H_2O$$
 (2.15)

Changes in pH caused by reduction:

If acid tailings (oxidized tailings) are flooded and then poised by the reduction of iron compounds, the pH normally rises to between 6 and 7. This can be explained by rewriting equations 2.8 and 2.12

$$C_6H_{12}O_6 + 6H_2O = 6CO_2 + 24H^{\dagger} + 24e^{\dagger}$$

24Fe(OH)₃ + 72H^{*} +24e^{*} = 24Fe²⁺ + 72H₂O

To transfer 24e' to Fe(OH)₃ an extra 48H⁺ are required above those produced by the oxidation of the glucose molecule, and are taken out of the tailings solution. The pH value therefore rises. Other reactions occur in alkaline tailings changing the pH to about the neutral point. Hesse (1971) found that the reduction in pH of calcareous waterlogged materials could be explained quantitatively for CaCO₃ – H₂O –CO₂ system as:

$$pH = 6.00-0.67logP_{co2} + 0.33log(HCO_3) - 0.33log(Ca^{2+})$$
(2.16)

Experiments showed that all soils, regardless of their initial pH value, assumed neutrality after about 15 weeks of waterlogged conditions. Thus the pH of all waterlogged tailings tends to move towards neutrality (see also figure 2.2). The redox potential and pH should be determined to measure the severity of reduction in tailings.

Freshly deposited gold tailings that dry out (drainage and evaporation) are in an alkaline trend but as oxidation progresses the trend becomes acid.

2.2.2 Percolating (drainage or leaching)

Percolating (or leaching) water results when rainfall over a given period is higher than the potential evaporation over that period causing a net downward movement of water. The actual infiltration into the tailings depends on the intensity of the rain, water storage capacity of the tailings, permeability of the tailings, and steepness of the slope. A widely used approach to calculate the depth (z) to which a wetting front will penetrate into a slope in time (t) is that originally proposed by Lumb (1975),

$$z = Kt$$

$$n(\theta_f - \theta_i)$$
(2.17)

where K is the saturated hydraulic conductivity, n is the porosity and θ_f and θ_i are the final and initial degrees of saturation respectively. The downward movement of water can remove various substances from higher layers in the tailings and transport them to lower layers, or eliminate them from the tailings by drainage (leaching). Components within the tailings vary in solubility and mobility by water, and can in general be grouped in the following order (Schroeder, 1984):

- Salts more soluble than gypsum (NaCl, Na₂SO₄, MgSO₄, etc.)
- CaSO₄
- CaCO₃ (if pH is higher than 7 the solubility of lime is very low but the solubility increases as the pH drops below 7)
- · Adsorbed cations on colloids (Na, K, Ca, Mg)
- SiO₂
- Fe₂O₃, Al₂O₃, and clay

Naturally the more soluble a substance is, the easier it is leached out of the profile, or deeper into the tailings where they accumulate. Sesquioxides and clay are very difficult to leach, except by special processes.

The leaching method for establishing vegetation on gold tailings dams was developed in the 1960s and is the only methodology with a proven long-term track record. It has been shown that the downward movement of the acid zone in coarse tailings by leaching generally takes place at the rate of 4 to 5 cm per day (James and Mrost, 1965). Observations confirmed that the zone of high acidity could be moved to a depth sufficient to sustain plant growth. Leaching usually takes place without disturbing the surface of the tailings much to limit the risk of storm damage (Cook, 1985).

2.2.3. Ascending water

Ascending water results when the rainfall over a given period is less than the potential evaporation over that period. In the absence of vegetation, and when the surface is subject to solar radiation and wind effects, evaporation occurs entirely from the tailings. Evaporation of water from the tailings not only dries the tailings but salts can accumulate in the surface layer of the tailings.

Salts dissolved in solution are normally measured by preparing a saturated extract. The total salinity of this solution is determined by measuring the electrical conductivity (EC). For a range of mixed salt solutions, the approximate relationship between concentration and EC at 25 °C is:

The concentration of cations or anions

$$(mmol_c) \cong 0.1 \text{xEC } (mS \text{ m}^{-1})$$
 (2.18)

The simplest classification of salt-affected material is based on EC:

Saline materials EC>400 mS m⁻¹ Non-saline materials EC<400 mS m⁻¹

Richards (1954) generalized plant susceptibility to soluble salt as follows:

EC (mS m ⁻¹)	Plant susceptibility
0 - 200	Salinity effects negligible
200 - 400	Very sensitive crops affected
400 - 800	Most crops affected
800 - 1600	Only salt-tolerant crops yield satisfactorily
> 1600	Very few salt-tolerant crops yield satisfactorily

According to Fitter and Hay (1987) there are three main effects of salinity on plant growth:

- 1. Direct toxicities e.g. sodium, chlorine, boron
- Ionic imbalances in the plant
- A reduction in the availability of water by lowering the osmotic potential. The change in water potential caused by salts can be calculated as follows:

Osmotic potential (kPa)
$$\cong$$
 -0.4xEC (mS m⁻¹) (2.19)

According to Maas and Hoffman (1977), salinity damage is most prevalent during germination and in the early stages of growth. Although the pH of fresh tailings varies between neutral to alkaline it is very difficult to establish vegetation mainly because of the high salt concentrations (van der Nest, 1994).

To leach salts out of the root zone or to maintain acceptable salinity extra water is needed which, expressed as a fraction of the total water use, is known as the leaching fraction, abbreviated LF and express as:

$$LF = D_{dw}/D_{iw}$$

The depth ratio is also equal to the ratio of the EC of the irrigation water to the EC of the drainage water, therefore:

$$LF = D_{dw}/D_{iw} = EC_{iw}/EC_{dw}$$
(2.20)

If EC_{iw} is known and a limit is set for EC_{dw} , then the leaching fraction is also a leaching requirement, LR, and can be calculated using equation 2.20. The choice of the limit for EC_{dw} is based on crop tolerance data (Ayers and Westcot, 1985).

2.2.4. Runoff

Whenever the rate of water applied to the tailings surface exceeds the infiltration rate of the tailings, free water tends to accumulate on the surface. Depressional storage is defined as the water, which collects in the depressions when the application rate exceeds the infiltration capacity of the tailings (Onstad, 1984). Only when the

depressional storage is filled can runoff begin. Runoff thus represents the portion of water supplied to the surface, which neither is absorbed by the tailings nor accumulates on the surface but runs down slope and eventually collects in channels.

Runoff is generally undesirable since it results in loss of water and often causes erosion, the amount of which increases with increasing rate and velocity of runoff (Williams and Berndt, 1977). According to a study done by Blight (1991) on gold tailings in South Africa, it was concluded that erosion losses resulting from rainfall and wind are roughly estimated to be of the order of 500 t.ha⁻¹.a⁻¹. It was also concluded that most of the erosion occurred from the slopes of a tailings dam, and very little from the upper-most surface. According to Blight (1991), erosion losses are roughly proportional to slope length and relatively little occurs from slopes flatter than 20° or steeper than 40° on gold tailings dams. Blight (1991) found that erosion losses reach a maximum for slope angles between 25° and 35°.

The way to prevent erosion is to protect the tailings surface against raindrop splash, to increase the tailings infiltration capacity and surface storage, and to obstruct overland flow so as to prevent it from gathering velocity (Renard *et al.* 1991, Dvorak and Novak, 1994). The Chamber of Mines has used an instrument known as the COMET (Chamber of Mines Erosion Tester) to test the erodibility of tailings and then, on the basis of erodibilty determined, different erosion control strategies have been recommended (the COMET method was later discredited and withdrawn, Dawson, 2002).

2.2.5. Water stagnation (waterlogged)

It is as well to be quite clear what is meant by waterlogged tailings. In unsaturated tailings the fine pores may or may not contain water, depending on the water content, and the large pores are filled with air. When both fine and large pores are completely filled with water the tailings are waterlogged. Even so, there are several different kinds of waterlogged tailings:

- Tailings permanently submerged under water (tailings below the phreatic waterline and tailings under the decant pond around the penstock)
- Tailings periodically waterlogged by submergence (as fresh slurry is deposited)
- · Tailings periodically and artificially waterlogged by irrigation.

The chemical properties of waterlogged tailings depend mainly upon the fact that they are oxygen deficient and were discussed under redox reactions (2.2.1.2).

2.2.6. Water seepage

The stability of a tailings dam depends on the interplay between the forces which tend to produce failure by inducing large movements along some set of critical surfaces, and the strength of the tailings which resists such movements (Perloff and Baron, 1976). The shearing resistance along potential failure surfaces is, in part, determined by the effective stresses on these surfaces. Thus, seepage affects the stability of tailings dams in two ways:

 The pore water pressure in the flow region changes the effective stresses on the potential failure surfaces from those for the static ground water condition. The seepage forces are body forces. Hence, when they act in a direction that tends to produce failure, the stability of a tailings dam is adversely affected. Seepage forces may cause a sloughing-in of the tailings dam if flow of water occurs through the toe of a tailings dam.

The tailings dam must be stable in all of its physical aspects. The primary consideration is the factor of safety of the impoundment walls against failure. Water table measurements can be used to determine what is happening to the phreatic surface and whether it is likely to threaten the stability of the slopes. It may be necessary to implement additional drainage networks and stabilising buttresses in order to achieve acceptable factors of safety (Chamber of Mines, 1983).

During periods of prolonged rainfall, otherwise stable slopes have been observed to fail in a fashion that has become known a "surficial sloughing". This applies to both natural slopes and man-made slopes such as tailings dams (van Schalkwyk and Thomas, 1991, and Crabb and Atkinson, 1991). In the case of the Merriespruit tailings dam failure, although there was some conjecture that the liquefaction failure could have been triggered by an initial surficial failure caused by saturation of the outer slope by over-irrigation (Fourie et al, 1997) overtopping was the basic cause. An approximate method as well as a numerical method was developed by Fourie et al (1997) to evaluate the effect of rainfall (irrigation) on the stability of man made-slopes.

2.3 Environmental hazards of tailings linked to water

The most serious environmental hazards of tailings dams associated with water can be summarized as follows:

2.3.1 Acid mine drainage (AMD)

Acid mine drainage (AMD) is, arguably, the most scrious and widespread threat posed to the environment by mining and mineral processing. AMD arises when sulphides contained in the ore or wastes are exposed to oxidation and the products are flushed by water. As the pH of the system drops, the oxidation reaction become catalysed by bacteria, and the rate of oxidation can increase by 2 to 3 orders of magnitude. A variety of metals can be mobilised under low pH conditions (Rosner, et al. 2001).

The potential of acid mine drainage depends on; the amount of sulphide minerals, the depth of the oxidation zone within the tailings, the amounts of alkaline minerals within the tailings, and the rate of seepage from the tailings impoundment. In most cases the initial risk of AMD is through contamination of surface run-off. The acidification of water bodies in the then Transvaal due to AMD was reported by Harrisson, (1958), and metal contamination by van der Merwe et al., (1990), and Wittmann et al., 1977.

Alternative treatments for AMD (Williams, 2000 and DME 1995b) include:

- Submerging potential acid forming mine waste below water
- Deep burial
- Soil covers

- Alkaline buffering
- Biological polishing in wetlands
- Remove reactive sulphide
- Control bacterial action

2.3.2 Salinity

Apart from AMD, the major water quality issues with mine water are salinity and suspended load. Salinity resulted from the neutralisation of acids, mineral processing, and evaporation of stored water. Mine site salinity can be reduced through minimising the evaporative area of stored water, discharging surplus water where possible and vegetating the side slopes.

2.3.3 Erosion and sedimentation

Natural erosion rates and soil formation rates are from 0.01 to 0.11 mm/year (Reid, 1994) but for tailings dams the erosion rate can be as high as 35mm/year if the numbers given by (Blight, 1991) are converted. Where the erosion products flow offsite it results in the sedimentation of watercourses and pollution of neighbouring soils. The suspended load from tailings dams can be reduced through establishing a vegetative cover and/or rock armouring or rock-cladding the slopes. The only way to prevent sedimentation of watercourses, and pollution of soils, is to catch the runoff in paddocks (the paddocks must be designed to cater for a 1:100 year flood, Chamber of Mines, 1983).

2.3.4 Cyanide

Cyanide is used in the extraction of fine-grained gold attached to crushed and ground ore. To prevent cyanide gas from being emitted it must be used under high pH (about 12) conditions and therefore the initial pH of the tailings when deposited is alkaline. The cyanide dissolves the gold to form a gold cyanide solution, which is collected on activated carbon, and the gold is then recovered by electrolysis. Where excessive cyanide is applied, usually due to the presence of other metals high cyanide levels can pass to the tailings storage, where lower pH can result in cyanide gas emissions. According to Lotz (2001) the rational hazard of cyanide being present in South African tailings structures is likely to be small.

2.3.5. Air pollution

An almost universal problem associated with unrehabilitated tailings is blowing dust. Methods of dust abatement include suppressants such as bitumen or paper mulches, rock mulching, irrigation, vegetative ground cover, and windbreaks (Ward, 1987). In the 1950's, a concerted effort was directed at the identification of the best means of controlling dust pollution on tailings dams in the Witwatersrand area. Surfacing with rock did not work due to piping of the underlying tailings. The results obtained from numerous trials led to the conclusion that grassing was by far the most effective means (Grange, 1973, Wells, 1987). Hence grassing is generally the only option considered today. Vegetating tailings is made difficult by the acids and salts within the tailings and wind induced sandblasting effect on seedlings. Sandblasting can destroy the total grassing effort on a tailings dam (van der Nest, 1994). Dust control

of the top surface of a tailings dam, when not yet vegetated, is commonly done by ridge ploughing the surface. A series of ridges is ploughed up running at right angles to the direction of the prevailing wind. Any measure capable of destroying the wind's kinetic energy will be effective to protect the surface against wind erosion.

Vegetating tailings dams has a number of advantages:

- Vegetated tailings dams are more aesthetically pleasing
- A good vegetative cover dramatically reduces the potential for surface erosion
- A vegetative surface dramatically increase infiltration, making the vegetation more self-sustaining, and reduces runoff and any sediments and contaminants it may carry
- A vegetated surface will better support native fauna and insects
- A vegetated surface creates a foundation for the establishment of biodiversity.

Because the establishment of vegetation on gold tailings can suppress or control some of the environmental hazards associated with tailings, vegetating had become the norm in the rehabilitation of gold tailings dams. The role of water in the establishment of vegetation (in terms of water balance) will only be very briefly discussed because models such as ACRU revolves around soil water budgeting and a good literature review of all the components of the water budget is given by Schulze (1995).

2.4 Water balance for a tailings dam

Because all water that falls within the catchment area of the residue deposit is polluted, it is necessary to operate a tailings dam as a closed system from which water is not released. It is therefore essential to do a water balance calculation for each subcatchment of a tailings dam complex to check that the design will ensure that the closed system can be maintained. The water balance is stated as follows:

Water surplus = Water input – Water stored – Water losses

For the operating phase of a tailings dam the water input would consist of:

- Water contained in the feed from the tailings delivery line
- Rainfall on the surface of the dam, and in the catchment of the return water reservoir
- · Other water deposition
 - Excess water pumped from underground
 - Disposing of contaminated stormwater or other effluent
 - Recycling excess water from return water dam to evaporate

The water losses would consist of:

- The discharge from the penstock to the return water dam
- The seepage into the underdrainage system
- Seepage losses into the foundation of the dam and return water dam that are irrecoverable
- · Evaporation from the surface area of the dam and return water dam
- · Spillage and overflows

The water stored would consist of:

- Water stored in the return water dam and catchment paddocks
- Water retained in the pores of the tailings

- · Water contained on top of the dam
- Water retained in the drainage system

Over any interval of time during the life of the dam, the change in storage will equal the inflow minus the losses while the integral of the changes in storage may be used to calculate water levels at any time. At no time may the calculated water level encroach on the minimum freeboard.

2.4.1 Availability of water in tailings

The growth of vegetation on tailings dams is broadly controlled by climate primarily through constraints due to temperature, rainfall, and exposure to wind. In a given climatic region, tailings adds further constraints through 1) texture and structure which together influence both the amount of water which can be held in the profile and the ease with which roots can penetrate and 2) the tailings chemistry (pH, EC, nutrients). These factors together determine the fertility of the tailings.

2.4.1.1 The water cycle

The tailings profile lies at the heart of the hydrological cycle, shown in figure 2.4, and can be regarded as a bank account with additions and removals controlling the balance which in this case is the amount of water stored in the tailings profile.

The balance sheet has the following components:

 Rain (or irrigation) delivers water to the tailings surface. Not all the water will, however, necessarily enter the tailings. Some remains on vegetation and is lost by evaporation and if the rate of supply exceeds the ability of the tailings to absorb water, it will run off the tailings surface possibly causing erosion or even spillages. Pradel and Raad (1993) extend the infiltration model of Green and Ampt (1911) to show that the time (T) necessary to saturate the soil to depth (z) is:

$$T = \{(\theta_s - \theta_i)/K\}[z - \psi_m \ln\{(\psi_m + z)/\psi_m\}\}]$$
 (2.21)

Where θ_s and θ_i are the saturated and in-situ volumetric water content—respectively, K is the hydraulic conductivity of the material in the wetted zone, and ψ_m is the wetting-front matric suction. The infiltration rate (v) at which water enters the soil surface is:

$$v = K[(z + \psi_m)/z]$$
 (2.22)

- After periods of heavy rain (or continued irrigation) the ability of the tailings to hold water may be exceeded and drainage will occur (drainage is defined as the water that moved beyond the root zone). Throughput of water will leach salts and acids from the tailings (James and Mrost, 1965).
- The water held in the profile (root zone) is the reservoir supplying the water evaporating from the tailings surface and maintains the water supply to plants between rain or irrigation events. In dry conditions the extraction of water by plants becomes limited by the supply from the tailings, with resultant water

- stress. The rate of evaporation from the tailings surface is also controlled by the dryness of the tailings.
- Upward movement of water into a profile will occur if moist tailings occur below dry tailings. Salt build up can then occur (Williams, 2000).

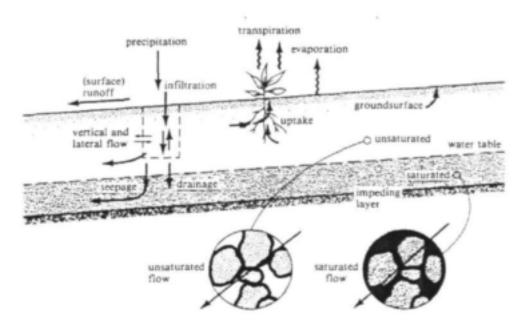


Figure 2.4. Some terms applied to modes of water flow in the soil-plant-atmosphere continuum (from Singer and Munns, 1992).

Short term imbalances between gains and losses of water by a profile results in a net change in water content. The tailings have an upper limit to the amount of water they can hold, known as field capacity (or drained upper limit). There tends to be a lower limit to the amount of water held in the profile known as the permanent wilting point, which is the limit in terms of plant uptake, although evaporation from the tailings surface can reduce the water content further. Thus, in tailings covered by vegetation the water content fluctuates in the short term between field capacity and the permanent wilting point. The storage pores of tailings is between 0.05 and 0.15 cm³ cm⁻³ of slimes, and so in a 1 m deep profile this fluctuation is equivalent to between 50 and 150 mm of rain.

2.4.1.2 Water efficiency

Water is used most efficiently when the most advantage is gained from the least amount of water. Efficiency based on available water takes into account losses through runoff, seepage, drainage, and evaporation. The general water balance equation can be written as follows (Manning, 1987):

T =
$$(P + I + \Delta S) - (R + Es + D)$$
 (2.23)
Water for yield water gains – water losses

Where T is the transpiration (or, evaporation from the crop Ev) (mm), P the precipitation (mm), I the amount of irrigation (mm), ΔS is water extracted from the root zone (mm), R the runoff (mm), Es the evaporation from the slimes surface (mm), and D deep drainage/seepage (mm).

It is not possible to prevent these losses completely, nor is it always desirable. For example, occasional leaching is needed to control salt. However, runoff and seepage from a tailings dam become a hazard elsewhere by raising water tables and enhancing salt accumulation. Transpiration tends to increase proportionately with growth, but direct evaporation, runoff, seepage, and drainage, do not. In fact they tend to decrease. Improved plant cover shades the tailings, thereby reducing evaporation and plants on the surface may reduce runoff (Singer and Munns, 1992).

Water use efficiency (WUE) is defined as (Tanner and Sinclair, 1983):

$$WUE = Y/T$$
 kg mm⁻¹ ha⁻¹ (2.24)

Where Y is the yield (kg ha-1), and T transpiration (mm).

2.4.1.3 Water extraction by plant roots

Roots play an important role in the survival and productive potential of plants by providing anchorage for the plant, as well as being involved in the uptake of water and nutrients needed for growth and development (Simons and Ezell, 1982). Water supply to the plant canopy is controlled largely by the depth and density of rooting (Gardner, 1960; Taylor and Klepper, 1978). In the hydrological context, the most important function of roots is that of water uptake.

Extending root systems develop a distribution such that the maximum concentration of roots, initially near the soil surface, moves continually down the profile. As evaporation and root extraction deplete the upper soil layers of their moisture, roots tend to grow preferentially into the profile so that the "centre of gravity" (Hillel and Talpaz, 1976) of the extraction process moves progressively downward (Wild, 1988). According to Ruark et al., (1982) numerous investigators report that 60 – 80% of the root volume is to be found in the top 200 mm of soil. This is especially true for fine roots. The more uniformly distributed a root system is in the vertical plane, the more efficient it is at extracting water from the soil profile (Meyer et al., 1990).

According to Arya et al., (1975) water is first extracted from the surface wet layers where the rooting distribution is most dense, and only once the surface layers have become depleted, is the transpiration demand met by the more sparsely rooted, but moist, lower soil layers. It should be noted that it is not the actual water potential that is important in the uptake of water by roots, but the difference in water potential between the soil and the roots (McGowan and Tzimas, 1985). It is always important to bear in mind that roots grow to where the water is, water does not "search" for roots (Meyer et al. 1990). According to Wiersum (1981) the total root surface area per unit field area is in the same order of magnitude as the Leaf Area Index (LAI) indicating that the flux of transpiration water through the plant needs about the same surface area for entrance as for exit.

Root distribution is controlled largely by the genes within the plant and to some extent by the soil type. Grasses develop a mat of fibrous roots, with little modification, and usually penetrate less than 1m into the soil (Throughton, 1957). Each plant has two root systems. Seminal roots arise from the germinating embryo, and are very soon replaced by the nodal system that arises from the culms. Individual nodal roots may last one to several years. The root hairs of grasses are often long persistent, in contrast to most other plants in which they are short lived (Metcalfe, 1960).

According to Borg and Grimes (1986) root development is inhibited severely by factors such as high soil bulk density, a high water table, low soil fertility, and low pH. According to Doornbos and Pruit (1977) the rooting depth of grass is between 0.5 m and 0.7 m and the readily available fraction of available water for grass is 0.45.

2.5 Methods to vegetate gold tailings

The main objective with the establishment of vegetation on tailings is to obtain a selfsustaining plant community that is dynamic and able to change as the rehabilitated site ages and matures. The suitability of tailings as a rooting medium depends on its physical properties (available water, aeration, temperature, etc.), chemical properties, (supply of nutrients, pH, buffer capacity, etc.) and organic matter content. Problems that can be associated with tailings, include (van der Nest, 1994):

- · Deficiency in available nutrients,
- · An acid generating potential,
- High salt content,
- Heavy metal toxicity,
- A low water retention capacity,
- Poor aeration properties, and
- Very low buffer capacity (low exchange capacity).

This low fertility makes tailings a hostile environment for vegetation establishment. The following methods have been developed to overcome largely the chemical problems of tailings (acidity, salinity and nutrient deficiency).

2.5.1 Leaching

The leaching method was developed in the 1960's and is still in use today in modified form. The basic philosophy behind the method is that the high acid and salt content of oxidized tailings, limiting the establishment of vegetation, can be leached beyond the rooting zone. The leaching is done by the application of a fine mist of water to the surface by means of micro-jets fitted to an irrigation system. The duration of leaching is from 9 to 15 months. This should be followed by a maintenance programme of about 5 years duration. Leaching is normally done only on the side slopes and the so-called "no cultivation method" was developed where leaching takes place without disturbing the oxidised surface of the tailings to limit the risk of storm damage (Cook, 1987).

The "no cultivation" method of establishing vegetation on side slopes proceeds as follows (Cook, 1987):

- Leaching equipment is erected.
- Bales of mulch, or orange bags in which a mixture of stoloniferous grass roots
 has been grown in soil, are placed across the bases of erosion gullies at
 frequent intervals to prevent further erosion until the vegetation is established
- Agricultural lime at 7.5 tons/ha and super phosphate at 300 kg/ha is broadcast by hand over the area
- A mulch of veld grass, preferably cut in an area where a variety of grasses (particular Hyparrhenia hirta) grow, is spread at a rate of 200 bales/ha (if the pH of the tailings is below 3 the mulch is spread at a rate of 400 bales/ha).
- Leaching is started. Water is sprayed onto the surface of the tailings from the micro jets at a rate that is just below the optimum rate of infiltration into the tailings
- Hand planted subjects are planted (Table 2.1)

Table 2.1 Hand Planted Species

Name	Common name	Number of plants/ha	
Cynodon aethiopicus	Star grass	1400	
Cortaderia selloana	Pampas grass	350	
Pennisetum macrorum	Hippo grass	350	
Pennisetum clandestinum	Kikuyu	700	
Populus canescens	Popular	175	
Carpobrotus edulis	Hottentot fig	80	
Coronilla varia	Crown vetch	100	

- The seedmix is prepared for sowing and sown. Legume seeds are inoculated, all the seeds are mixed together and lime (100 kg) is used as a distribution and germination aid. The following seed mix is used (Table 2.2)
- Four days later 2:3:2 (22) fertiliser is applied at 300 kg/ha and repeated when the seedlings reach the 3 rd leaf stage, about three weeks after sowing
- Leaching continues until a good grass cover has been established and then a "toughening-up" process starts during which the application of water is decreased gradually. After no leaching has taken place for a period of at least two months, the leaching pipes are removed if no severe stress signs are apparent in the vegetation.

The maintenance programme must be suited to the species and its habitat, for instance, grass demands cutting and if not possible, controlled burning at the appropriate season together with requisite treatment after the reappearance of the green shoots, such as fertilising and liming. Selective fertiliser application to stoloniferous varieties only is preferred to reduce excessive moribund and a heavy canopy-type cover. Other forms of after care include the treatment of patches of dead vegetation, bare soil unreceptive of plants, and eroded sites by conservation or anti-erosion measures (Chamber of Mines, 1979).

Remark: The general guide of water needed for the leaching method is based on 5mm water per day during the leaching period of 9 to 15 months. The water needed range thus between 1350 mm and 2250 mm (Cook, 2002).

Table 2.2 Species used in the seed mix

Name	Common name	Kg/ha
Cynodon dactylon	Kweek	2.5
Eragrostis curvula	Weeping love grass	1.25
Dactylis glomerata	Rough Cocksfoot	2.5
Chloris gayana	Rhodes grass	2.5
Festuca elatior var. arundinacea	Fescue type 31	2.5
Agrostis tenuis	Colonial bent grass	2.25
Poa pratensis	Kentucky blue grass	1.25
Lolium perenne	Perennial rye grass	1.25
Bromus catharticus	Smooth broom	1.25
Atriplex semiboccata	Creeping salt bush	1.0
Trifolium repens	White clover	1.25
Medicago sativa	Lucerne	1.25
Melilutus alba	Sweet clover	1.25
Brassica napus	Rape	0.25

2.5.2 Chemical amelioration (Liming)

The chemical amelioration method focussed on the amelioration of the tailings and addresses the problematic properties of the material, rather than emphasising the selection of plant species. The basic philosophy behind the chemical amelioration method is that the active as well as the potential acidity of gold tailings can be neutralised by lime thus eliminating the need for leaching. The basic principles of the approach are (van der Nest, 1994):

- Firstly, a detailed geo-chemical analysis of the tailings is conducted in order to determine the exact quantities of lime and fertiliser to be applied.
- The correct type and amount of lime is then incorporated into the material before the establishment of vegetation. The lime requirement is determined by taking the active and potential acidity into account, by means of acid-base accounting methods. This ensures that the pH does not drop below 6 to 6.5, being the optimum pH level for plant growth. The incorporation of lime to a sufficient depth is critical, as lime is relatively immobile in gold tailings, which is further detrimentally affected by the relatively poor solubility of agricultural lime.
- Before seeding, organic matter is incorporated into the top 300 mm of the tailings material in order to facilitate cation exchange of plant nutrients, and to enhance the physical properties of the tailings for optimum vegetation growth. The large amounts of organic matter incorporated into the tailings, also stabilise the loose material against storm damage.
- A temporary irrigation system is erected, in order to supply the seedlings with sufficient amounts of water. The application of water on a controlled basis will also eliminate various other factors viz: quick consolidation of tailings material after incorporation of lime, enhancement of chemical reaction of the incorporated lime, elimination of the formation of crusts on the surface and the abrasion effect of particles on young seedlings, and lowering the salinity concentrations which is detrimental during germination and in early stages of

- seedling growth. Leaching of active acidity also takes place during the initial stages of vegetation establishment due to the application of water as a fine mist (this was confirmed by Beukes, 1998).
- A mother crop (usually wheat) is used before the establishment of indigenous climax species, which requires optimum conditions for germination. The advantages of the use of a mother crop include the quick stabilisation of the loose material on the side slope, which is vulnerable to crosion and therefore unstable. The mother crop also supplies large amounts of organic matter to the inert quartz material. The establishment of a mother crop also has the advantage of a shading effect on young grass seedlings, which are relative sensitive to excessive heat.

Remark: The general guide of water needed to establish vegetation under irrigation for the chemical amelioration method is 3 mm per day for a period of 6 to 9 months. The water needed range thus between 540 mm to 810 mm.

2.5.3 Revised leaching

The revised leaching method is the same as the leaching method except for the way lime is applied to the tailings. To prevent lime from washing down the slope when broadcasted as for the leaching method, small trenches, approximately 150mm deep and 300mm apart are dug parallel to the contour of the slope and filled with lime prior to the leaching programme. The trenches are preferred above working the lime into the tailings, as for the chemical amelioration method, to reduce erosion risks.

2.5.4 Minimum cultivation with topsoil

This method is the same as the leaching method except once again the way in which lime is applied. For this method the lime is mixed with topsoil and this amended topsoil is then applied to a depth of 50mm on the tailings surface and worked into the tailings to a shallow depth during the seeding and fertiliser programme. Thereafter a leaching programme is followed. Topsoil is used to improve the physical and chemical conditions of the seedbed.

2.5.5 Elementary amelioration

This method was applied on tailings that are favourable for vegetation establishment. For these tailings it was found that the lime treatment used for the leaching method was more than enough to neutralise the acids present and that there was no need for leaching. The surface preparation and seed mixture are as for the leaching method. Lime and super phosphate are lightly worked into the tailings prior to seeding. After seeding an intensive fertiliser programme is followed for the first 10 weeks after germination. The amount of water needed to establish vegetation is as for the chemical amelioration method.

2.5.6 Alternative methods

Alternative methods include the development of more acid tolerant species and/or methods to establish natural veld species (ecotypes) on the tailings dams (Dawson, 1985, Morrey 1992, and Weiersbye & Witkowski, 1998). Slope flattening, to modify

erosion forces, to improve cultivation methods, and to work towards lower maintenance cost is a relatively new rehabilitation method (although propagated for a long time [Chamber of Mines, 1983]) for gold tailings dams (Theunissen & van Deventer, 2001).

2.6 The sustainability of rehabilitation methods

Weiersbye and Witkowski (1998) undertook a study of tailings dams in three gold mine regions, Carltonville, Klerksdorp and Welkom, assessing 56 tailings dams in total. Altogether 196 aspects, comprising 738 sites were assessed for total cover and plant growth form composition. In addition, 254 intensive 100m surveys were undertaken. The ages of slimes on the sites surveyed spanned the range from recent to 58 years old. The main findings of the study were:

- Generally, within 7 years, aerial cover upon vegetated slopes has declined to <10% of the original cover. The oxidation status of the slopes at the time of vegetation, and the methods used had little effect on the persistence of the introduced cover.
- The steep gradient of the slopes together with the prevailing chemical conditions of the tailings contribute heavily to the decline in introduced cover
- Species diversity of vegetated sites was initially low, and declined rapidly with age (<5 species by 4 years) and the persistence of introduced vegetation (primarily grasses) on tailings was low (<6 years)
- The species used for vegetation purposes were predominantly shallow-rooting pasture grasses and herbaceous weeds, which require high nutrient and water inputs. The species were largely intolerant of untreated tailings and failed to propagate (i.e. duration of cover is limited to the lifetime of an individual)
- The existing vegetation strategies and the existing suite of species used were therefore unsustainable, environmentally and economically unsound.

Their final conclusion was that the current tailings amendment regime (leaching, high lime, fertiliser and water inputs) would inhibit, rather than promote the growth of tailings tolerant species. They proposed that more restrained amendment practices, which encourage the development, rather than the inhibition, of tailings-tolerant flora, must be utilized.

2.7 What is a self-sustaining plant community?

An ecosystem refers to the number of organisms and their interactions, both with each other and with their non-living environment (Ryke, 1972). The interactions can involve transfer of matter or energy, or simply behavioural interaction. In practice, terrestrial ecologist deal with much more finite entities, which are usually based on plant communities. The term plant community is used very generally and can be applied to vegetation types of any size or longevity (Barbour et al, 1987). A vegetated tailings dam can be referred to as a community.

The term biodiversity is used when we want to describe the variance within the community (Barbour et al, 1987) and the following terms apply:

Species richness- The number of species in the same area within a community

- Species evenness- This refers to the distribution of individuals among the species
- Species diversity- Species diversity is species richness expressed in terms of species evenness.

Constancy refers to the degree of variation of ecosystem variables about their mean values. Stability is the tendency of ecosystem variables to return to their previous values if altered by a stress and is a complex term that consists of distinctly different qualities (Barbour et al. 1987):

- Resistance-The ability of a community to remain unchanged during a period of stress
- Resilience- The ability of a community to return to normal following a period of stress or disturbance
- Variance- The ability to exhibit patches of variable abundance in some of the component species
- · Persistence- The ability to remain relatively unchanged over time.

In nature different species of plants have different functions with regard to their role in colonizing an area. The first plants to colonize an area are called pioneer species, which are usually herbaceous, fast growing, annuals that change the environment to the extent that it's favourable for the germination and growth of longer living species (Barbour et al, 1987). After a time period other species of plants start to colonize the area and the pioneer species start to dwindle in numbers and after a long period of time a climax community appears (Barbour et al, 1987). The final species composition differs vastly from the original species composition and this process of changing from a pioneer community through to a climax community is called succession (Barbour et al, 1987). In the long term, vegetative rehabilitation of mining wastes aims at, as far as possible, the proper ecological integration of the reclaimed area into the surrounding landscape, which is sustainable and requires minimal maintenance (van der Nest, 1994). A certain succession pattern is therefore needed. Recent ecological concepts recognize the role of the substrate and nutrients in affecting the rates and directions of succession patterns. Nutrient additions can prolong site occupancy by some species and favour the presence of some over others (Bush and Van Auken, 1986). Cause and effect relationships among individual plant species and soil development are often difficult to demonstrate (Bush and Van Auken, 1986), although investigators commonly credit some plant species as being "soil builders" or "site degraders" (Miles, 1985). Soil formation processes and the effects of succession on soil development and vice versa in tailings are not well known.

The following generalizations can be made about ecosystem behaviour (Nunney, 1980, Connel and Sousa, 1983)

- Multiple, locally stable states separated by transition thresholds are much more likely than global stability
- · Directional change is more likely to be jumpy than smooth
- Constancy relates mostly to the strength and variability of external driving forces

- Stability is more likely to be encountered at large spatial scales than small, very short or very long rather than intermediate time scales, and at high integrative levels than low
- Resilience is enhanced by previous exposure to stress of the same kind and magnitude, conversely resilience to totally novel stresses is unlikely
- · Environmental patchiness favours the persistence of particular organisms, and
- There is no simple relationship between diversity and interconnectivity on the one hand and constancy, stability and resilience on the other.

Grasses dominate in the rehabilitation industry and these grasses are typically called climax grasses due to their role in natural communities. The fact that we don't know what a real climax community (succession speaking) on a tailings dam looks like, makes the expression "climax grasses" a bit erroneous. Due to the harsh edaphic conditions of the tailings material and the difference between the tailings dam environment (slope, aspect etc) and the surrounding environment (natural veld, or cultivated land or urbanised land), a climax community on a tailings dam could look totally different from the climax community of the surrounding environment. Although restoration ecology has as a primary goal the re-establishment of the plant and animal communities native to the area, few long-term studies are available to indicate if this is a realistic goal (Jordan, et al, 1987). Ideally species selection should be based on (Bradshaw & Chadwick, 1980):

- Ecological and environmental constraints
- Native species, and
- Proposed land use.

Most grasses are herbaceous. They flourish during favourable periods of the year, completing their annual growth and reproduction while the weather is warm and wet, and dying back in cold or dry seasons (Theunissen, 1996). Perennials negotiate unfavourable periods as dormant rootstocks or rhizomes, and annuals survive as seed.

In the most widespread form of photosynthesis in higher plants, primary assimilation of CO₂ from the atmosphere, as well as photosynthetic reduction of carbon, both occur in all the chlorophyll-bearing cells of the leaf mesophyll (Salisbury and Ross, 1985). This is called the C₃-pathway, because CO₂ being initially fixed as three-carbon chains. The other principal form of higher plant photosynthesis takes place by the C₄-pathway, in which the CO₂ is fixed initially into four-carbon chains (Salisbury and Ross, 1985). Both the C₃ and C₄ pathways of photosynthesis are found within the Poaceae. Grass species with the C₄-pathway have a much higher rate of CO₂ uptake than those in which it is absent and because it operates most efficiently in high temperatures and high light intensity, it occurs widely in tropical and sub-tropical grasses, often associated with drier or saline habitats. Temperate grasses (northern hemisphere, or elsewhere only at high altitude and moist habitats) gain no advantage from this additional pathway so they retain the C₃-pathway alone (Theunissen, 1996).

According to van Wyk (1995) a good and healthy grass cover implies the following:

 Providing a more or less complete ground cover preferably with no open spaces that exceeds 0.5 m² after one to two growing seasons

- A grass cover consisting of several healthy growing species representing at least 70% perennial species from the second season onwards
- A grass cover in which creepers dominate on the side slopes and along water courses (high erosion risk areas)
- · A grass cover which can regenerate itself from seed, or vegetatively
- · A grass cover that can combat erosion and dust pollution, effectively
- · A grass cover that is not permanently damage by fire

2.8 Nutrient cycles

There are sixteen different elements known to be essential for the growth and development of plants. Plant communities differ in their utilization of nutrients and the rate at which the nutrients are returned to the soil. Early successional communities accumulate very small amounts of nutrients in their tissues but return nutrients rapidly to the soil. Climax communities, in turn, may require larger quantities of certain nutrients and store these nutrients in their tissue, returning limited amounts to the soil. Climax communities in general have fewer leaks in nutrient cycles and more efficiently hold the nutrients in the plant-soil-plant cycle (Elliot et al. 1994).

The amounts of organic material in soils depend on the annual input of organic matter and the rate of decomposition (Schlesinger, 1991). For vegetated tailings dams the most important source of organic residues are from the established vegetation. Climate is a major factor influencing the rate of decomposition. Clay is considered to stabilize organic matter by protecting it both physically and chemically. Chemical protection results from adsorption on to clay surfaces such that bacteria cannot utilize it (Rowell, 1994). Because of the low clay content of tailings it would not be possible to raise organic material to high levels. The final substrate conditions, including organic matter levels and forms and stability of N reserves are a function of climate and parent materials as well as vegetation (Keever, 1983). The ratios of elements in decomposed organic matter are approximately constant. For soils in temperate regions the ratio of C:N is close to 10:1, that of C:P close to 50:1 and that of C:S close to 100:1 (Rowell, 1994).

2.9 Sustainable land management

The main objective with the establishment of vegetation on gold tailings is to obtain a self-sustaining plant community that is dynamic and able to change as the rehabilitated site ages and matures. The negative physical and chemical characteristics of gold tailings make it a difficult substrate to ameliorate in order to establish a sustainable vegetative cover that requires little or no land management (after care). The Earth Summit held in Rio de Janeiro in 1992 substantially enhanced thinking on sustainability issues and developed an action plan (Agenda 21) for making development/land use more environmentally, socially, and economically sustainable. Sustainable land management has emerged as a new issue, receiving attention from scientists and policy makers. A sustainable land management system must satisfy a large variety of requirements, including technological feasibility, economic viability, political desirability, administrative manageability, social acceptability, and environmental soundness (Zinck and Farshad, 1995).

2.9.1 Evaluation of sustainable land management

Evaluation of the sustainability of land management requires that there be an adequate methodology by which reliable and objective assessments can be made. Decisions as to whether or not a particular type of land use (rehabilitation system) is sustainable in a given environment over a stated period of time can potentially be assessed using a framework approach. A framework for evaluating sustainable land management (FESLM) was developed by an International Working Group (IWG), as a recommended procedure by which sustainability of current and alternative land use systems could be assessed (Smyth and Dumanski, 1993).

Sustainable land management, in the context of the FESLM, has been defined by the IWG as follows:

- " Sustainable land management combines technologies, policies and activities aimed at integrating socio-economic principles with environmental concerns so as to simultaneously:
 - Maintain or enhance productivity/services (Productivity)
 - Reduce the level of production risk (Security/Risk)
 - Protect the quality/potential of natural resources and prevent soil and water degradation (Protection)
 - Be economically viable (Viability)
 - Be socially acceptable (Acceptability)"

These five goals productivity, security, protection, viability, and acceptability-have been described as the pillars of sustainable land management (Dumanski and Smyth, 1993), they are the (sustainability) criteria against which the findings of the FESLM must be tested and monitored. All five "pillars" or criteria, must be satisfied simultaneous for a land use to be considered sustainable, all pillars are rated as being equally important in the achievement of sustainability.

The FESLM makes use of a logical pathway procedure and proceeds through five main stages (figure 2.5). The stages are:

Stage 1. The objective- the purpose of the land management system being evaluated

Stage 2. The means- the management practices, inputs and circumstances by which the objectives of the land use system are to be achieved

Stage 3. Evaluation factors- identification of all physical, biological, social and economic factors which potentially bear a part on the sustainability of the system

Stage 4. Diagnostic criteria- establishing cause-and effect relationships between factors, collecting evidence of trends in these relationships, on the site and projecting a pattern of future trends

Stage 5. Indicators and thresholds- identification of the conditions of sustainability, or the measures beyond which the system can be judged to be unsustainable

Within the context of sustainability, the terms indicators and thresholds have been defined as follows:

- Indicators- attributes that measure or reflect environmental status or conditions of sustainability
- Thresholds- levels of indicators beyond which a system undergoes significant change, that is, points at which stimuli provoke significant responses.

This framework or a modification thereof can be used to evaluate the sustainability of different rehabilitation methods.

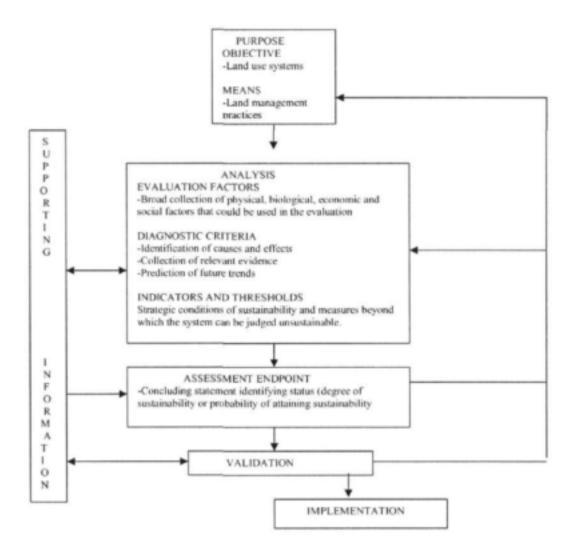


Figure 2.5 Summary flowchart of the FESLM (Dumanski and Smyth, 1995).

2.10 Monitoring of rehabilitated tailings dams

To achieve sustainability, "re-vegetated ecosystems" should be managed to produce a steady state (i.e., maintain biological potential). Monitoring is the regular surveillance of the condition of something therefore keeping track of quality but it does not change it. Quality control involves both monitoring and control, where control means to influence or regulate (Pierce & Gilliland, 1997). Because one goal of sustainable land management should be to achieve good tailings quality, it is necessary to go beyond simply monitoring and to focus on quality management. Tailings quality will be in the hands of land managers if they have the training to recognise, and respond to, adverse tailings quality. Consequently the path to tailings quality assessment must include increasing the interpretative abilities of the land manager.

The main goals behind a monitoring programme are:

- Evaluating tailings quality. Dynamic assessment requires a monitoring system to provide a regular surveillance of tailings quality attributes or indicators. Monitoring has been commonplace for air and water but not for tailings (or even for soils). With regard to changes in tailings quality, standards are needed to assess if the recorded changes are within natural variation or optimal range of the tailings attribute in question, or if the changes are related to management practices that may require changes if quality is deteriorating (Carter et al. 1997).
- For sustainable land management. For rehabilitation purposes tailings quality can be defined (in line with Anderson and Gregorich, 1984) as "the sustained capability of the tailings to accept, store and recycle water, air, nutrients and energy" while sustainable management implies (in line with Doran et al. 1996) "maintaining tailings quality, maintaining biological productivity and maintaining environmental quality". The definition for sustainable management implies that the inherent capacity of the tailings for plant growth must be maintained through the management of the rehabilitated area.
- Improving our understanding of "re-vegetated ecosystems". For "re-vegetated ecosystems", the biological productivity, stocks, and exchange of nutrients, influence of tailings-land characteristics on water quality and hydrologic response, and the regulation of other ecological processes need to be characterized, quantified, and modelled (Miller and Wali, 1995).
- To prove compliance with statutory and regulation requirements. In order to meet the requirements, related to partial or total closure of a tailings dam the regulations and conditions pertaining to acts listed under Section 1.2 must be satisfied.

A useful framework to evaluate tailings quality can be based on the same sequence used for soils: functions, processes, attributes, or properties, attribute indicators, and methodology (Hattingh *et al*, 2001).

Chapter 3

The amelioration, seeding, and amounts of irrigation water applied for the different rehabilitation methods

3.1 Introduction

Recognition and evaluation of potential problems associated with rehabilitation of mine tailings are essential to an orderly and successful rehabilitation effort. The general approach followed is that of problem identification, evaluation, rehabilitation, monitoring, and maintenance (Bradshaw & Chadwick, 1980). In this chapter the focus is only on rehabilitation methods, monitoring will be discussed in subsequent chapters. Evaluation of topography, climate, vegetation, and land use provides information for rehabilitation methodology with regard to land shaping and species selection. Evaluation of the physical and chemical constraints of the tailings provides important information with regard to the amelioration of the tailings (liming, nutrient additions, organic amendments, use of topsoil, leaching, etc.). Although evaluation is an important part of any rehabilitation project it will not be discussed further because for this study the primary goal was to determine the sustainability of the established vegetation cover and as secondary goal to quantify the amounts of water needed for the different rehabilitation methods.

In the mid 1990's when rehabilitation of decommissioned tailing dams in the Welkom area started, Anglo Gold Free State (at that time Freegold) set aside President Steyn no. 6 tailings dam (now FS S 6) for research purposes to specifically address aspects of rehabilitation. The FS S 6 tailings dam was also used for this project. The experimental site was on the south facing, lower slope of the tailings dam. The choice of the experimental site was restricted to this particular dam and slope aspect. A tailings dam with harsher conditions for the establishment of vegetation would have been more appropriate for a study such as this.

The experimental site is about 1320m above sea level and receiving a summer rainfall (September to March) of 455 mm on average per annum. The natural veld lies within the Dry Cymbopogon-Themeda Veld Type (Central Variation) (Acocks, 1988). The grass veld are dominated by Themeda triandra with Cymbopogon plurinodis the tallest grass, but usually not common. The importance of Aristida congesta, subsp. congesta, Eragrostis lehmanniana, and Tragus koeleriodes shows the more arid nature of this veld (Acocks, 1988).

Five rehabilitation methods were selected for the study, namely:

- Leaching method
- Revised leaching with lime filled trenches on contour (referred to as "revised leaching" in text to follow)
- Minimum cultivation with topsoil, (referred to as "minimum cultivation" in text to follow),
- Elementary amelioration, and
- Chemical amelioration (to eliminate the need for leaching)

Two additional irrigation systems, drip irrigation and sprinkler irrigation, were also evaluated but only for the chemical amelioration method. The seven different treatments were replicated four times giving a total of 28 plots. The area of a single plot was 160m^2 and the plots were randomly allocated to the different rehabilitation methods (except for the sprinkler irrigation system where the four plots were next to one another). The methods were described in the literature review (Section 2.5) and therefore only the surface preparation, amelioration, and seed mixture as applied in the experiments will be described. The plot layout is given in Appendix A.

3.2 Surface preparation and amelioration

3.2.1 Leaching method (plots no. 4, 11, 13 and 21)

Where severe erosion gullies were present on the four plots allocated to the leaching method, the surface was smoothed off by hand with pick and fork, and the rest of the area was kept undisturbed. The equivalent of 10 tons dolomitic lime per hectare and 132 kg P ha⁻¹ in the form of super phosphate were applied onto the surface.

3.2.2 Revised leaching method (plots no. 10, 16, 33, and 36)

Lateral trenches roughly 150 mm deep and 300 mm apart, were formed parallel to the contour on the four plots allocated to the revised leaching method. The trenches were filled with the equivalent of 10 tons dolomitic lime per hectare. The equivalent of 33 kg P ha⁻¹ in the form of super phosphate was applied onto the surface.

3.2.3 Elementary amelioration method (plots no. 1, 3, 17 and 18)

Where severe erosion gullies were present on the four plots allocated to the elementary amelioration method, the surface was smoothed off by hand, with pick and fork. The equivalent of 10 tons dolomitic lime per hectare and 33 kg P ha⁻¹ in the form of super phosphate were applied onto the surface and worked into the tailings to a depth of about 100 mm.

3.2.4 Minimum cultivation method (plots no. 7, 12, 20, and 30)

The surface of the four plots allocated to the minimum cultivation method was smoothed off and loosened to a depth of about 100 mm. Topsoil mixed with the equivalent of 10 tons dolomitic lime per hectare and 33 kg P ha⁻¹ in the form of super phosphate was applied to a depth of 50 mm on top of the tailings and worked into the top 100 mm of the tailings.

3.2.5 Chemical amelioration method (plots no. 8, 14, 19, and 22)

The whole area of the four plots allocated to the chemical amelioration method was smoothed off and loosened to a depth of 300 mm. The equivalent of 30 tons of dolomitic lime, 10 tons of compost and 220 kg P ha⁻¹ in the form of super phosphate were applied onto the surface and worked into the tailings to a depth of about 300 mm.

3.2.6 Chemical amelioration with drip irrigation (plots no. 2, 5, 6, and 9) and with sprinkler irrigation (plots no. 25, 26, 27, and 28)

The surface preparation and amelioration for these were exactly as for the chemical amelioration method. The drip irrigation system was evaluated because it is not so conspicuous and therefore less likely to be stolen (theft of irrigation equipment is a major problem on certain tailings dams). The sprinkler irrigation system was evaluated because it is a cheaper system than the micro jet system traditionally used on tailings dams (the micro jet system is the most effective system for leaching). For all the other methods a micro-jet irrigation system was installed.

3.3 Leaching before seeding

For the leaching method, the revised leaching method, and minimum cultivation method, leaching prior to seeding was done for each day of April 1998 and September 1998 and for 10 days in October 1998. The irrigation was turned on for ± 20 minutes at a time (the average time before initiation of runoff), three times a day.

3.4 Seeding and fertiliser application at seeding

The seed cocktail for the leaching, revised leaching, elementary amelioration, and minimum cultivation methods is summarised in Table 3.1. The seed cocktail was applied on the surface and covered with mulch. The quantity of mulch applied was the equivalent of 5 tons per hectare on all the experimental plots except for the minimum cultivation method (no mulch). The mulch was obtained from Virginia Town Council and contains mainly grass. Grass species that could be identified in the mulch were Aristida congesta, Chloris virgata, Cymbopogon excavatus, Cynodon dactylon, Enneapogon cenchroides, Hyparrhenia hirta and Hyparrhenia tamba. The seed cocktail for the chemical amelioration method (for the micro jet, drip and sprinkler irrigation systems) is summarised in Table 3.2. The same mulch and quantity was used for the chemical amelioration trails as for the other trails.

Table 3.1The seeding cocktail and amounts seeded for the leaching, revised leaching, elementary amelioration, and minimum cultivation methods

Botanical name	Common name	Amount seeded (kg/ha)
Cynodon dactylon	Couch grass	2.5
Eragrostis curvula	Weeping love grass	1.25
Eragrostis tef	Teff	0.25
Dactylis glomerata	Rough cocksfoot	2.5
Chloris gayana	Rhodes grass	2.5
Festuca arundinaceae	Fescue type 31	2.5
Agrostis tenuis	Colonial Bent grass	2.25
Poa pratensis	Kentucky blue grass	1.25
Lolium perenne	Perennial rye grass	1.25
Bromus catharticus	Smooth brome	1.25
Atriplex semibiccuta	Creeping saltbush	1.0
Trifolium repens	White clover	1.25
Medicago sativa	Lucerne	1.25
Melilotus alba	Sweet clover	1.25
Brassica nupus	Rape	0.25
Atriplex nummularia	Old man salt bush	0.5

Table 3.2. The seed cocktail and amounts seeded for the chemical amelioration methods

Botanical name	Common name	Amount seeded (kg/ha)
Cynodon dactylon	Couch grass	4.0
Eragrostis curvula	Weeping love grass	5.0
Chloris gayana	Rhodes grass	5.0
Digitaria eriantha	Finger grass	2.0
Cenchrus ciliaris	Buffalo grass	2.0
Medicago sativa	Lucerne	1.0
Melilutus alba	Sweet clover	1.0
Mother crop	Wheat	50.0

The seed mixture used in the experiments differs from that of the natural veld. The species of general occurrence in the natural veld are *Themedia triandra*, *Aristida congesta* subsp. *congesta*, *Eragrostis lehmanniana*, *Eragrostis superba*, *Cynodon dactylon*, *Setaria flabellata* and *Tragus koelerioides*. The aim of re-vegetation (for all methods) was not to recreate the natural plant community but to establish a vegetative surface cover not only to reduce wind and water erosion but also to obtain a self-sustaining plant community that is dynamic and able to change as the rehabilitated site ages and matures

The equivalent amount of NPK applied per hectare at seeding for the leaching, revised leaching and minimum cultivation methods were, 39 kg N, 29 kg P, and 39 kg K. For the elementary amelioration method only 200 kg lime/ha was applied with seeding. The chemical amelioration method received the equivalent of 84 kg N, 84 kg P, and 500 kg K per hectare at seeding.

3.5 Summary of ameliorants (lime, compost, fertilisers) up to seeding for each rehabilitation method

The total amounts of ameliorants used for each method is summarised in Table 3.3.

Table 3.3 Summary of ameliorants used for each method up to seeding

Method	Lime	Compost	Fertilisers (kg.ha ⁻¹)		
	Ton.ha ⁻¹	Ton.ha ⁻¹	N	N P	
Leaching	10	0	39	161	39
Revised leaching	10	0	39	62	39
Elementary amelioration	10	0	0	33	0
Minimum cultivation	10	0	39	62	39
Chemical amelioration	30	10	84	304	500

3.6 Measurements

External inputs in the form of fertilisers and irrigation for all rehabilitation methods were recorded. Water meters were installed to measure the total volume of irrigation water used for every rehabilitation method (problems were experience in the form of mull functioning and theft of water meters, and if a meter was mull functioning the water application for those plots were extrapolated from plots where the meters were functioning). The rainfall was also recorded over the whole period of the experiment.

The water application (irrigation) for the period May 2000 to April 2001 should

have been zero for all methods (as requested by members of the steering committee) but due to a misunderstanding between the area manager of the Free State region, the project leader and the rehabilitation ecologist, a full leaching and vegetation establishment programme was followed for that period. Although this prolonged irrigation may reflect negatively on the amount of water used it had provide a good curve to indicate that the increase in leaching with successive amounts of leaching was progressively smaller. From the curve the required leaching could be estimated (see section 4.5).

Table 3.4 Amount of irrigation water applied (mm) over the experimental period

Period	Nov 98 – Oct 99	Nov 99 – April 00	May 00 – April 01	May 01 – March 02	Total
Leaching	1400	1129	1867	0	4405
Revised leaching	1400	1129	1867	0	4405
Elementary amelioration	942	875	534	0	2351
Minimum cultivation	1400	1130	1867	0	4405
Chemical amelioration	942	875	534	0	2351
Drip irrigation	822	278	230	0	1330
Sprinkler irrigation	2200	875	669	0	3744

Table 3.5 Rainfall (mm) over the experimental period

Month	1998	1999	2000	2001	2002	Total
January		114	140	40	40	334
February		50	31	58	29	168
March		54	108	62	24	248
April		45	27	58	End	130
May		33	0	0		33
June		0	0	13		13
July		0	0	0		0
August		0	0	0		0
September		0	10	6		16
October	27	43	71	29		170
November	182	0	33	29		244
December	181	111	121	149		562
Total	390	450	541	444	93	1918

3.7. Discussion: chemical properties of the tailings changed through amelioration

Samples of the tailings at depth intervals of 0-15 cm, 15-30 cm, and 30-60 cm were taken on each experimental plot before amelioration and about six weeks after seeding. The samples were sent to the Institute for Soil, Climate, and Water, for chemical analysis. The results of these tests are summarised in Appendix A.

The average values and standard deviation of the different chemical attributes, after amelioration, for the 0-30 cm layer, are summarised in table 3.6.

A one-sided, two-sample t procedure was used to test the null hypothesis of no change of a specific chemical parameter with amelioration. Using P-values of <0.025 and <0.005 to reject the null hypothesis, chemical parameters that markedly changed for the different rehabilitation methods are summarised in Table 3.7

Table 3.6 Average and standard deviations of the chemical attributes for the 0-30 cm

layer, after amelioration

Chemical parameter		M1	M2	M3	M4	M5	M6	M7
pH (H ₂ O)	Avg	5.7	6.5	5.9	5.5	7.5	6.3	5.9
	Sidv	0.35	1.48	0.45	0.33	0.12	0.89	0.63
EC (mS/m)	Avg	368	353	332	342	333	371	349
	Sidv	29.2	39.8	61.9	52.6	14.2	9.5	46.0
Na (cmol+/kg)	Avg	0.21	0.22	0.17	0.23	0.23	0.28	0.18
-	Stdv	0.06	0.08	0.04	0.03	0.11	0.06	0.06
K (cmol+/kg)	Avg	0.41	0.41	0.22	0.35	0.24	0.40	0.50
	Stdv	0.21	0.16	0.04	0.10	0.05	0.01	0.14
Mg (cmol+/kg)	Avg	1.10	1.51	1.07	1.28	1.13	1.94	1.32
	Sidv	0.35	0.86	0.33	0.23	0.43	0.57	0.07
Ca (cmol+/kg)	Avg	14.03	14.00	11.71	12.60	15.40	13.16	15.26
	Stdv	1.78	5.04	1.14	3.32	2.66	2.53	1.63
Al (cmol+/kg)	Avg	0.44	0.87	0.50	0.54	0.02	0	0.02
	Stdv	0.24	0.46	0.18	0.04	0.03	0	0.05
CEC (cmol+/kg)	Avg	1.69	1.39	1.62	2.00	3.46	2.93	3.01
	Stdv	0.26	0.86	0.39	0.12	0.43	0.64	0.05
P (mg/kg)	Avg	14.8	17.8	14.5	13.8	15.3	12.5	23.3
	Stdv	3.9	4.3	4.1	4.2	5.0	2.08	8.5
SO ₄ (mg/kg)	Avg	660	660	682	573	634	649	712
	Stdv	63.0	64.0	66.0	93.4	64.1	93.8	13.1
Cl (mg/kg)	Avg	59.8	61.0	69.8	54.3	57.3	63.0	55.8
	Stdv	8.5	5.1	8.9	11.5	6.8	8.1	11.9

M 1= Leaching

M 5= Chemical amelioration

M 2= Revised leaching

M 6= Chemical amelioration (drip)

M 3= Elementary amelioration

M 7= Chemical Amelioration (sprinkler)

M 4= Minimum cultivation

Table 3.7 Chemical parameters improved through amelioration (0-30 cm depth) for a given method and the amounts of ameliorants used

Chemical parameter	Method 1	Method 2	Method 3	Method 4	Method 5	Method 6	Method 7
pН	**	*	**	**	**	**	**
EC (mS/m)							
Na							
K			**			**	
Mg						**	**
Ca			**				**
Al			**	**	**	**	**
CEC							**
P						**	
SO ₄							
CI							
Ameliorants applied							
Dolomitic lime Tons/ha	10	10	10	10	30	30	30
K kg/ha	39	39	76	39	500	500	500
P kg/ha	161	62	56	62	304	304	304
Compost Tons/ha	0	0	0	0	10	10	10
Topsoil Tons/ha				270			
B - 0 035 - 0 005				8 4 1 4 - B	41 1 1		

* P< 0.025> 0.005

** P ≤ 0.005

Method I= Leaching

Method 2= Revised leaching

Method 3= Elementary amelioration

Method 4= Minimum cultivation

Method 5= Chemical amelioration

Method 6= Chemical amelioration (drip)

Method 7= Chemical Amelioration (sprinkler)

The null hypothesis, that all means of a given chemical attribute between the different rehabilitation methods for the 0-30cm layer were equal, was rejected and Scheffe's method was used to distinguish between differences in pairs of population means. The chemical attributes for multiple comparisons that differs significantly at the 95% confidence interval, is summarised in Table 3.8.

Table 3.8. Chemical attributes that differ significantly at the 95% confidence interval, between the different rehabilitation methods, after amelioration, according to the

Scheffe method of multiple comparison (0-30 cm laver)

	M1	M2	M3	M4	M5	M6	M7
M1					pH, Al, CEC	Na, Mg, Al	Al, CEC
M2			Cl		Al, CEC	Al, P	Al, CEC
М3		Cl		Na	pH, Al, CEC	K, Mg, Al, CEC	Al, CEC, Cl
M4			Na		pH, Al, CEC	Al	pH, Al, CEC
M5	pH, Al, CEC	Al, CEC	pH, Al CEC	pH, Al CEC		EC, K	K
M6	Na, Mg Al	Al, P	K, Mg Al, CEC	Al	EC, K		
М7	Al, CEC	Al, CEC	Al, CEC Cl	pH, Al CEC	K		

M1= Leaching

M5= Chemical amelioration

M2= Revised leaching

M6= Chemical amelioration (drip)

M3= Elementary amelioration

M7= Chemical Amelioration (sprinkler)

M4= Minimum cultivation

For depths deeper than 30 cm, none of the rehabilitation methods improve any of the chemical parameters significantly. The null hypothesis, that the means of a given chemical attribute between the different rehabilitation methods are the same, was rejected. The Scheffe method was used to distinguished between pairs of means that differ. The chemical attributes that differ significantly between the different methods, for a confidence interval of 95%, are summarised in Table 3.9.

Differences in chemical attributes between the different methods for the 0-30 cm layer

There were no significant differences between any of the chemical attributes for the leaching methods (M1, M2, and M4). For the chemical amelioration methods, K and EC differ significantly between M5 and M6 while K differ significantly between M5 and M7. If the leaching methods are compared with the chemical amelioration methods then Al for the leaching methods differ significantly from all the chemical amelioration methods. The CEC of the leaching methods (M1, M2, and M4) differ significantly from that of M5 and M7. The pH of M1 and M4 differ from that of M5 as well as the pH between M4 and M7.

Chemical attributes of the elementary amelioration method (M3) that differ significantly from that of the leaching methods were Na (between M4) and Cl (between M2). The CEC and Al of the elementary amelioration method differ significantly from those of the chemical amelioration methods.

The differences between the chemical attributes will be discussed/explained under the different ameliorants (lime, compost, and fertilisers) used.

Differences in chemical attributes between the different methods for the 30-60 cm layer

Between the different leaching methods (M1, M2, and M4) the only chemical attribute that significantly differ was Na and only between M1 and M4. Between the chemical amelioration methods there were differences in SO₄ (between M5 and M7), and EC, Al and P (between M6 and M7). When the leaching and chemical methods are compared then the differences in chemical attributes were mainly in terms of pH and Al although there were also differences in Na (between M1 and M7), and in SO₄ (between M4 and M5).

Chemical attributes that differ significantly between the elementary amelioration method (M3) and the other methods were Cl (between M2) and SO₄ (between M5).

The changes in chemical parameters are illustrated schematically in figure 3.1 to 3.4 for the different methods.

Table 3.9 Chemical attributes that differ significantly at the 95% confidence level, between the different rehabilitation methods, after amelioration, according to the Scheffe method of multiple comparison (30-60 cm layer)

	M1	M2	M3	M4	M5	M6	M7
M1	473 E 85			Na		Al	Na
M2		\$25 SEC. 125	Cl		pH	pH, Al	pН
M3		C1	719 732				
M4	Na			2.33260	SO ₄	Al	Al
M5		pН	SO ₄				SO ₄
M6	Al	pH, Al		A1			EC, Al, P
M7	Na	pH			SO ₄	EC, Al, P	2000

M1= Leaching

M5= Chemical amelioration

M2= Revised leaching

M6= Chemical amelioration (drip)

M3= Elementary amelioration

M7= Chemical Amelioration (sprinkler)

M4= Minimum cultivation

3.7.1 Liming

Liming tailings with dolomitic lime increased the pH of the tailings and decreased the exchangeable Al markedly for all the methods except for the revised leaching method (Table 3.7 and figure 3.1a and b). The revised leaching method where the lime was applied into trenches was, therefore, not as effective in neutralising acid and precipitating Al, as broadcasting lime on, or incorporating the lime into the tailings. The scatter of data around the regression line (figure3.1b) is due to the fact that Aluminium in equilibrium with gibbsite can be present as Al3+, AlOH2+ and Al(OH)+ which when displaced by 1 M KCl, and determined by titration, is related to the charge on the ions. Although the regression equation indicates that the aluminium concentration will be zero at a pH of 7.2, little aluminium is present in solutions above a pH 5.5 (Rowell, 1994). According to Efroymson et al. (1997) the benchmark value for Al is 0.3 ppm in solution. Aluminium interferes with cell division in roots,

decreases root respiration, fixes P in unavailable forms in roots, interferes with uptake, transport, and use of Ca, Mg, P, K, and water, and interferes with enzyme activities (Foy et al. 1978). The dolomitic lime contains Ca and Mg and the levels of these elements were also markedly changed with liming except once again for the revised leaching method (figure 3.3 and 3.4). The CEC also increased with an increase in pH (indicating pH dependant charges) but the CEC only changed significantly where topsoil (method 4) or compost (method 5, 6, and 7) were also incorporated into the tailings (Table 3.7 and figure 3.1a).

If the different rehabilitation methods are compared (Table 3.8) then the 30 tons lime applied for the chemical amelioration methods (M5, M6 and M7) compared to the 10 tons applied for the other methods had a marked effect on pH, Al and CEC, six weeks after amelioration. The reasons is as explained in the previous paragraph.

3.7.2 Nutrient additions

The phosphorus levels increased in all methods. The background value of 4 to 5 mg/kg, for phosphorus in the tailings, compares well with the background values of the natural veld. The amount of phosphorus applied in the chemical amelioration method (304 kg P/ha) is high compared to the other methods (that range between 56 kg and 161 kg P/ha). The build up of phosphorus may be excessively high. The potassium level increased significantly for application rates higher than 76 kg/ha (Table 3.7). However, the application rate of potassium for the chemical amelioration method is 6 to 12 times higher than that of the other methods although it did not increase the potassium level significantly more. If the values for the three chemical amelioration plots are compared then it appears that the theoretical increase of 0.32 cmol+/kg (amount applied as fertiliser) were realised only in the plots of method 7. The potassium had either precipitated as jarosite or being leached. Potassium differs only significantly between the chemical amelioration methods (Table 3.8).

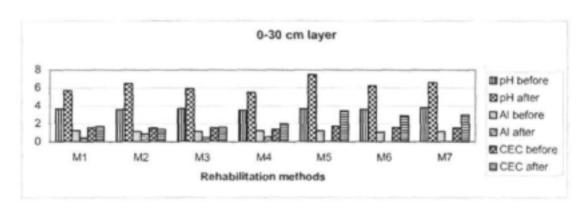
3.7.3 Organic amendments

Organic amendments have direct chemical (binding of toxic metals) and biological effects (stimulation of biological activity) as well as on the physical conditions (water-holding and structure formation) of soils (Gregorich et al. 1997). The waterholding capacity was measured on samples taken from three plots of the leaching method (no compost) and from three plots of the chemical amelioration method. The results are summarised in Table 3.10. The P-value for a one-sided, two-sample t-test is 0.0048 indicating that the addition of compost (chemical amelioration) improved the water-holding capacity of the tailings. The increased water-holding capacity (in terms of plant available water) is, however, much higher (46.8 mm/0.3m) compared to values obtained in other trials conducted on the same tailings dam of 34.8 mm/0.3m for an addition of 10ton compost per ha. The only other chemical parameter that did increase significantly (but in combination with lime application) is the cation exchange capacity (CEC), which is also reflected in Table 3.8. The addition of compost had not lowered the electrical conductivity of the tailings significantly although laboratory tests indicated that the electrical conductivity could be reduced markedly through the addition of compost.

The organic content of the tailings was not monitored in this study. Experience from other dams had shown that the organic content increased during the establishing phase when the tailings is relatively wet (low aeration) but once irrigation is withdrawn the organic content decline. Envirogreen is presently investigated different methods (earthworms, decomposers etc.) to built up the organic content in tailings.

Table 3.10. Plant available water in mm/0.3m for two depths intervals and two rehabilitation methods

	Plot	0-30 cm layer	30-60 cm layer	
	4	24.3	20.1	
Leaching	11	23.0	19.9	
	21	28.3	23.3	
	Average	25.2		
	Stdev	2.76	1.91	
	8	41.7	23.4	
Chemical	14	47.0	20.5	
amelioration	19	51.9	18.2	
	Average	46.87	20.7	
	Stdev	5.1	2.61	



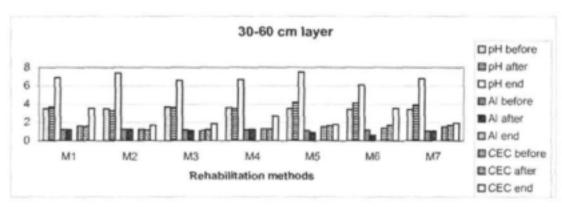


Figure 3.1a. Change in chemical attributes (pH, Al and CEC) through amelioration by liming and composting (Al & CEC in cmol+/kg)

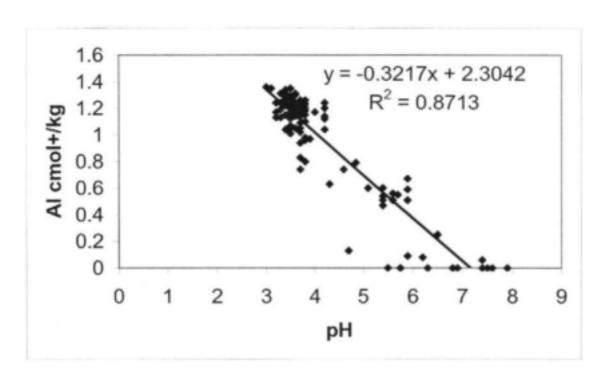


Figure 3.1b. Relationship between pH and Al content (number of data points =112)

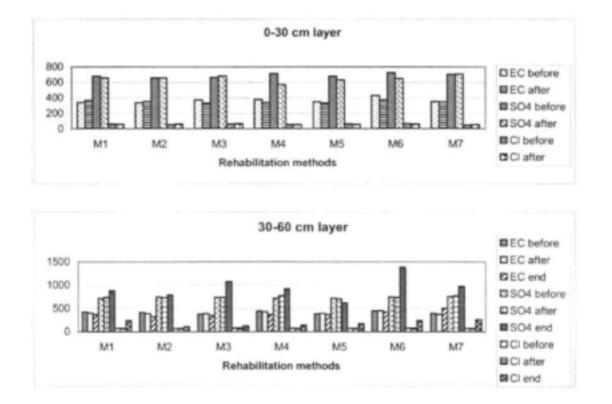
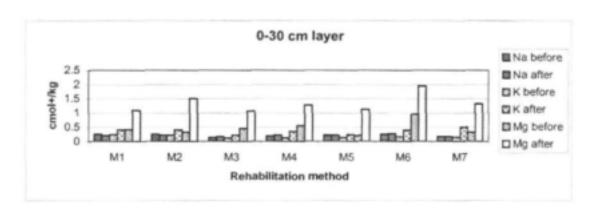


Figure 3.2 Change in chemical attributes (EC, SO₄ and Cl) through amelioration (EC in mS/m and SO₄ & Cl in mg/kg)



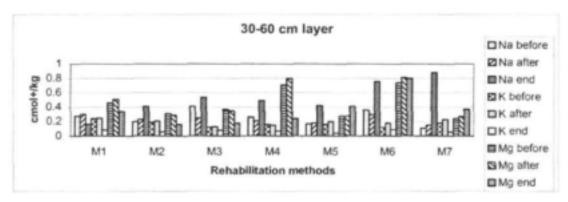
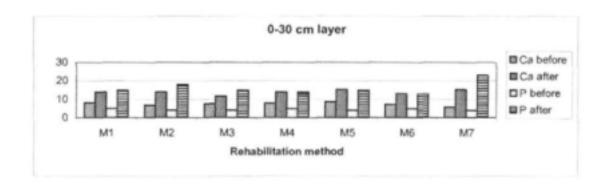


Figure 3.3. Change in chemical attributes (Na, K, and Mg) through amelioration



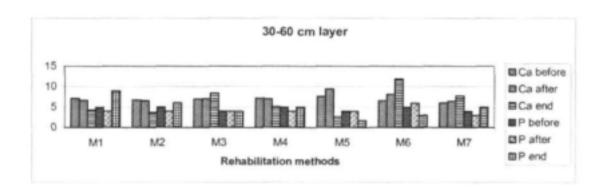


Figure 3.4. Change of the chemical attributes Ca (mmol+/kg) and P (mg/kg) through amelioration

3.7.4 Leaching

At the time of sampling (approximately six weeks after seeding) the effect of leaching would be minimal as the amount of water applied for all methods up to that point was almost the same. Chemical attributes that were significantly different between the leaching and chemical ameliorated methods were pH and Al (Table 3.8) indicating that all free acids were not leached at this stage. The effect of leaching will be more thoroughly evaluated in the next chapter.

For the leaching methods (M1, M2, and M4), within the 0-30 cm layer, not a single chemical attribute differs significantly (Table 3.8), while for the 30-60 cm layer only sodium differ significantly between M1 and M4 (Table 3.9). The chemical attributes of the different leaching methods were at this stage very similar.

3.8. Amounts of water applied

Over the experimental period the amount of water applied for a leaching method was about double that of the chemical amelioration method under a micro-jet system. The amount of water applied for the chemical amelioration method, under a sprinkler system, was about the same as that of a leaching method. The amount of water applied in the drip irrigation system was the least, about one third of a leaching method under micro-jet irrigation. The beneficial effects of leaching in terms of improving the chemical properties of the tailings for plant growth will be discussed further in chapter 4. If the water application were discontinued at the correct time then the water application for the leaching methods would be 2538mm, which is close to the guideline of 2250mm. (The estimated amount of water needed to leach this particular tailings dam was 1400mm (see section 4.5) which agree with Dawson & Cook comments at a steering meeting that nine months of leaching is adequate for this benign tailings).

3.8.1 Water use efficiency

Water is used most efficiently when the most advantage is gained from the least amount of water. Efficiency based on available water takes into account losses through runoff, seepage, drainage, and evaporation. The general water balance equation for production under irrigation can be written as follows:

$$T = (P + I + \Delta S) - (R + Es + D)$$
Water for yield water gains – water losses (3.1)

Where T is the transpiration (or, evaporation from the crop Ev) (mm), P the precipitation (mm), I the amount of irrigation (mm), ΔS the water extracted from the root zone (mm), R the runoff (mm), Es the evaporation from the soil surface (mm), and D the deep drainage/seepage (mm).

Water use efficiency (WUE) in terms of transpiration is defined as:

$$WUE = Y/T$$
 kg mm⁻¹ ha⁻¹ 3.2a

Where Y is the yield (kg ha-1), and T the transpiration (mm).

Water use efficiency in terms of evapotranspiration is defined as:

$$WUE = Y/(T+E)$$
 kg.mm⁻¹ha⁻¹ 3.2b

Where Y is the yield (kg ha-1), T the transpiration (mm), and E the evaporation (mm).

In this study, biomass or the different components of the water balance were not measured and therefore water use efficiency could not be quantified. However, some members from the steering committee requested that it should be addressed qualitatively.

3.8.2 Components of the water balance

Transpiration (evaporation from plants)

Because water is lost through the stomata at the same time as CO₂ is taken in for use in photosynthesis, water loss through transpiration is an inevitable cost of dry matter production. The empirical method most widely tried in South Africa for the estimation of evapo-transpiration, has been the method based on evaporation from the class A-evaporation pan (SIRI, 1984). This method assumes that over a given period, evapo-transpiration (ET) is directly proportional to pan evaporation (Eo). Stated differently,

$$ET = f.Eo.$$
 3.3

Where, f is the empirical constant of proportionality known as the crop factor.

The crop factor for grass (*Eragrostis curvula*) and the A-pan evaporation values for the Welkom area are given in Table 3.11.

Table 3.11 A-Pan evaporation values for Welkom and crop factor for grass.

Month	A-Pan (mm/d)	Crop factor	
January	7.9	0.5	
February	6.5	0.5	
March	5.5	0.5	
April	4.9	0.4	
May	3.6	0.3	
June	2.6	0.2	
July	3.1	0.2	
August	4.4	0.2	
September	6.0	0.3	
October	7.7	0.4	
November	8.8	0.5	
December	8.6	0.5	

A-pan values from Land Type Memoir 4 & Crop factors from Land Type Memoir 2

Biomass or productivity models are either based on climatic indices, such as temperature and rainfall, or they make use of a soil water budget. Rosenzweig (1968) used total evaporation (i.e. "actual evapo-transpiration") values from 26 environments ranging from desert to tundra to tropical forests to predict net annual above ground primary production of terrestrial plant communities. The equation developed by Rosenzweig (1968) was

$$\log Y = 1.66 \log ET - 1.66$$
 3.4

Where Y is the net annual aboveground production (g.m²), and ET the annual evapotranspiration (mm).

The Miami model as used in the ACRU model (Schultze, 1995), consists of the following two equations:

$$P_{pm} = Y_L (1 + e^{1.315 \cdot 0.119T}_{an})^{-1}$$
3.5a

$$P_{pm} = Y_L(1 - e^{-0.000664P_{an}})$$
3.5b

These relationships show the dependence of net primary production, P_{pm} (t.ha⁻¹a⁻¹), on annual mean air temperature, T_{an} (°C), and for the dependence of net primary production on annual precipitation, P_{an} (mm). Y_L is an upper yield limit.

Other factors influencing biomass variation in reclaimed mine areas are biomass composition (Burley et al, 1989) and fertilisers (Bush & Van Auken, 1986). Equation 3.5b was used to calculate an estimated biomass production but P_{an} was taken as the sum of rainfall and irrigation received over a growing season (October to April) and Y_L was taken as 4000 kg/ha, double the value given by Rutherford (1978) for the average biomass in grasslands of the South African Highveld. The evapo-transpiration (ET) was calculated over the same period from the evaporation values and crop factors as given in Table 3.11, using equation 3.3. The results for three growing seasons are summarised in Table 3.12.

Table 3.12 Estimated biomass and water efficiency in terms of ET, and measured basal cover for the leaching technique and the chemical amelioration technique.

Performance parameter	Leaching technique			Chemical amelioration technique		
	99/00	00/01	01/02	99/00	00/01	01/02
Biomass (kg/ha)	2505	2355	722	2065	1520	722
Water use efficiency (eq. 3.2b)	3.38	3.18	0.97	2.79	2.05	0.97
Basal cover	6.2	7.0	3.1	4.5	5.9	3.5

Runoff, irrigation efficiency, and drainage

Runoff and water loss due to poor irrigation design can be considered as the only negative water losses in terms of rehabilitation as this water can cause erosion and is lost for plant utilisation or for leaching purposes. The Soil Conservation Service (SCS) of the United States Department of Agriculture developed a procedure for estimating runoff depths and volumes from small catchments (< 30 km² in area). The USDA (1985) and Schmidt and Schulze (1987) derived the following runoff equation from first principles:

$$Q = (P_g - I_a)$$

$$P_g - I_a + S$$
(3.6)

Equation 11 holds only if Pg > Ia

Where Q is the runoff depth (mm), Pg the gross precipitation (mm), Ia the initial abstraction (mm) before runoff commences, consisting mainly of interception, infiltration, and depression storage, and S the potential maximum retention (mm), which is equated to a soil water deficit. In order to eliminate the necessity of estimating both Ia and S, Ia may be expressed in terms of S by the empirical relationship

$$I_a = cS (3.7)$$

Where c is the regression coefficient, commonly referred to as the coefficient of initial abstraction. The coefficient of abstraction varies dependent on vegetation, site, and management characteristics.

The runoff equation thus become

$$Q = \frac{(P_g - cS)^2}{P_g + S(1-c)}$$
(3.8)

S has been transformed to a catchments response index to rainfall, called the runoff Curve Number, CN. The potential retention S can be calculated from the CN as:

$$S = 25.4(1000/CN - 10)$$
 (3.9)

The potential retention S can also be conceived as a soil water deficit. The soil water deficit is taken as the difference between water retention at porosity and the actual water content just prior to the rainfall event. The critical soil depth for which the soil water deficit, S, is calculated for runoff generation is a variable, depending on climate, catchments conditions and soil properties. No experimental procedures were followed in this study to define CN-values in terms of vegetation cover conditions thereby eliminating the use of equation 3.8. Runoff losses were taken as 25% of the rainfall (the same as found by Hensley et al. (2000) on Bonheim and Swartland soils at Glenn).

Irrigation efficiency is defined as the net amount of water added to the root zone divided by the amount of water taken from some source (Hillel, 1980). The irrigation efficiency (ie) was not measured in this study, and the following values were chosen:

- Mist irrigation system = 0.85
- Drip irrigation system = 0.90
- Sprinkler irrigation system = 0.6

The total applied water (P+I.i_c) minus evapo-transpiration (ET) minus runoff will give the amount of water that can be drained (D) (leach) through the root zone. The total amount drained (D) minus the leaching requirement (LR), the amount necessary to prevent salt build up in the root zone, will give the leaching fraction (LF) that is beneficial in leaching salts and acids from the tailings. The leaching requirement for the particular irrigation water quality (EC=92mS/m) and the EC (1220mS/m) of the tailings water that will cause a 50% reduction in grass biomass production is 0.075.

A summary of the **estimated water balance components** over the three-year study period for the different methods is given in Table 3.13. The estimated leaching fraction for the leaching, revised leaching, and minimum cultivation method is 1920 mm over the study period. The estimated leaching fraction for the elementary amelioration, and chemical amelioration was 749 mm, and for the drip and sprinkler irrigation systems 332mm and 955 mm respectively. All the rehabilitation methods were therefore leaching methods for the first 18 months except for the drip irrigation system. For the following year only leaching methods were leaching and for the last year all methods were rain fed (no irrigation) production systems. For a given quantity of available irrigation water the leaching fraction will decrease as the water quality decreases because the leaching requirement increases. The water quantity and water quality is the two factors that influence the success of the leaching method to a large extent (Dawson & Cook, 2002).

Table 3.13. Estimated water balance components (in mm) over the study period for the different rehabilitation methods

Period	Water balance components	MI	M2	M3	M4	M5	M6	M7
Nov 98-	Precipitation	702	702	702	702	702	702	702
Oct 99	Irrigation x i _c	1190	1190	801	1190	801	740	1320
	Evapotranspiration	872	872	872	872	872	872	872
	Runoff	176	176	176	176	176	176	176
	Leaching requirement	105	105	71	105	71	62	165
	Leaching fraction	739	739	384	739	384	332	809
Nov 99-	Precipitation	417	417	417	417	417	417	417
April 00	Irrigation x i _e	960	960	744	960	744	250	525
F I	Evapotranspiration	626	626	626	626	626	626	626
	Runoff	104	104	104	104	104	104	104
	Leaching requirement	85	85	66	85	66	21	40
	Leaching fraction	562	562	365	562	365	0	166
May 00-	Precipitation	453	453	453	453	453	453	453
April 01	Irrigation x i _e	1587	1587	454	1587	454	230	401
E R	Evapotranspiration	872	872	872	872	872	872	872
	Runoff	113	113	113	113	113	113	113
	Leaching requirement	140	140	40	140	40	17	50
	Leaching fraction	619	619	0	619	0	0	0
May 01-	Precipitation	319	319	319	319	319	319	319
1	Irrigation x ic	0	0	0	0	0	0	0
	Evapotranspiration	813	813	813	813	813	813	813
	Runoff	80	80	80	80	80	80	80
	Leaching requirement	0	0	0	0	0	0	0
	Leaching fraction	0	0	0	0	0	0	0

M1=leaching method

M2=revised leaching method

M3=elementary amelioration method

M4=minimum cultivation method

M5=chemical amelioration method

M6=chemical amelioration (drip irrigation)

M7=chemical amelioration (sprinkler irrigation)

3.9 Remarks

The leaching method is to some extent a chemical amelioration method (addition of lime) and the chemical amelioration method in this study was to some extent a leaching method. Furthermore, the experiment was not planned to prove/disprove the claims of a particular method but rather to determine the sustainability of the vegetation cover and to quantify the water needed for a particular method. The lack of control plots for each method makes any deduction rather speculative. The acid problem in gold tailings, as is understand today, and the way it is addressed in the leaching and chemical method, needs to be carefully evaluated.

Pyrite oxidation - mineral formation - neutralisation of acid

The oxidation of sulphidic tailings produces sulphate salts (e.g., rozenite=FeSO₄.4H₂O, melanterite= FeSO₄.7H₂O) as well as acidity. The electrical conductivity of soil solutions tends to increase as the pH decreases and bitter tasting salts are visually observed to accumulate at the tailings surface, as the tailings dry out. Undoubtedly Al and other cations, in addition to Fe, are associated with the SO₄²⁻, and the acidic character of Fe and Al sulphate salts is an important property that must be considered in reclamation strategies (Fanning & Burch, 1997). The salts form as intermediate phases but, ultimately, Fe²⁺ is oxidized and hydrolysed to form one or more of the minerals associated with mine drainage ochre (figure 3.5)(Bigham & Murad, 1997).

This "model", based primarily on field observations and physical data, has therefore a strong kinetic bias with little consideration of solubility controls and other important thermodynamic factors, but can in conjunction with titration curves give a clearer picture, of how to ameliorate acid tailings, or how analytical tests to determine extractable acidity should be modified to be applicable to gold tailings.

The extractable acidity (titrateable acidity) before amelioration is the acidity that must be neutralised at the onset of amelioration (liming or leaching). The average titrateable acidity, for all plots before amelioration, was 1.47cmol+/kg indicating that, for a dry density of 1.35 Mg/m³, 3ton lime per hectare is required to neutralise the extractable acidity. However, the soluble Ca increases from 7.46 cmol+/kg before amelioration to 13.73 cmol+/kg after amelioration. If this increase in Ca is attributed only to the dissolution of the added lime then 12.7ton lime per hectare had dissolved. How can this large discrepancy be explained?

When pyrite oxidises under acid conditions, the initial products are expected to be sulphuric acid and ferrous sulphate

$$FeS_2 + 3.5 O_2 + H_2O = FeSO_4 + H_2SO_4$$
 3.10

One mole of H₂SO₄ is produced for each mole of pyrite for which the S is oxidised by this reaction. A second mole of sulphuric acid can be produced if the FeSO₄ is totally oxidised and hydrolysed to form an iron hydroxide mineral, such as goethite.

$$FeSO_4 + 0.25 O_2 + 1.5 H_2O = FeOOH + H_2SO_4$$
 3.11

Reaction 3.11 can be divided into an oxidation step (reaction 2.4) and a hydrolysis step (reaction 2.5) [Stumm & Morgan, 1981] (see literature review, section 2.2.1.1).

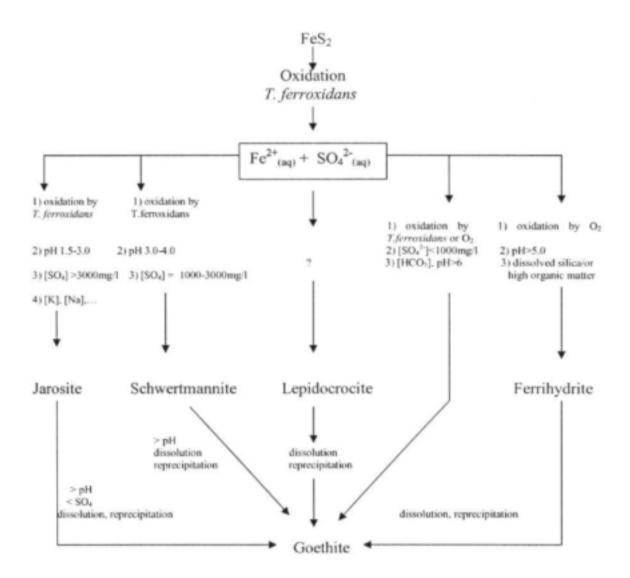


Figure 3.5 Biogeochemical model for the precipitation of various minerals occurring in mine drainage ochre (Bigham & Murad, 1997)

The equilibrated pH ranges between 3.2 and 3.9 for solutions containing 5mmol and 1 mmol FeSO₄, respectively (Fanning & Burch, 1997). The amount of acid released upon the oxidation and hydrolysis of FeSO₄ to sulphate bearing (Fe³⁺) minerals would be expected to be less than if the product was FeOOH. The oxidation and hydrolysis of FeSO₄ to jarosite may be represented by reaction 3.12

$$3 \text{ FeSO}_4 + 0.75 \text{ O}_2 + 4.5 \text{ H}_2\text{O} + \text{K}^+ = \text{KFe}_3(\text{SO}_4)_2(\text{OH})_6 + \text{H}_2\text{SO}_4 + \text{H}^+$$
 3.12

Assuming that the H⁺, shown on the right side of the equation as not associated with SO₄²⁺, is consumed in the reaction to release the K⁺ for the left side of the equation from some mineral in the system, only 1/3 mole of H₂SO₄ is produced per mole of FeSO₄ by this reaction, as opposed to one mole of H₂SO₄ per mole of FeSO₄ when the

product of the reaction is FeOOH (reaction 3.11). An additional 1.5 moles of H₂SO₄ would be released from the three moles of Fe if the jarosite were to dissolve and precipitate as FeOOH as shown in reaction 3.13

$$KFe_3(SO_4)_2(OH)_6 = 3FeOOH + 1.5 H_2SO_4 + 0.5 K_2SO_4$$
 3.13

Alternatively, if FeSO₄ were to oxidise and hydrolyse to shwertmannite, as represented by Fe₈O₈(OH)₆SO₄, 7/8 mole of H₂SO₄ would be released per mole of FeSO₄ as shown in reaction 3.14

$$8 \text{ FeSO}_4 + 2 \text{ O}_2 + 10 \text{ H}_2\text{O} = \text{Fe}_8\text{O}_8(\text{OH})_6\text{SO}_4 + 7 \text{ H}_2\text{SO}_4$$
 3.14

Hydrolysis of schwertmannite to FeOOH would release the additional 1/8 mole of H₂SO₄ per mole of Fe involved in the reaction, or one mole for the 8 moles of Fe in a mole of schwertmannite as shown in reaction 3.15.

$$Fe_8O_8(OH)_6SO_4 + 2 H_2O = 8 FeOOH + H_2SO_4$$
 3.15

Measuring the titrateable acidity according to the standard agricultural method will under-estimate the extractable acidity grossly if iron sulphate salts are present. Fanning & Burch (1997) found that the end point of the titration of FeSO₄ with a base is close to that predicted from equation 3.11 if the duration is long enough (8 days) and Fe can oxidise and hydrolyse. The results of this study indicate that the titrateable acidity was about four times lower than the actual extractable acidity. No data was gathered in this study of the amounts of iron sulphate salts or the type and contents of iron mineral in the tailings. If control plots were included (leaching without lime, chemical amelioration with and without lime, and with and without compost etc) data could have been obtained about certain chemical processes in action within the tailings. For example, how long does it take for the leaching of free acids (H⁺), leaching of salts buffering the pH (e.g., FeSO₄, Al(OH)_x) species etc.)? The time needed to leach the reserve acidity will dependent on the exact composition of iron salts and iron minerals present in the tailings. The leaching method will be more successful the more advanced the weathering process (oxidation) because the risk of potential re-acidification is then very low.

Neutralisation of acids with lime

Under strongly acidic conditions, the acidity generated from the oxidation of sulphates is neutralised by CaCO₃ according to the following reaction (Day, 1994)

$$CaCO_3 + H_2SO_4 = CaSO_4 + H_2CO_3^0 \text{ or } CO_2(g) + H_2O$$
 3.16

Under mildly acidic to mildly alkaline conditions, the reaction will be as follows:

$$CaCO_3 + H^+ + SO_4^{2-} = CaSO_4 + HCO_3^-$$
 3.17

Carbonates neutralise the acidity under mildly acidic to mildly alkaline conditions incompletely, and the amount of lime applied to counteract future potential acidity (chemical amelioration method) can be under estimated by a factor of two. The iron sulphate will under mildly acidic conditions be converted directly to goethiet (if the

pH>6) but the conversion also requires high HCO₃ concentrations (figure 3.5). Carlson & Schwertmann, (1990), had shown that the proportion of lepidocrocite to goethite decreased from 100 to 0% as (HCO₃) increased from 0 to 16 mmol/l. Several laboratory studies have also shown SO₄ to enhance the formation of goethite over other iron oxyhydroxides even though SO₄ is not a structural component of these minerals (Carlson & Schwertmann, 1990). For solutions in equilibrium with lime and gypsum (reaction 3.17) the equilibrium constant K_{eq} can be written as

$$K_{\text{eq}} = \underbrace{[HCO_3]}_{[H^+][SO_4^2]}$$
(3.18)

The bicarbonate content was not monitored in this study. Under strongly acidic conditions (reaction 3.16) the molar ratio of calcium to sulphate in drainage water would be expected to be less than or equal to 1 and under less acidic conditions (reaction 3.17) the ratio will be greater than 1 due to the formation of bicarbonate. When the slimes are treated with lime, the jarosite will be unstable and through dissolution, precipitated as goethite. One mole of jarosite will form 3 moles goethite and 1.5 moles sulphuric acid, which under mildly acidic conditions require 3 moles of lime to be neutralised. The 10 tons lime (13 tons in total minus 3 ton for titrateable acidity) can therefore neutralise 33 3333 moles of jarosite, which boils down to a jarosite content of 0.4% for the tailings. The jarosite content of tailings studied by Rosner et al. (2001), range between 1 and 7% with an average of 3%. Titrateable acidity measurement procedures should be modified to be more applicable for rehabilitation of materials containing iron sulphate minerals.

3.10 Summary and conclusions

The lime needed to turn the oxidised tailings back to a potential acidic sulphate material is about 13 tons per hectare. For the chemical amelioration method 30 tons lime per ha were applied while for all the other methods 10 tons lime per ha were applied. For this reason, the chemical attributes of the tailings six weeks after amelioration differs between the leaching methods and the chemical ameliorated methods primarily in pH, Al and CEC indicating that the additional reserve acidity was not completely leached out at that stage. The only real anomaly is between method 6 and the leaching methods where significant differences in Na, Mg, and P exist.

The lime added cause changes in the following chemical attributes: pH, CEC, Al, Ca, and Mg. Standard agricultural chemical methods to determine the lime required to neutralise active and reserve acidity (H* and Al*) is not appropriate for materials with a high content of iron sulphate minerals (melanterite, rozenite, jarosite, and schwertmannite) as these minerals had also reserve acidity. The amount of phosphate fertilisers applied is probably on the high side when compared to the phosphate content of the surrounding soils. This high phosphate content can prevent certain grass species, occurring in the natural veld, from colonising on the ameliorated tailings. High potassium applications should be avoided because the potassium either become fixed or leached through the root zone.

The amount of water applied for all methods was on the high side because the irrigation application was incorrectly extended for another season. If the amount of

water applied during the extended period is subtracted from the total amount of water applied then the amount of water applied is within the general guideline for the leaching methods but for the chemical amelioration methods the amounts of water applied exceeds the general guide of water needed to establish vegetation.

All methods were successful in creating a tailings medium suitable (not necessarily optimal) for plant growth. With respect to plant production, the function of the ameliorated tailings is to nurture and sustain plant growth. The function of tailings for plant production can be subdivided into several components as follows: a medium for plant growth; regulate and partition water; gas and energy flow; and serve as a buffer or filter system. Creating these function components, in tailings involves changing the tailings present chemical, physical, and biological properties. The different rehabilitation methods had predominantly changed only the chemical properties of the tailings although for the chemical amelioration method the deeper cultivation and the addition of compost had changed the physical and biological properties also to a certain degree.

The ability of the tailings to sustain plant production depends largely on the way their properties are altered as a result of amelioration. The potential yield depends first of all on the genetic capacity of the plant. Climate will impose a limit on the yield directly through sunlight energy input or air temperature, indirectly on its control on the temperature of the tailings, rainfall inputs, and potential evaporation. The physical characteristics of the tailings impose limitations on growth through water supply, aeration, and root distribution (these properties are interrelated). Chemical characteristics of tailings impose limitations through the availability of nutrients and toxic elements (chemical properties that affect these aspects are CEC, pE, pH, EC, ESP, organic matter content and mineralogy). Biological processes are involved in making nutrients available (N, P and S) by mineralization of organic matter and N fixation.

The quality of the created growth medium will be discussed in chapter 4 and the quality of the established vegetation cover will be discussed in chapter 5.

Chapter 4

Monitoring of tailings quality

4.1 Introduction

The ability to initiate and maintain vegetative cover will be the final, most important, test of any rehabilitation project (Bradshaw, 1996). In contrast to natural ecosystems, in which equilibriums are established that reduce export of nutrients from the system. "re-vegetated ecosystems" in the early stages of development are characterised by management inputs (fertilisers, irrigation) to maintain the masses of soil organic matter and biogeochemicals (Schlesinger, 1994). To achieve sustainability, "revegetated ecosystems" should be managed to produce a steady state (i.e., maintain biological potential). Monitoring is the regular surveillance of the condition of something, thereby keeping track of quality but it does not change it. Quality control involves both monitoring and control, where control means to influence or regulate (Pierce & Gilliland, 1997). Because one goal of sustainable land management should be to achieve good tailings quality, it is necessary to go beyond simply monitoring and to focus on quality management. Tailings quality will be in the hands of land managers only if they have the training to recognise, and respond to, adverse tailings quality. Because the necessary indicators or threshold values to assess tailings quality had not yet been developed, the monitoring data collected during this investigation will be handled according to statistical quality control (SQC) concepts and procedures as proposed by Pierce & Gilliland (1997), to assess the changes in chemical attributes of the tailings for the different rehabilitation methods.

4.1.1 Statistical quality control- an overview

Statistical quality control (SQC) is a method to help control processes. It uses simple control charts, produced by sampling a quality parameter over time, to determine if a specific process operates within the range of "natural variation". In SQC, a process is considered to be "in statistical control" if it operates within the range of natural variation and is considered to be "out of control" if other variations resulting from "specific causes" are present in the process (Pierce et al., 1997). Tailings properties and processes vary over time and space. A single measurement or a set of measurements at a given time and place may carry little information about a property or the processes affecting it. Only by measuring a property over time and space can its nature be understood.

The charting of measurements is a standard tool in Statistical Process Control (SPC). Charts are used as it provides a history of measured aspects of the process. Charts show variation and sometimes trends and cycles as well. Sample means and standard deviations of a quality control parameter are plotted over time on a control chart. The procedure is briefly:

Let q_i be a quality attributes of interest, and let the mean of q_i be μq_i and the standard deviation of q_i be σq_i . Then the centre line, the upper control limit (UCL), and the lower control limit (LCL) become:

 $UCL = \mu q_i + k \sigma q_i$

Centre line = µqi

$$LCL = \mu q_i - k\sigma q_i$$

Where k is the distance of the control limits from the centre line, expressed in standard deviation units. The equations for the centre line and the control limits depend on the type of data being generated and plotted, and on the estimates. For sample means, x, and standard deviations, s, of subgroups of n measurements on a continuous variable, the control limits for k = 3 are:

x-chart:

$$UCL = X + 3s'/(c_4\sqrt{n})$$

Centre line = X

$$LCL = X - 3s \%(c_4 \sqrt{n})$$

s-chart:

$$UCL = s' + 3\sqrt{(1-c_4^2)(s'/c_4)}$$

Centre line = s'

$$LCL = s' - 3\sqrt{(1-c_4^2)(s'/c_4)}$$

Where X is the average of the subgroup means x_i , s' is the average of the subgroup standard deviations s_i , and c_4 is a constant that depends on the sample size n and adjust for bias (Ryan, 1989). For n = 4, $c_4 = 0.9213$. The estimates X and s'/c_4 are, respectively, unbiased estimates of the mean, X, and the standard deviation, σ , of the process if the process variable is normally distributed and the subgroup measurements are random samples of size n from the distribution.

In some applications, it may be desirable to control within a specific level, that is, to specify standard values for the mean and standard deviation of tailings quality attributes or indicators and to use these standards to establish control charts. The selection of standards would be important in tailings quality control, since standards in measurement and for control limits will assist in the detection of real changes in tailings quality. Unfortunately standards for tailings attributes, indicators, or threshold values do not exist presently.

4.2 Chemical attributes of the tailings that were monitored during the study

The nutrient availability (Ca²⁺, Mg²⁺, K⁺, P, and SO₄²⁻), soluble salts (EC), pH, exchangeable Al, and cation exchange capacity (CEC) were monitored by taking composite tailings samples for each rehabilitation method once a year (except at the beginning and end of the study period where composite samples were taken from each plot) and analysed according to the Handbook of Standard Soil Testing Methods for Advisory Purposes (The Non-Affiliated Soil Analyses Work Committee, 1990). The

samples were sent each time to the same laboratory, the soil laboratory of the Institute for Soil, Climate, and Water (ISCW). The results are summarised in Appendix A.

The average values and standard deviations of the chemical attributes for the 0-30 cm layer at the end of the study period are summarised in Table 4.1

Table 4.1 Average values and standard deviations of the chemical attributes for the different rehabilitation methods at the end of the study period (0-30 cm layer)

Chemical parameter		M1	M2	M3	M4	M5	M6	M7
pH (H ₂ O)	Avg	7.4	7.6	7.2	7.5	7.8	7.0	7.6
	Stdv	0.55	0.24	0.33	0.18	0.06	0.89	0.25
EC (mS/m)	Avg	258	207	348	300	118	434	342
	Stdv	175.9	127.8	139.3	117.7	25	115.1	191.0
Na (cmol+/kg)	Avg	0.47	0.29	0.61	0.47	0.15	0.67	0.46
	Stdv	0.44	0.19	0.51	0.27	0.04	0.43	0.35
K (cmol+/kg)	Avg	0.19	0.12	0.14	0.16	0.17	0.15	0.14
	Stdv	0.08	0.04	0.04	0.03	0.09	0.02	0.04
Mg (cmol+/kg)	Avg	0.84	1.00	0.70	0.98	1.17	1.61	0.79
	Stdv	0.34	0.40	0.26	0.44	0.11	0.66	0.10
Ca (cmol+/kg)	Avg	2.60	2.30	4.76	3.33	1.95	8.91	2.41
	Stdv	1.29	0.98	3.60	0.93	0.16	2.19	0.87
Al (cmol+/kg)	Avg	0	0	0	0	0	0	0
	Stdv	0	0	0	0	0	0	0
CEC (cmol+/kg)	Avg	2.44	2.13	1.91	2.32	3.00	2.00	2.20
	Stdv	1.47	1.10	0.49	1.09	2.69	0.75	0.47
P (mg/kg)	Avg	31.5	24.0	15.5	23.8	30.7	14.5	22.0
	Stdv	17.7	3.4	6.9	7.0	6.4	7.8	6.9
SO ₄ (mg/kg)	Avg	616	377	944	630	77	1258	502
	Stdv	481	348	575	413	61	207	355
Cl (mg/kg)	Avg	237	107	242	196	65	313	213
	Stdv	143	82	226	97	23.5	186	169

Method 1= Leaching

Method 2= Revised leaching

Method 3= Elementary amelioration

Method 4= Minimum cultivation

Method 5= Chemical amelioration

Method 6= Chemical amelioration (drip)

Method 7= Chemical Amelioration (sprinkler)

A one-sided, two-sample t procedure was used to test the null hypothesis of no change of a specific chemical parameter between tailings six weeks after amelioration and tailings condition at the end of the project, for a given rehabilitation method. Using P-values of <0.025 and <0.005 to reject the null hypothesis, chemical parameters that markedly changed over the study period for the different rehabilitation methods are summarised in Table 4.2.

Table 4.2 Chemical attributes that had changed within the 0-30 cm layer over the

study period

Chemical parameter	Method 1	Method 2	Method 3	Method 4	Method 5	Method 6	Method 7
pH	**	**	**	**	**	**	**
EC (mS/m)					*		
Na							
K							
Mg	**				**		**
Ca	*	**		*	**		*
Al							
CEC							
P		**	*	*	**		*
SO ₄					**	*	
Cl							
Total nutrients applied during maintenance							
N kg/ha		99	99	99	99	99	99
K kg/ha		99	99	99	99	99	99
P kg/ha		75	75	75	75	75	75

Method 3= Elementary amelioration

Method 5= Chemical amelioration

Method 6= Chemical amelioration (drip)

Method 7= Chemical Amelioration (sprinkler)

The null hypothesis for all means of a given chemical attribute to be equal between the different rehabilitation methods were rejected and Scheffe's method was used to identify which means were significantly different at the 95% confidence interval. The chemical attributes that significantly differs between the different rehabilitation methods are summarised in Table 4.3

If the chemical attributes for the leaching methods (M1, M2, and M4) are compared then it is only the Ca content for method 4 that significantly differs and therefore the leaching methods was viewed as similar enough to be grouped together. For the chemical amelioration methods (M5, M6, and M7) it is the EC, Ca, and Cl contents of Method 6 that differs significantly from the other two methods. The chemical amelioration methods were also lumped together for ease of comparison with the leaching methods. If the leaching and the chemical ameliorated methods are compared then, after amelioration the attributes that differ were pH, CEC and Al, while at the end of the study, the chemical attributes that differ significantly were Ca, Cl, and EC, indicating that at the end of the study period the excess reserve acidity was leached out, and more salts were leached from the rooting zone of the leaching methods. The chemical attributes at the end of the study period between the different methods were actually very similar in that only three of the eleven chemical attributes been monitored, differs significantly.

^{**} P < 0.005

Method I= Leaching

Method 2= Revised leaching

Table 4.3 Chemical attributes that differs significantly at the 95% confidence interval between the different rehabilitation methods, at the end of the project, according to

the Scheffe method of multiple comparison (0-30 cm layer).

	M1	M2	M3	M4	M5	M6	M7
M1	THE REAL PROPERTY.	3	Na, Cl	Ca		Ca	
M2			pH, Cl	Ca		Ca, Cl	
М3	Na, Cl	pH, Cl			pH, EC Mg, P		
M4	Ca	Ca			pH, EC Ca	Ca	
M5			pH, EC Mg, P	рН, Са		EC, Ca Cl	Mg
M6	Ca	Ca, Cl			EC, Ca Cl		Ca
M7					Mg	Ca	1873

M1= Leaching

M2= Revised leaching

M3= Elementary amelioration

M4= Minimum cultivation

M5= Chemical amelioration

M6= Chemical amelioration (drip)

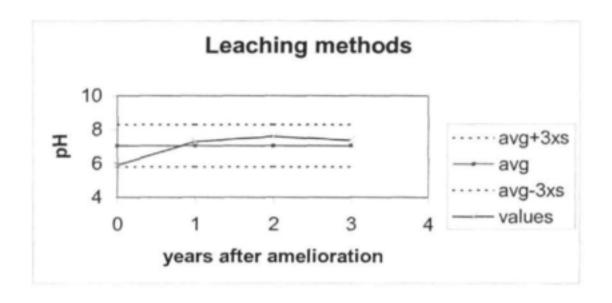
M7= Chemical Amelioration (sprinkler)

Each chemical attribute monitored will be discussed separately and illustrated as control charts, not for each method, but as the combination of the leaching methods (methods 1, 2, and 4), and the combination of chemical amelioration methods (methods 5, 6, and 7).

4.2.1 pH (H₂O)

The pH of the tailings within the upper 30 cm layer for the leaching methods was after amelioration at the lower control limit but increased as leaching progressed and was above a value of 7 up to the end of the study period (Figure 4.1). For the chemical amelioration methods the pH of the tailings within the upper 30 cm layer was after amelioration almost 7 and at the end of the study period above 7. For both methods it seems that within the study period there were no processes in action to cause the pH to get out of control. The leaching and neutralisation actions taken were, therefore, effective to control the pH. However, over time there is a risk of acidity rising back up into the rooting zone by means of capillary action or through oxidation of pyrite, but this acidity will be neutralised by the additional lime applied in the chemical amelioration method accompanied by an increase in salt content. For the leaching method the pH will be lowered because there is no additional lime to neutralise the acid but the salinity will remain more or less constant.

The following standards can be set for pH as control limits, lower limit pH 6, and upper limit pH 8 (Kiniry et al. 1983). Once the pH drops below 6 the activity of organisms that can biologically oxidise pyrite increases to reach a peak at around pH 3.5. The pH can drop very rapidly once Fe³⁺ contributes to the oxidising of pyrite (Stumm & Morgan, 1981).



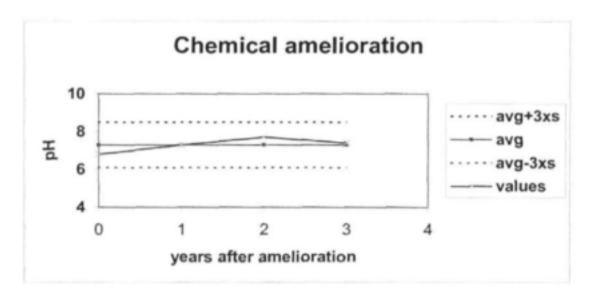
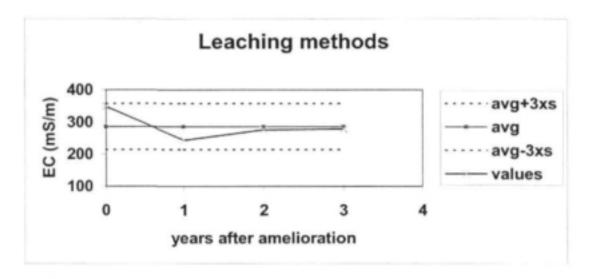


Figure 4.1 Control charts of pH(H₂O) for the chemical amelioration and leaching method over the study period

4.2.2 Electrical conductivity (EC)

The electrical conductivity (EC) usually gives a good indication of dissolved salts. For this particular tailings material there was a very low correlation between salt content [sum of cations (S-value) minus the CEC (T-value)] and EC. For example before amelioration the average S-value minus T-value for all plots was 7.92cmol+/kg and the electric conductivity 374mS/m while after amelioration the S- minus T-value was 13.68cmol+/kg and the EC 350mS/m. The presence of soluble ion pairs could lower the electric conductivity of the solution, which according to Jurinak *et al.* (1987) is particularly important in solutions where SO₄²⁻ are dominant as is the case for this tailings material. In solutions where sulphate concentrations exceeds 1 000 mg/l, more than half the calcium could be present in the form of the CaSO₄⁰ ion pair (USDI, 1970). The CaSO₄⁰ ion pair had no effect on the electrical conductivity and the measured electrical conductivity, therefore, underestimates the total dissolved

solids. In semi-arid regions osmotic potential influences root growth, and although an EC value of less than 400 mS/m is regarded as indicating non-salinity conditions, this criterion may not be valid for this tailings material because of the formation of ion pairs. An upper limit for EC of 600 mS/m is suggested instead of 800 mS/m and can be adjusted as more information becomes available. The EC was controlled below a value of 400 mS/m by both the leaching and chemical amelioration methods (Figure 4.2).



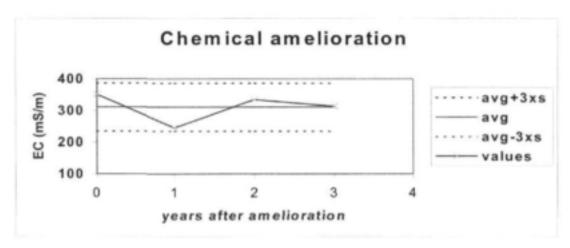


Figure 4.2 Control charts of the electrical conductivity for the leaching and chemical amelioration methods over the study period

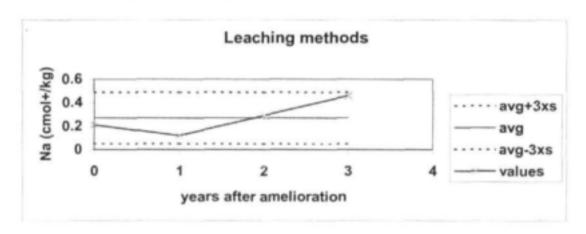
4.2.3. Cations Na, K, Mg, and Ca

Each cation follows the same type of trend in the leaching and chemical amelioration methods (Figures 4.3, 4.4, 4.5 and 4.6). All cations decrease initially, Ca decreased continuously but seems to reach a steady level at the end of the study period (a sharp increase in Ca is usually a good indication that pyrite had been oxidised to form acids, which when neutralised by lime form gypsum and calcium bicarbonate (the high solubility of calcium bicarbonate causes a sharp increase in measured Ca). Potassium also seems to reach a more or less steady level but the sodium and magnesium were on the increase. The increase of magnesium and sodium is most likely due to salts moving from the deeper layers to the surface layer after irrigation was ceased

(unfortunately the chemical attributes of the 30-60 cm layer were not monitored for each season).

The ratio of the cations (Ca:Mg:K:Na) at the end of the study period was of the order of 71:18:3:8 (100), compared to just after amelioration of 88:8:2:2 (100). Leaching had helped to get the ratios closer to "normal 65:25:8:2(100)" except for potassium, which is on the low side, and sodium on the high side. With amelioration high quantities of potassium were applied, for the chemical amelioration methods, but had either leached from the surface layer or been fixed in the precipitation of jarosite (KFe₃(SO₄)(OH)₆). Knowing the exact mechanism of potassium loss can help in managing potassium properly because it is a very important nutrient, especially for grasses.

Large amounts of dolomitic lime were applied during amelioration, especially for the chemical amelioration method (30 ton/ha), but the amount left over at the end of the study period is unknown because analyses of the acid potential to neutralisation potential of the tailings, due to financial constraints were not conducted. The increase in Ca after amelioration for the chemical amelioration methods was on average 8.4cmol+/kg indicating that for a dry density of 1.35 Mg/m³ about 17 tons of dolomite was dissolved. Therefore, theoretically 13ton dolomitic lime was still available for neutralisation of potential acidity.



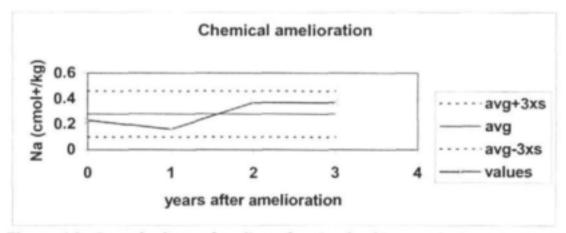
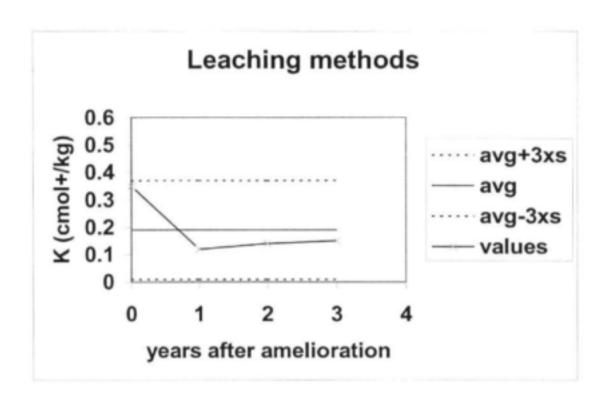


Figure 4.3 Control chart of sodium for the leaching methods and chemical amelioration methods over the study period.



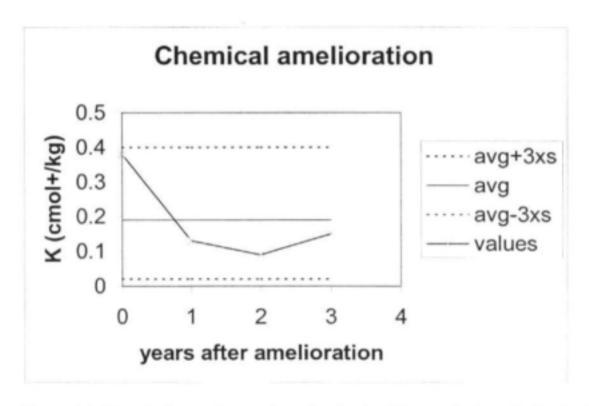
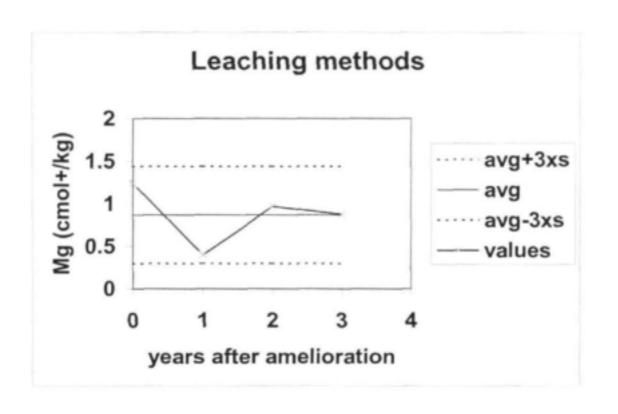


Figure 4.4 Control charts of potassium for the leaching methods and chemical amelioration methods



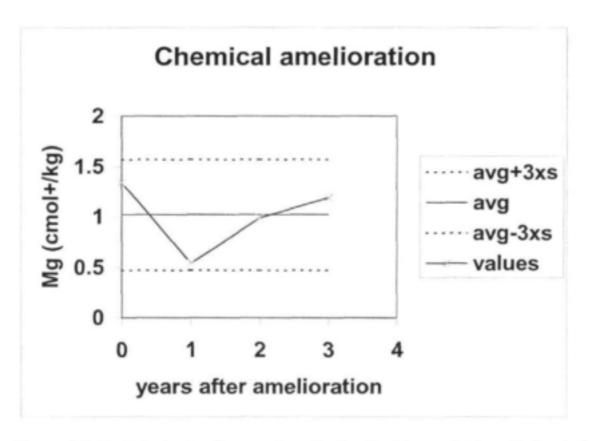
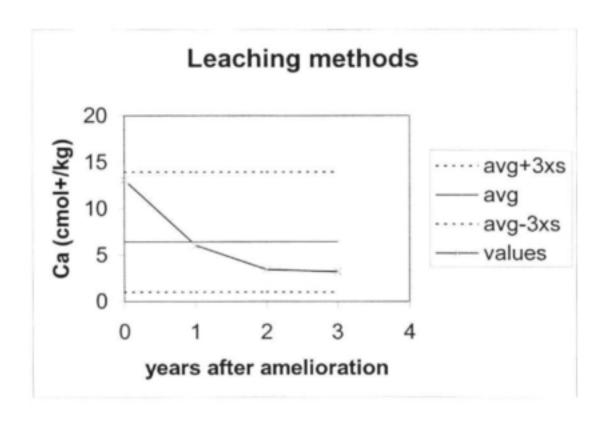


Figure 4.5 Control charts of magnesium for the leaching methods and chemical amelioration methods over the study period



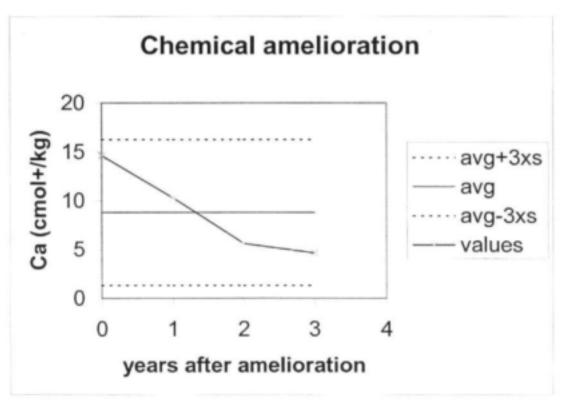
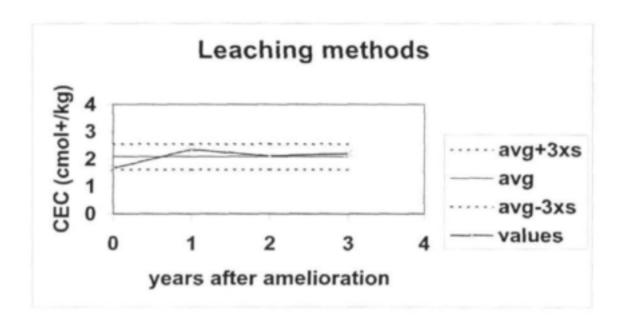


Figure 4.6 Control charts of calcium for the leaching methods and chemical amelioration methods over the study period

4.2.4 Cation exchange capacity

The pH and amount of organic matter influence the CEC of the tailings. As the pH, or organic content increases, the CEC increases (Figures 3.1a. and 4.7). The lowering of the CEC in the second season for the chemical amelioration methods could be an indication of the rapid decomposition of the added compost (because the pH had actually increased). The organic matter content was unfortunately not monitored. If the organic matter decomposes so rapidly then the increase in water holding capacity associated with the increase in organic matter content will also decline.



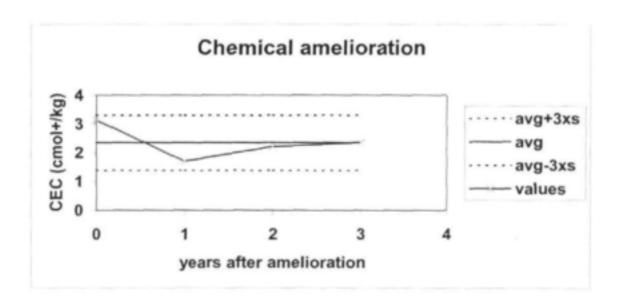
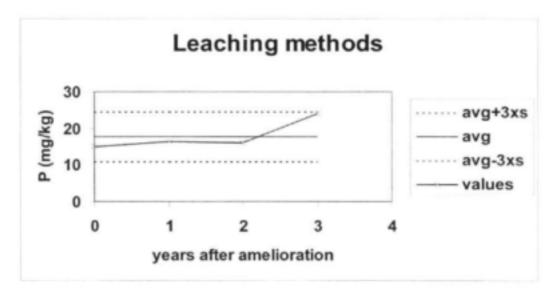


Figure 4.7 Control charts of the cation exchange capacity for the leaching methods and the chemical amelioration methods over the study period

4.2.5. Anions; phosphorus, sulphate, and chlorine

For the leaching and chemical amelioration methods the phosphorus, sulphate, and chlorine content increased rather sharply at the end of the study period (figures 4.9 and 4.10). For sulphate and chlorine, the increase could be due to salts moving through capillary rise from lower layers to the surface layer (this is also manifested by an increase in the sodium and magnesium content). Phosphorus on the other hand is characterised by a low mobility (Forstner & Kersten, 1988) and the increased phosphorus content cannot be attributed to phosphorus salts moving from lower layers by capillary action to the surface layer. The phosphorus concentration is largely controlled by the concentration of Fe, Al, and Ca ions (Bolt and Bruggenwert, 1976). At pH values above 7, Ca is the dominant cation controlling the concentration of phosphorus. The calcium content was at it lowest at the end of the study period (figure 4.6) and phosphorous sorption should therefore be lower.



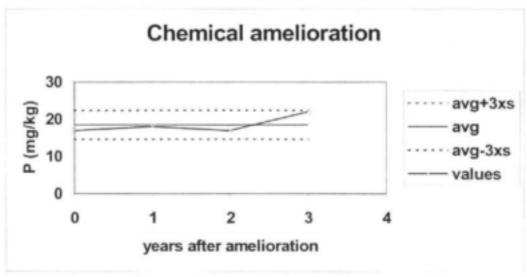
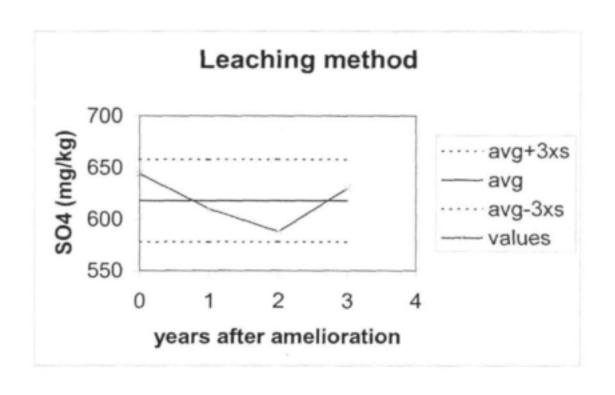


Figure 4.8 Control charts of phosphorus for the leaching methods and chemical amelioration methods over the study period



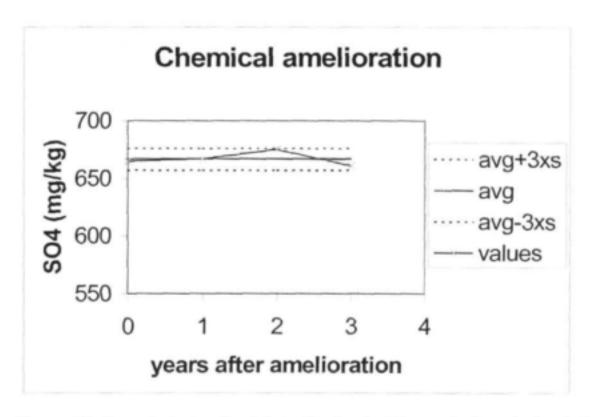
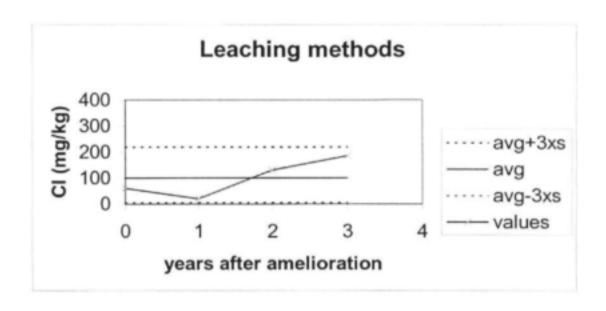


Figure 4.9 Control charts of sulphate for the leaching methods and chemical amelioration methods over the study period



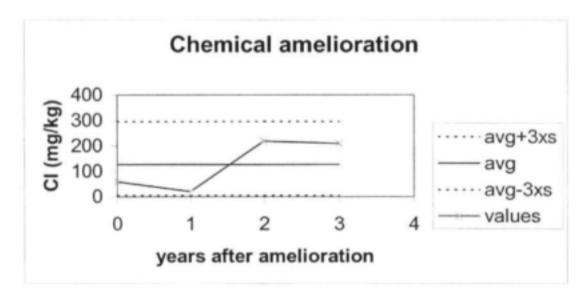


Figure 4.10 Control charts of chlorine for the leaching methods and chemical amelioration methods over the study period

4.3 The chemical attributes of the 30-60 cm layer

The chemical attributes of the 30-60 cm layer were not monitored each year, ruling out control charts. The values before amelioration, after amelioration and at the end of the project were used to give a picture of changes in chemical attributes in this layer. The changes of the chemical attributes for the 30-60 cm layer are schematically illustrated in histograms (figures 4.11 to 4.15)

A one-sided, two-sample t procedure was used to test the null hypothesis of no change of a specific chemical parameter after amelioration compared with that at the end of the project (in chapter 3 it was stated that there was no significant change in any chemical attribute after amelioration). Using P-values of <0.025 and <0.005 to reject the null hypothesis, chemical parameters that markedly changed for the different rehabilitation methods are summarised in Table 4.4

Table 4.4 Chemical attributes that had changed within the 30-60 cm layer over the study period

Chemical parameter	Method 1	Method 2	Method 3	Method 4	Method 5	Method 6	Method 7
pH	**	**	**	**	**	*	**
EC (mS/m)				*			*
Na		*			*		**
K		*			*		
Mg							*
Ca							
Al#							
CEC		*					
P							
SO ₄						**	**
C1					*	*	**

* P< 0.025> 0.005

** P ≤ 0.005

Method 1= Leaching

Method 2= Revised leaching

Method 3= Elementary amelioration

Method 4= Minimum cultivation

Method 5= Chemical amelioration

Method 6= Chemical amelioration (drip)

Method 7= Chemical Amelioration (sprinkler)

was not measured at the end of the project

The null hypothesis of all means of a given chemical attribute to be equal between the different rehabilitation methods was rejected and Scheffe's method was used to distinguish between differences in means for the different rehabilitation methods. The results are summarised in Table 4.5 for attributes that differ significantly at the 95% confidence interval between different rehabilitation methods.

Table 4.5 Chemical attributes that differs significantly at the 95% confidence interval between the different rehabilitation methods, according to the Scheffe method.

	M1	M2	M3	M4	M5	M6	M7
Mi	SECRETARIS .	li .	Ca				
М2			pH, SO ₄				EC, Na, Mg, Cl
М3	Ca	pH, SO ₄			pH, K, Ca	CEC	EC, K, Mg, Cl
M4							EC, Na, Mg
M5			pH, K, Ca			K, Ca, P, SO ₄	EC, Na, Ca, SO ₄
M6			CEC		K, Ca, P, SO ₄		SO ₄
М7		EC, Na, Mg, Cl	EC, K, Mg, Cl	EC, Na, Mg	EC, Na, Ca, SO ₄	SO ₄	29/05/20

M1= Leaching

M2= Revised leaching

M3= Elementary amelioration

M4= Minimum cultivation

M5= Chemical amelioration

M6= Chemical amelioration (drip)

M7= Chemical Amelioration (sprinkler)

For the leaching methods (M1, M2, and M4) there are no chemical attributes that differ significantly between the different methods. If the leaching methods are compared with the chemical amelioration methods the differences are related to M1, M4 and M7 in terms of EC, Na, and Mg. There is a build up of salts (EC and Na) for the drip and sprinkler irrigation systems indicating that the leaching requirement over

the last season of irrigation was not met. The higher Mg content of the chemical ameliorated methods can be attributed to the threefold higher dolomitic lime application. For the chemical amelioration methods the chemical attributes differ mainly in terms of EC, Na, Ca, and SO₄ and can be explained by the amount of leaching within these trials. The estimated amount of leaching in the last season of irrigation was 365, 0, and 166mm for M5, M6, and M7, respectively. The Na, Ca, and SO₄ contents are the lowest for M5, with the highest leaching, and the highest for M6, with the least amount of leaching.

4.3.1 pH, CEC and Aluminium

The pH had changed significantly towards the end of the project (Table 4.2 and figure 4.11), for all the rehabilitation methods. As indicated in chapter 3 all methods were actually leaching methods (for at least 18 months) and the change in the pH of the deeper layer can be attributed to the effect of leaching. The rooting depth ranges between 40 cm to 55 cm indicating that the lower layer had been changed into a favourable rooting medium. The increase in pH causes the free Al to precipitate removing the toxic effect of Al on plant growth (Al exists as free cations if the pH drops below 5.5, Hsu & Bates, 1964, Rowell, 1994). The Al was unfortunately not measured at the end of the project, although it will be low (if the regression equation of Figure 3.1b applies).

The CEC increased with the increase in pH but the change was only significant for the revised leaching method.

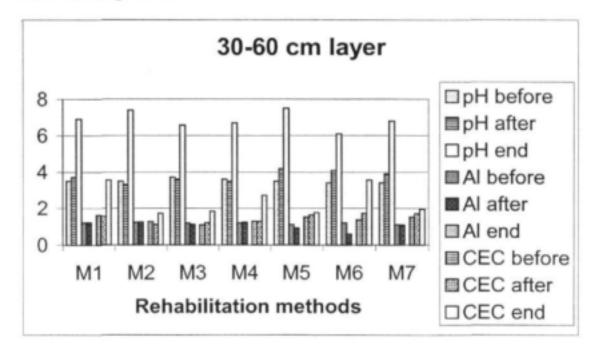


Figure 4.11. Change in chemical attributes pH, Al (cmol+/kg), and CEC (cmol+/kg) within the 30-60 cm layer over the study period

4.3.2 Electrical conductivity, sulphate, and chlorine

The sulphate and chlorine content increased significantly for the chemical amelioration methods under drip irrigation and sprinkler irrigation (Table 4.2 and figure 4.12). The increase in these parameters is attributed to insufficient leaching (less than the leaching requirement for the particular quality of irrigation water). For an irrigation efficiency of 60%, the estimated leaching fraction for the sprinkler system would be sufficient to prevent salt build up, which implies that the irrigation efficiency was lower than 60% (The drip irrigation system met the leaching requirement only for the first season). The EC changed significantly for the chemical amelioration method under sprinkler irrigation as well as for the minimum cultivation method.

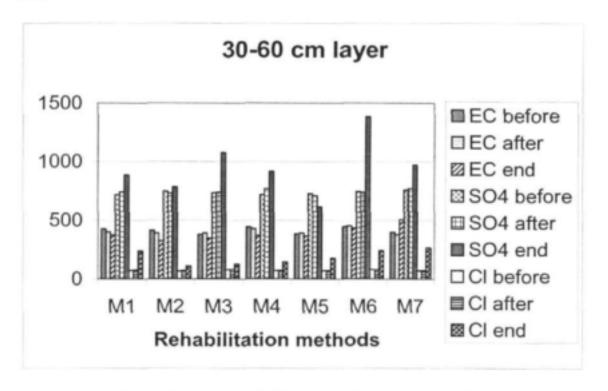


Figure 4.12. Changes in the electrical conductivity (mS/m), sulphate (mg/kg), and chlorine (mg/kg) content for the different rehabilitation methods over the study period

4.3.3. The cations Na, K, and Mg

For all methods, except the leaching method, the sodium content increases over time but the change was significant only for the revised leaching, chemical amelioration, and chemical amelioration under sprinkler irrigation methods (Table 4.2, figure 4.13). Potassium decreases for all methods but the change was not statistically significant. Magnesium decreases for all the leaching methods, and increases for all the chemical amelioration methods although the change was only statistically significant for the chemical amelioration method under sprinkler irrigation.

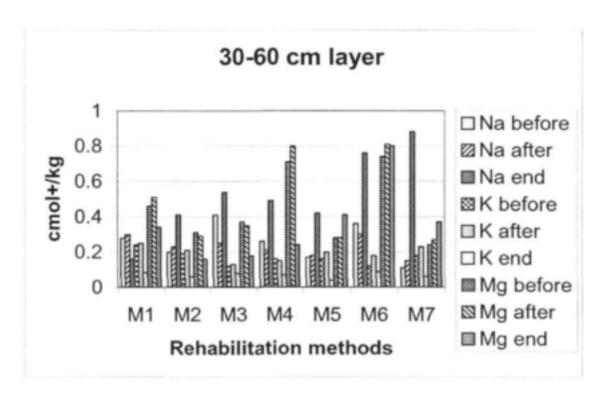


Figure 4.13. Change in the cations within the 30 to 60 cm layer for all methods over the study period

4.3.4 Calcium and phosphorus

In general the calcium decreased for the leaching methods (M1, M2 and M4) and increased for the other methods (figure 4.14) but none of the changes was statistically significant. For most methods the phosphorus increased over time but the change was not statistically significant (Table 4.2, figure 4.14).

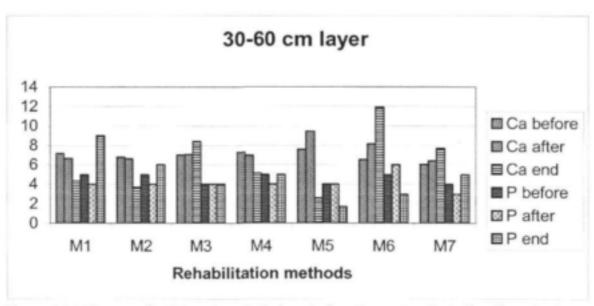


Figure 4.14. Change of calcium (cmol+/kg) and phosphorus (mg/kg), for all methods, over time.

4.4 Chemical attributes of tailings dams rehabilitated in the past using different rehabilitation methods

At present there are no set standards for the chemical attributes of rehabilitated tailings and, therefore, to assess the "tailings quality" obtained in this study it was decided to compare the chemical attributes of this study with the chemical attributes of tailings rehabilitated in the past, which currently support a good vegetation cover. The following tailings dams were selected to represent the different methods:

- 1. Leaching method (selected by Mr Cook and Mr Dawson)
 - 1L1 East Champ D'or (vegetated in the early 1960's)
 - 2L3 Consolidated Main Reef (Fleurhof- vegetated late 1960's)
 - 3L44 City Deep (Wemmer Pan-vegetated in the late 1970's)
 - 4L48 East Rand Proprietary Mines (ERPM Dam 1-vegetated in the mid 1990's)
 - 4L50 ERPM Dam 4-vegetated in the mid 1990s
 - 2L24 Durban Roodepoort Deep –vegetated in mid 1990's
- 2. Chemical amelioration (selected by Mr van Deventer)
 - Stilfontein no 5 –vegetated in 1993
 - Saaiplaas –vegetated in 1996
 - PS 5- vegetated in 1999
 - Oryx –vegetated in 1997
 - 2L24 DRD-vegetated 1999
- 3. Others
 - PS 3-vegetated 1996 (revised leaching)
 - Beatrix –vegetated mid 1990's (topsoil)

The chemical analyses of the tailings from these dams are presented in Appendix C.

Only the data from the leaching and chemical amelioration methods will be discussed. A one-sided, two-sample t procedure was used to test the null hypothesis of no difference for a specific chemical parameter between tailings rehabilitated in the past and tailings rehabilitated in this study. Using P-values of <0.025 and <0.005 to reject the null hypothesis, chemical parameters that markedly differ are summarised in Table 4.6.

Table 4.6. Chemical parameters that markedly differ between tailings of other rehabilitated dams and tailings rehabilitated in this study

Chemical attribute	Leach/OL 0-30 cm	Leach/OL 30-60 cm	Che/Och 0-30 cm	Che/Och 30-60 cm	Che/OL 0-30 cm	Che/OL 30-60 cm
рН		**		**		*
Na	**	**			*	**
K	**	**			**	*
Mg	*			*		
CEC	**				*	
Cl	**	**			**	++

^{*}P<0.025 > 0.005

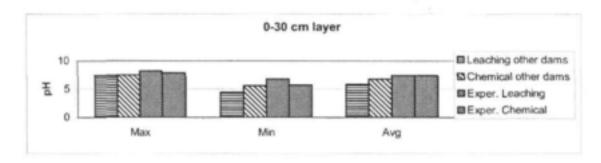
^{**} P<0.005

Leach/OL-leaching of this study compared to leaching of other dams

Che/OL-chemical method of this study compared to leaching of other dams

Che/Och-chemical method of this study compared to chemical method of other dams

The differences between the chemical attributes for the different methods are also schematically illustrated in Figure 4.15 to 4.25. The differences in terms of pH, K, and Mg are on the positive side for the experimental sites as these values are higher (more favourable for plant growth) than the present status of these parameters for the other rehabilitated dams. The pH value of the 30-60 cm layer is in some instances very low (below 4) implying a high Al content. The root development within this zone was however fairly good indicating that Hyparrhenia hirta is well adapted to high Al levels. If the chemical parameters can be kept within the upper and lower control limits in future (through land management) then the tailings of the experimental sites should have a better overall chemical quality. The negative differences are in terms of Na and Cl, which were higher for the experimental sites. These higher values cannot be attributed to the rehabilitation method per se but rather to the geology or quality of the irrigation water. The Karoo sedimentary rocks, in the Welkom area are characterised by high sodium and chlorine contents and the fossil waters in the gold bearing strata is of low quality. Karoo sedimentary rocks are absent in the Johannesburg area where the other leaching dams were situated. High sodium contents (ESP>15) had primarily a negative effect on the physical conditions of soils. However, even if all the sodium were adsorbed (ESP=28), the negative effect would be minimal because of the low clay content (±3%) and high salt content (S-value>>Tvalue). Therefore, if a stable vegetation cover could be sustained by the present chemical quality of other rehabilitated tailings, then the tailings quality of the experimental sites, if maintained, should also be able to support a stable vegetation cover



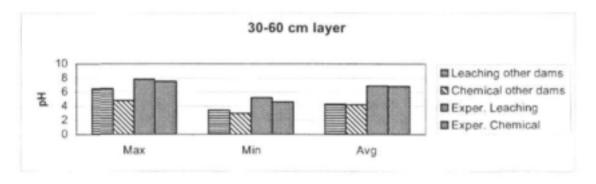
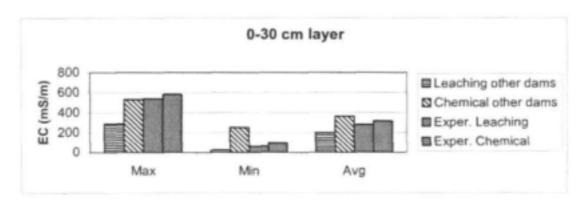


Figure 4.15. The range of pH values for other rehabilitated dams compared to the range in pH values of the experimental site tailings at the end of the study period



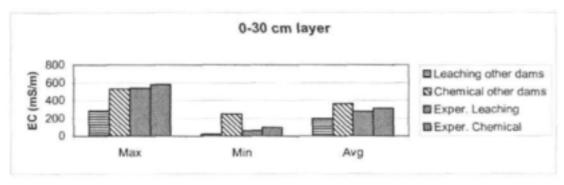
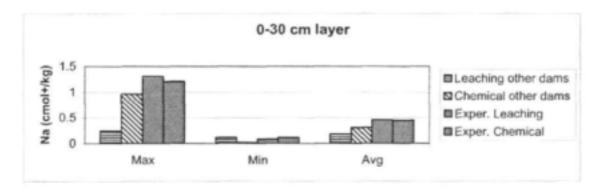


Figure 4.16. The range of values of the electrical conductivity for other rehabilitated dams compared to the values of the experimental site tailings at the end of the study period



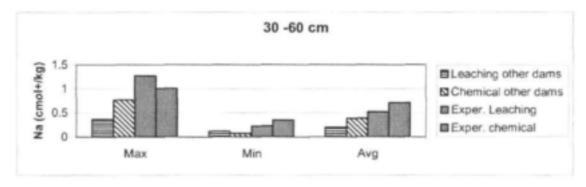


Figure 4.17. The range of values for sodium in other rehabilitated dams compared to the values of the experimental site tailings at the end of the study period

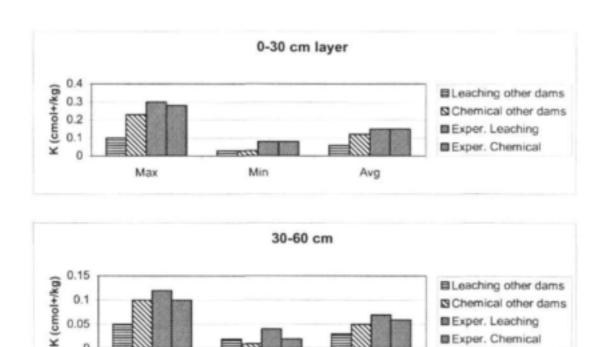


Figure 4.18. The range in potassium content of other rehabilitated dams compared to the potassium content of the tailings at the end of the study period

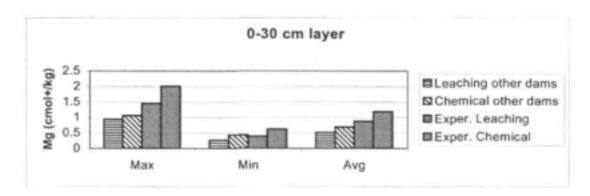
Avg

Min

0

Max

Exper. Chemical



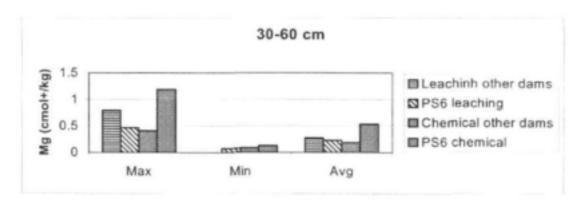
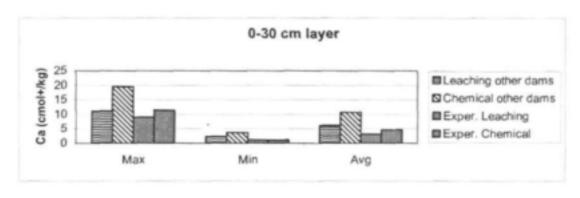


Figure 4.19. The range in magnesium content of other rehabilitated dams compared to the range in magnesium content of the tailings at the end of the study period



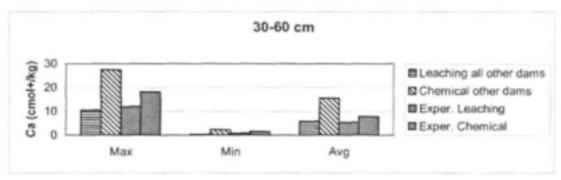
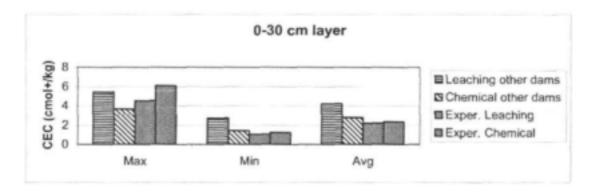


Figure 4.20. The range in calcium content of other rehabilitated dams compared to the calcium content of the experimental site tailings at the end of the study period



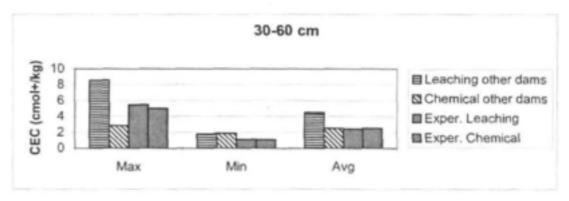


Figure 4.21. The range in cation exchange capacity of other rehabilitated dams compared to the cation exchange capacity of the tailings at the end of the study period

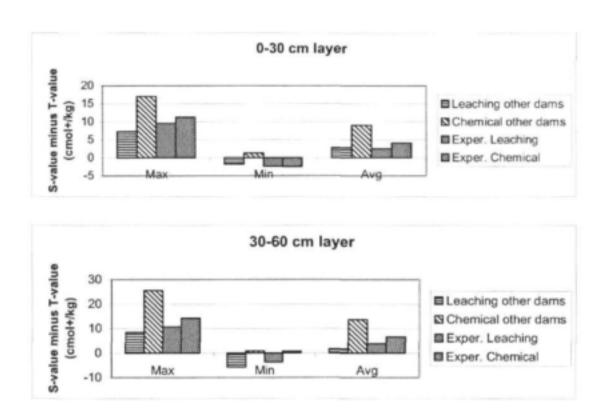


Figure 4.22. The range in free salt content of other rehabilitated dams compared to the free salt content of the tailings at the end of the study period

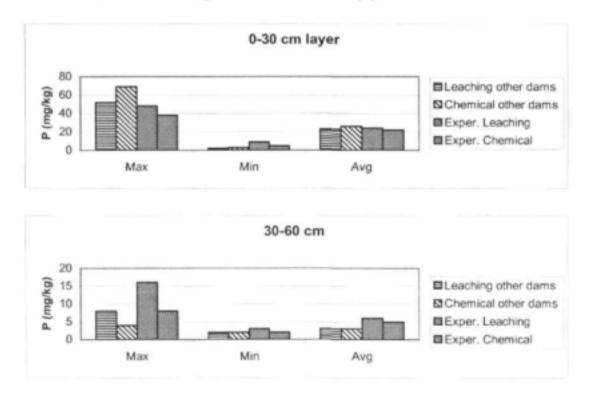
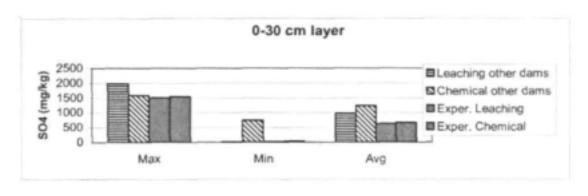


Figure 4.23. The range in phosphorus content of other rehabilitated dams compared to the phosphorus content of the experimental site tailings at the end of the study period



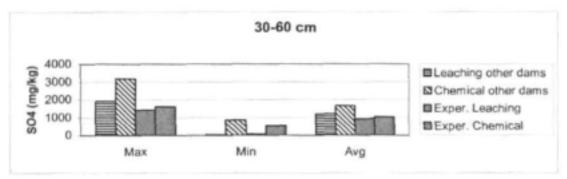
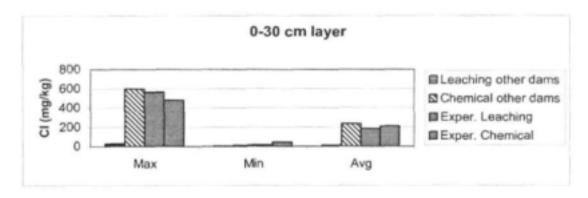


Figure 4.24. The range in sulphate content of other rehabilitated dams compared to the sulphate content of the experimental site tailings at the end of the study period



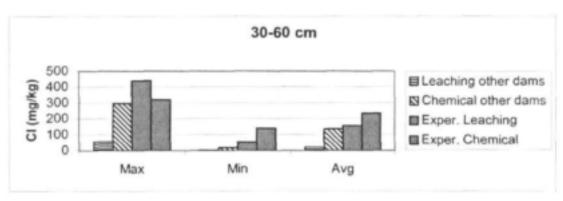


Figure 4.25. The range in chlorine content of other rehabilitated dams compared to the chlorine content of the experimental site tailings at the end of the study period

4.5 Discussion and conclusions

Vegetation establishment problems that can be associated with tailings, were earlier identified to include (van der Nest, 1994):

- · Deficiency in available nutrients,
- · An acid generating potential,
- · High salt content,
- · Heavy metal toxicity,
- · A low water retention capacity,
- · High runoff,
- · Poor aeration properties, and
- · Very low buffer capacity (low exchange capacity).

Leaching method

The leaching method addressed the deficiency in available nutrients through fertilisation, the acidity through leaching and liming, and the salt content through leaching. Heavy metal toxicity, although not monitored, is likely to be reduced through an increase in pH, as most of these elements tend to precipitate as hydroxides at a pH \geq 6.5. Free Al was monitored and definitely precipitated once the pH increased above 6. The leaching of free salts, as monitored through the electrical conductivity, was obscured because of the formation of ion pairs due to the high SO_4^2 content of the tailings. The percentage decrease in excess salt, taken as the excess of cations (S-value minus T-value), was plotted against the estimated leaching fraction (for all methods) and the following relationship was fitted to the data

$$log(100-y) = log100 - c(LF)$$

where y is the % excess cations leached, c is a constant, and LF is the leaching fraction in mm. For the best fit the value of c was 0.00041 and the coefficient of determination R² was 0.91. Using the equation the amount of salts leached for different LF was calculated and summarised in Table 4.7.

Table 4.7 Amount of salts leached as percentage of the total free salts after amelioration

LF (mm)	% free salts leached	Increase in salt leached
0	0	-
250	21	21
500	38	17
750	51	13
1000	61	10
1250	69	8
1500	76	7
1750	81	5
2000	85	4
2250	88	3

Assuming that for a leaching input of 250 mm, the return in % salt leached should be at least 10%, then the required leaching fraction would be 1000 mm. For a leaching fraction of 1000 mm, taking into account the amount of rainfall, the amount of irrigation water needed was about 1400 mm. At an application rate of 5 mm/day the total time needed for leaching would be 280 days. For this particular tailings dam, irrigation in terms of leaching could be stopped after nine months, which is the lower limit according to the guidelines provided (Section 2.5.1). The pH was above 6.5 within the 30-60 cm layer for all leaching methods after one year of leaching.

The CEC did increase slightly (though not significantly) due to an increase in pH. The total amount of water leached through the root zone, over the study period, was estimated at 2250 mm. For this estimated amount of leaching, 87% of the excess salts should be leached. The average excess salts after amelioration was 13.75 cmol+/kg and therefore at the end of leaching the value should be 1.8 cmol+/kg (the actual value after leaching was 2.33 cmol+/kg). The overall chemical quality of the tailings after leaching, compared to other rehabilitated tailings dams, is more than satisfactory to sustain a stable vegetation cover. The physical constraints of the tailings have, however, not been addressed.

The leaching method is suitable to change the chemical attributes of oxidised tailings (most of the potential acidity already converted to active acidity) but will be questionable for relatively fresh un-oxidized tailings because then only free salts can be removed (no acids can be removed).

Chemical amelioration method

The chemical amelioration method addressed the deficiency in available nutrients through fertilisation, the acidity through liming, the salt content through composting, the heavy metal toxicity through liming and composting, the low buffer capacity through composting, the water holding capacity through composting and aeration through cultivation (300 mm). As for the leaching method, fertilisation and liming were effective to elevate nutrient deficiencies, neutralise acidity, and eliminate Al toxicity. The effect of compost on salt content could not be evaluated rigorously because leaching also took place for the chemical amelioration method although less than for the leaching method. The estimated amount of water leached through the root zone, over the study period, was 865 mm (about 38% of the leaching method). The estimated excess salt should be 5.95 cmol+/kg at the end of leaching (the actual amount after leaching was 4.87 cmol+/kg). The compost in combination with liming did improve the CEC significantly but the change was not permanent, indicating that the compost decomposed rapidly. The compost also improved the water holding capacity significantly, but it was not monitored over the study period (this change was most likely temporary considering the rapid decomposition of the compost). Cone penetration tests indicated that the effective cultivation depth was about 170mm.

The chemical amelioration method is suitable to change the tailings material into a favourable growth medium for plants but the effectiveness of composting in improving the chemical- and physical properties of the tailings could not be properly assessed. The chemical amelioration method can be applied to un-oxidized tailings but uncertainty exists if applied to tailings with a high salt content with no leaching.

Future chemical conditions

The tailings condition at the experimental site were very favourable for the establishment of vegetation because the elementary amelioration method, with only 10 ton lime/ha and without a leaching programme, had chemical conditions similar to that of the leaching and chemical amelioration methods. If these experiments were conducted on tailings with harsher constraints on vegetation establishment, then the differences between the different methods could be more pronounced. On the long-term differences between the methods may arise because for the leaching methods, the future oxidation of pyrite will cause a lowering in pH but without a significant change in the salt content of the tailings. For the chemical amelioration method, where additional lime was added to neutralise potential acidity that can be generated, the pH will remain more or less constant but the salt content will increase. Over time the tailings will become probably more acidic for the leaching methods while for the chemical amelioration methods the tailings will become probably more saline.

In this study all methods could change the tailings into a favourable growing medium for grasses. There were only minor differences between the chemical attributes of the growing medium obtained through a leaching approach and the growing medium obtained through a chemical amelioration approached despite large differences in inputs.

Chapter 5

Vegetation monitoring

5.1 Introduction

The objective of the research project was to identify the rehabilitation method, which will produce the most sustainable vegetation cover at the end of the rehabilitation period. The question is how to evaluate a rehabilitation project or the sustainability of the vegetation cover.

The method of evaluating rehabilitation projects is largely a function of how rehabilitation is viewed. According to Bradshaw & Chadwick, (1980) certain rehabilitation scientists believe that if you cannot recreate the original system, then it is not worth doing rehabilitation work. In such cases the original land use or level of production is used to measure the success (quality) of rehabilitation. The purpose of many vegetation rehabilitation schemes is to overcome problems associated with abandoned land, and rehabilitation is therefore an ecological problem aimed at the establishment of a stable, self-sustainable ecosystem (Bradshaw, 1996). In this case the rehabilitation scheme must be evaluated according to the defined efforts and standards that were used. According to Cairns et al., (1996), self-sustainability can be regarded as a process of self-maintenance, and the existence of sufficient integrity in the ecosystem so that existing natural processes will keep the ecosystem intact. According to Barnard, (1995) rehabilitation should be aimed at satisfing the demands of sustainable development. The only way conditions achieved through rehabilitation can be viewed as sustainable, is if the economic value of the new resource is equal to the value of the resource that was destroyed during development (Barnard, 1995). It is clear from this definition that economic value is the criterion that is used to indicate rehabilitation quality. According to Mentis and Ellery (1994) the emphasis of rehabilitation should be the restoration of a natural dynamic state of ecological communities comprising of strongly or weakly interacting species. For this approach, Mentis and Ellery (1994) determined the rehabilitation success by comparing whether established vegetation on disturbed mine land was similar to vegetation on disturbed land not influenced by mining (e.g. road verges) that will converge to a similar climax vegetation state.

Most of the statements from authors in the previous paragraph refer to naturally degraded or disturbed soils, whereas the current research project addressed the revegetation of a man made feature resulting from mining. The "sediment" of this manmade feature will never revert to a medium similar to the surrounding soils. The "sediment" can, however, be ameliorated to a suitable growing medium, but this growing medium will place certain constraints on the final self-sustaining vegetation community that develops.

Thatcher (1979) studied the vegetation established on the tailings dams of the Witwatersrand. Important findings of the study were:

- A Hyparrhenia dominated community can be regarded as the secondary succession climax on tailings dams
- On tailings dams with a high basal cover (10-12%), Eragrostis curvula was the most important species

Cilliers (1998) regarded the *Hyparrhenia hirta* community as the most successionally advanced stage along road verges. Other rehabilitated tailings dams sampled in this study (previous chapter) were characterised by either a *Hyparrhenia*, an *Eragrostis* or a *Chloris* dominant plant community (Appendix C).

5.2 Monitoring as part of the rehabilitation process

During the rehabilitation process, certain ecological principles are applied, and if those principles are incomplete, the ecosystem will not function properly (Bradshaw, 1996). Re-established vegetation communities may either develop into a self-sustained ecosystem, or gradually deteriorate and retrogress to a state in which no regeneration of perennial plants occur, accompanied by an increase of bare patches (Bradshaw & Chadwick, 1980). Evaluation and monitoring not only help to steer the rehabilitation process by detecting shortfalls and maintenance problems, but also create a tool to test and refine our knowledge of rehabilitation itself and the ecological principles controlling it (Smyth, 1997). Mentis (1989) defined monitoring as the regular surveillance to test the null hypothesis of no change in predefined properties of a system which is vulnerable to impacts, the nature, timing and location of which are not necessarily known.

Morgenthal (2000), by monitoring, species frequency, basal cover, plant density, and biomass, during the period December 1996 to March 1999 was able to:

- Describe the community development over space and time
- Assess the vegetation in respect of ecological stability
- Evaluate the rehabilitation process in terms of community characteristics (species composition, life form spectra, diversity and biomass) and dynamics (vegetation change and rate of change)

for rehabilitated ash disposal sites, that were rehabilitated 1 and 7 years prior to the initiation of the monitoring program.

5.3 Approach, hypothesis and assumptions

The ability to initiate and maintain vegetative cover will be the final, most important, test of any rehabilitation project (Bradshaw, 1996). No guidelines for the assessment of the sustainability and rehabilitation success are provided by mining legislation in South Africa. For this study it was decided to use the plant communities presently occurring on vegetated tailings dams, with a good vegetative cover, as benchmarks to assess the quality of the rehabilitation methods used in this study. Apart from a good vegetation cover, the other criteria applied in the selection of the dams was that at least one of the seed mixtures used in this study, was used in the rehabilitation of these dams.

Hyparrhenia dominated on: East Chamd'or*, Fleurhof*, Wemmer pan* (all rehabilitated more than 30 years ago)

Eragrostis dominated on: ERPM Dam* 4, Stilfontein no 5 dam⁺ (rehabilitated 9 years ago)

Chloris dominate on: PS 5+, Saaiplaas 4+ and Oryx+ (rehabilitated 5 to 6 years ago)

^{*}Seed mixture used for methods 1 to 4

⁺ Seed mixture used for chemical amelioration methods 5 to 7

The hypothesis is that:

 The vegetation established under different rehabilitation methods should progress towards one of these dominant benchmark communities.

The assumptions made were:

- · These species are well adapted to the conditions prevailing on tailings dams
- Rehabilitation methods showing a trend in moving towards one of these dominant communities reveals a measure of success
- Environmental characteristics can modify species occurrence
- Sustainability of the vegetation cover is a function of community stability and species diversity

5.4 Procedure: Botanical surveys conducted

The current study involved evaluation of the alpha-diversity (specie evenness and richness), beta-diversity and basal cover. Each rehabilitation method was assessed annually (during March) using the wheel point technique to determine the frequency of species occurrence and plant basal cover. The upper 5m, the lower 6m and 2m along the edges of each plot was excluded because given the small plot sizes, plant performance may have been influenced by irrigation, species composition of bordering plots, amelioration methods of bordering plots and shade effects on the slope. Within each transect, the marked spikes of the wheel, was used to determine plant basal cover by scoring when the point of the spike intersected rooted living plant material at soil surface. The marked point was then scored as a hit and the plant species recorded. When the point failed to strike plant material, or the plant material struck was not rooted or living, the marked spike point was scored as a miss and the nearest rooted plant was recorded. The total number of hits expressed as a percentage of total points provides a measure of basal cover for a plot. The relative abundance of plant species is determined by the total number of occurrences of each species recorded expressed as a percentage of total points scored within a single plot. The results obtained from these studies are summarised in Tables (Appendix B) and consolidated in Table 5.1.

The main factors influencing species composition should be differences in rehabilitation methods (seed mixture and amelioration), and differences between the three years of surveys (succession and environmental stability). The average frequency of species occurrence and the standard deviation was calculated from the values obtained from the four replicate plots for a given rehabilitation method. The results are summarised in Appendix B. A one-sided, two-sample t procedure was used to test the null hypothesis of no change of a specific species with time for a given rehabilitation method.

[Remark: the 2000 vegetation survey was for a method as a whole and is a composite average, the standard deviation is unknown and the null hypothesis could not be tested between the 2000 and 2001 or 2000 and 2002, survey data]

Table 5.1 Species frequency (%) of the different rehabilitation methods over the study

period

Species		M1	1-00					M3		M	14	
	00	01	02	00	01	02	00	01	02	00	01	02
Eragrostis curvula	3.9	11	8.5	5.1	- 11	12.8	7.1	26	22	8.2	15	16.8
Dactylis glomerata	35.6	55	51.5	25	60	52.3	25.1	38	47	15.6	41	40
Lolium perenne	9.1		0	11.4	6	2	7.4	7	0	7.5	2	1.3
Cynodon dactylon	0.7	2	1	3.9	3	1.8	3.2	- 1	1.3	3.4	0	2.8
Polypogon monspeliensis	0			0	2	0.5	0			0		
Hyparrhenia hirta	0	1	0	0	0	0	0	0	0	0	.0	0
Chloris gayana	36.3	- 1	3.5	45.5	0	0.5	48.4	1	0	59.2	2	0.5
Agrostis tenuis	0	0	7.3	0	0	6	0	0	2	0	0	4.5
Cynodon aethiopicus	0.9			2.8			1.6			0	0	()
Festica elatior	9.7	0	0	3.6	0	0	5.7	0	0	4.1	0	0
Eragrostis tef	2.3	0	0	0	- 0	0	0.7	0	0		0	0
Medicago sativa	1.5	27	16.8	2.8	15	15.5		24	18	2	33	15.8
Melilutus alba	0	1	0.5	0	2	1.8	0		6.5	0	2	1.8
Atriplex semibaccata		*		0	*	0	0.8	- 1	0.5	0		2
Convza bonariensis		0	4.5		0	3.5		0	0	*	0	7.3
Cirsium vulgare	0	0	2.5	0	0	1.8	0	0	1	0	0	3.8
Lactuca serriola	0	0	3	0	0	1.3	0	0	1.8	0	0	3.3
Basal cover %	6.2	6.3	3.8	7.3	7.5	2.8	6.1	6.8	2.8	5.4	7.5	2.5
		M5			M6			M17				
	00	01	02	00	01	0.2	00	01	02			
Eragrostis curvula	20	28	40.3	26.9	16	17.8	23.6	18	29.3			
Dactylis glomerata	0	7	8	0	5	5.5	0	0	2.8			
Lolium perenne	0	2	0.5	0	- 1	*	1.2	2	0			
Cynoden dactylon	7.2	6	1.8	25.2	2	8.3	7.7	10	1.5			
Polypogon monspeliensis	1.5	1	*	2.6	7	2.8	2.8	0	*			
Hyparrhenia hirta	0	3	0.5	0	0	0	0	0	0.5			
Chloris gayana	62.8	0	0.5	36.7	0	0	37.9	2	0.5			
Agrostis tenuis	0	0	0.5	0	0	0	0	0	2.3			
Eragrostis tef	6,3	0	0	6	-0	0	12.6	0	0			
Medicago sativa	1.5	41	27.8	1.7	69	28.5	11.9	65	27.8			
Melilutus alba	0.7	10	5.3	0.9		3.8	2.3	2	7.8			
Atriplex semihaccata	0	1	0	0	*	()	0	2	0.3			
Conyza bonariensis		0	8.3		0	9.3		0	18.5			
Cirsium vulgare	0	0	3	0	0	8.8	0	0	2			
Lactuca serriola	0	0	3	0	0	4.8	0	0	6.8			
Basal cover %	4.6	5.5	4.7	4.9	5	2.5	4.1	7.3	3.3			

*Less than 0.5%

M1=Leaching method

M2=Revised leaching method

M3=Elementary amelioration method

M4=Minimum cultivation method

M5=Chemical amelioration method

M6=Chemical amelioration method (drip irrigation)

M7=Chemical amelioration method (sprinkler irrigation)

5.5 Discussion of results

5.5.1 Vegetation change

The change of the most dominant species over the three-year period is illustrated in histograms for each rehabilitation method (Figures 5.1 to 5.7). The average and standard deviations of the dominant species is summarised in Tables B4-B17 (Appendix B).

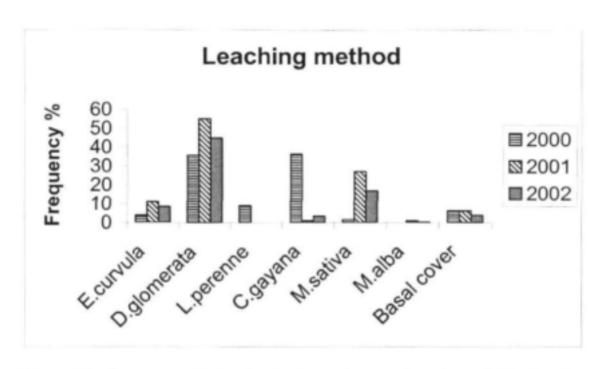


Figure 5.1. Frequency of the dominant species on the plots of the leaching rehabilitation method over the study period

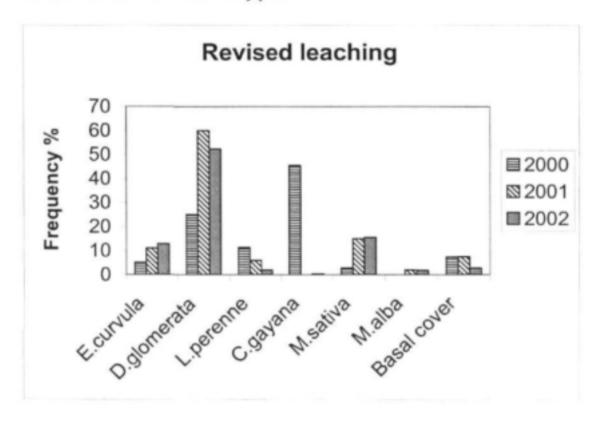


Figure 5.2 Frequency of dominant plant species on the plots of the revised leaching method over the study period

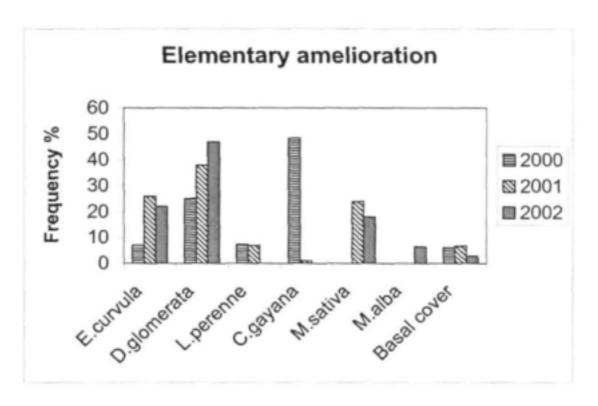


Figure 5.3 Frequency of the dominant plant species on the plots of the elementary rehabilitation method over the study period

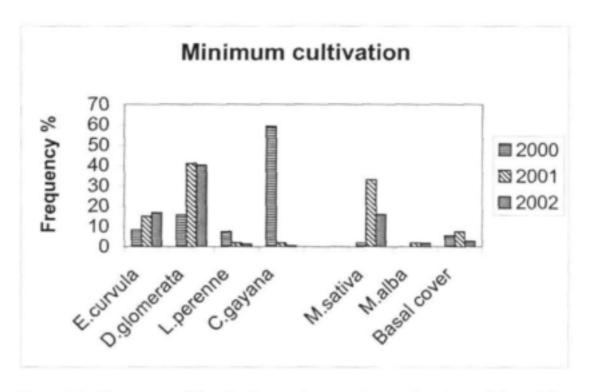


Figure 5.4. Frequency of the dominant plant species on the plots of the minimum cultivation method

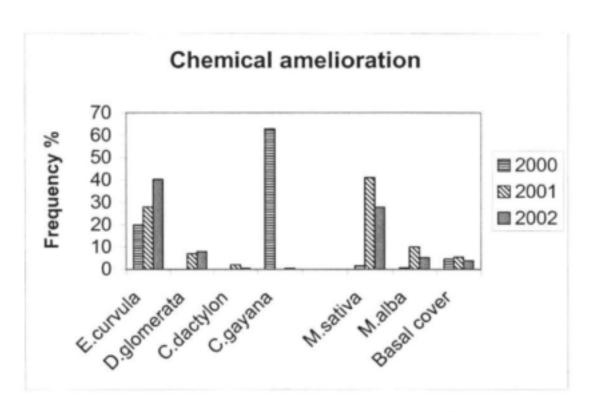


Figure 5.5 Frequency of the dominant plant species on the plots of the chemical amelioration method

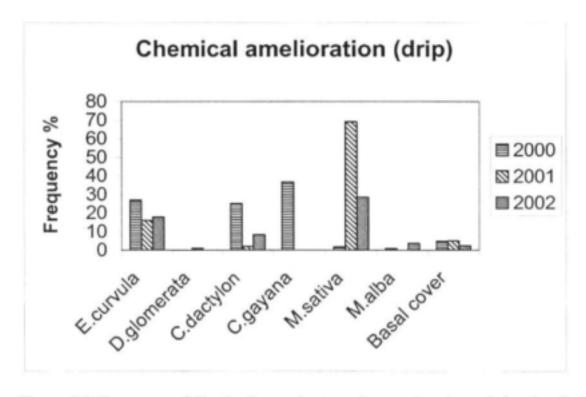


Figure 5.6 Frequency of the dominant plant species on the plots of the chemical amelioration method with drip irrigation

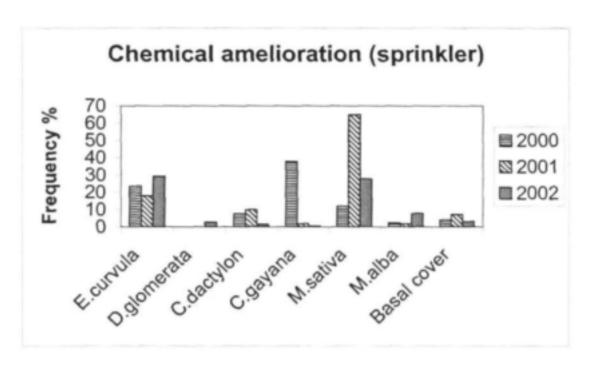


Figure 5.7 Frequency of the dominant plant species on the plots of the chemical amelioration method with sprinkler irrigation

One of the major questions asked about rehabilitated sites is the stability of these systems. According to Barbour et al. (1987), a stable ecosystem can be defined as an ecosystem with lack of change in vegetation composition and the dominance of longlived species. Qualitatively, the results indicate that all annual grasses in the original seed mixture (e.g. Eragrostis tef) disappear within 18 months from the experimental sites. Chloris gavana, a perennial, although the dominant grass species in the initial stages of the experiment, had disappeared within two years from most of the experimental plots. Eragrostis curvula steadily increased, over the study period, for most of the methods. Medicago sativa peaked in the second season for all methods and is the sub-dominant species, at the end of the study period, for most of the methods. Dactvlis glomerata is the dominant grass species for the leaching methods. The only species used in the seed mixtures that were frequently recorded are Eragrostis curvula, Dactylis glomerata, Lolium perenne, and Medicago sativa for the leaching methods, and Eragrostis curvula, Cynodon dactylon, Medicago sativa, and Melilutus alba for the chemical ameliorated plots. Dactylis glomerata and Lolium perenne were the only grass species that colonised the chemical amelioration plots from the leaching plots. The most dominant species, at the end of the study period, for the leaching methods were Dactylis glomerata, Medicago sativa and Eragrostis curvula and for the chemical amelioration method, Medicago sativa, Eragrostis curvula and Dactylis glomerata.

If Agrostis tenuis, Conyza bonariensis, Lactuca serriola, and Cirsium vulgare had not appear at the end of the study period on all plots then one could conclude that the revegetated ecosystem is stable in terms of dominance of long-lived species and lack of change in plant composition. However, plant community development is dependent on prevailing environmental conditions and is, therefore, one of the most important driving forces, besides competition, in community development.

Environmental characteristics

The three most important environmental characteristics that determine environmental stability are the growing medium, climate, and disturbances. The most important limiting factors for each with respect to re-vegetation of tailings dams are fertility, drought, and fire. The chemical, physical, and biological components of fertility will be discussed separately. Other physical habitat factors are slope gradient and aspect.

Chemical

As indicated in Chapter 4 both the leaching method and the chemical amelioration methods had turned the tailings into a growing medium, which is able to support vegetation. The average chemical attributes of the tailings (at the end of the study period) for the leaching and chemical amelioration methods as well as that of the surrounding soil is summarised in Table 5.2

Table 5.2 Chemical attributes of the surface 30 cm layer

	pH (H ₂ O)	EC mS/m	P mg/kg	Na*	K*	Ca*	Mg*	CEC*
Leaching methods	7.4	278	24	0.46	0.15	3.22	0.88	2.20
Chemical methods	7.4	314	22	0.37	0.15	4.65	1.19	2.35
Surrounding soil	6.3	25	1	0	0.50	1.70	0.80	4.90

^{*}cmol+/kg

The most important differences in chemical attributes between the tailings and surrounding soil are, EC, P, K, Ca, and CEC. (The surrounding soil seems to be slightly contaminated by AMD, hence the slightly acidic pH and S-value < CEC. Soils in the vicinity of the dam contain free lime). The tolerance levels of plant species occurring in the surrounding veld may be high enough to resist these differences in chemical attributes, and annuals (weeds) occurring on the surrounding soils such as Conyza bonariensis, Lactuca serriola, and Cirsium vulgare can colonise on the ameliorated tailings. Because there is no statistically significant difference between the chemical attributes of the leaching and chemical ameliorated methods, the species can colonise on all plots. The high phosphorus content of the ameliorated tailings can restrict perennials such as Themeda triandra, occurring in the surrounding veld, from colonising the tailings dam.

Physical

The physical conditions of the slimes were not monitored but are of importance in relation to plant growth in terms of water storage, gas exchange, energy (heat) exchange, and root development in general. Root development also depends on plant genotype, chemical attributes of the growing medium, and microbial factors (Singer & Munns, 1992). Root distribution and penetration resistance were measured in March 2001. The penetration resistance was measured after a 47 mm rainfall event that should have provide a uniform water content in all the experimental plots and thus eliminate water content as a factor in determining penetration resistance. Extensive work has shown that root growth slows dramatically, or even ceases altogether, when the cone penetration resistance exceed about 2000 kPa (Bengough & Mullins, 1990). From the cone penetration resistance values obtained (see Appendix

D), the percentage unrestricted root development (taking 2000 kPa as growth restriction for roots), for 5 cm increments in the tailings were calculated and are presented in figure 5.8

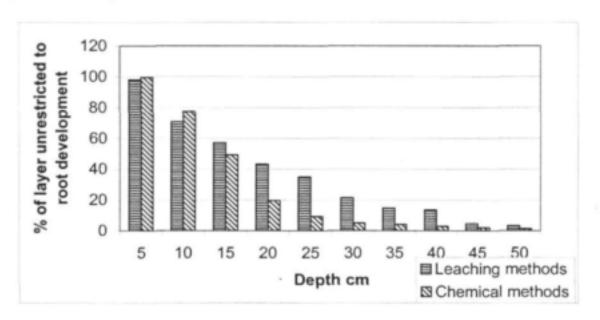


Figure 5.8 Percentage of layer unrestricted for root development, based on a penetration resistance limit of 2000 kPa.

In each of the experimental plots, test pits to a depth of 70 cm were dug, and the root abundance recorded on a scale of frequent (100-60%), medium (60-20%) and rare (<20%) (Table 5.3)

Table 5.3 Depth (cm) of root abundance

Experimental method	Frequent	Medium	Rare
Leaching (1)	5	30	45
Revised leaching (2)	11	28	50
Elementary amelioration (3)	21	37	42
Minimum cultivation (4)	8	20	32
Chemical amelioration (5)	13	25	49
Chemical amelioration (6)(drip)	13	29	47
Chemical amelioration (7) (sprinkler)	47	57	
Average methods (1,2 and 3)	12.3	31.6	45.6
Average methods (5 and 6)	13	27	48

Method 4 and 7 do not fit in the general pattern, in that method 4 with the least restriction for root development had the poorest root development and method 7 with the highest root restriction had the best root development. If the average root restriction values for the leaching methods (1,2, and 3) are compared with that of the chemical amelioration methods (5 and 6) (Figure 5.8) then the average values in Table 5.3 agree fairly well with the root restriction values. The lower level for frequent root abundance was 60% indicating that for both the leaching and chemical amelioration methods the depth of frequent root occurrence should be between 10 and 15 cm. For the medium root abundance the lower limit was 20 % indicating that for the leaching method the depth should be slightly more than 30 cm and for the chemical method the

depth should be 20 cm (Figure 5.8). Roots can, for both methods, occur up to a depth of 50 cm. As was indicated in Chapter 4, the chemical attributes up to a depth of 60 cm would not limit root development. The fact that 80% of the roots occur within the top 30 cm layer may be of concern due to the low water holding capacity of the tailings. However, according to Ruark et al., (1982), in soils, 80% of the roots can occur within the upper 20 cm. The higher root restriction for the chemical amelioration methods can be attributed to drier conditions in the lower layers (the leaching methods received much more irrigation water) and coupled with the rainfall event would overall be wetter than the chemical amelioration plots.

Other physical properties of the tailings such as, aeration, water-movement, and water regime may limit the colonising of species from the surrounding veld, rather than the strength (penetration resistance) of the tailings.

Biological

Biological processes are involved in making nutrients available (mineralization of organic matter and N fixation) and can limit plant growth through pests and diseases. The microbial activity was measured (Appendix E) but the rapid changes that can occur in populations due to changes in temperature, moisture content, aeration, etc. complicated interpretation. To understand the multifunctional nature of organic matter in soil processes such as; nutrient turnover and storage, structure formation/stability, water holding capacity etc., will require a suite of biological attributes (not only microbial activity) to be monitored (Gregorich, et al, 1997).

Physical habitat

The gradient of the tailings material and the aspect (the compass direction to which the slope faces) differs markedly from that of the surrounding soils. The average slope of the surrounding soil is 2% compared to 58% for the experimental plots. Steeper slopes cause a decrease in infiltration, therefore more runoff and a lower effective rainfall. The surrounding soils had no prominent aspect while the experimental plots being on the south facing slope would be cooler and wetter compared to north, east, and west facing slopes and the surrounding soils. Although actual differences in species composition, due to aspect, have been observed in road reserves, actual species differences between the experimental plots compared to the other aspects may only be observed a few years after rehabilitation. Experience from dams rehabilitated in the vicinity of the experimental plots indicate that for the seed mixture used by Envirogreen, Eragrostis curvula and Medicago sativa dominate on south facing slopes while Chloris gayana occurs for a limited period. The aspect of the experimental plots could be the main reason for the absence of Chloris gayana, and the dominance of Dactylis glomerata and Medicago sativa.

Climate and disturbances

The vegetation in this study was irrigated for three years (on average 1468 mm/a for the leaching methods and 825 mm/a for the chemical amelioration method) and the average rainfall per year, over the three-year period, was 533mm. Due to the theft of valves, water gauges and irrigation pipes, none of the plots was irrigated in the final year and in that period only 319mm of rain occured. This dramatic decrease in

available water from 2000mm/a to 319 mm for the leaching methods and from 1360mm/a to 319 mm for the chemical amelioration methods could have skewed the data of the last study year. The species composition had, except for weeds, not changed but the basal cover had decreased. A one-sided, two-sample t procedure was used to test the null hypothesis of no change of a specific species with time. Using Pvalues of <0.025 and <0.005 to reject the null hypothesis, species that markedly changed between 2001 and 2002 for the different rehabilitation methods are summarised in Table 5.4 (new corners were excluded). It is only for the sprinkler and drip irrigation plots that statistically significant changes in species frequency occur (see Table 5.4). This lack of change in vegetation composition, due to the high water stress applied to the system, is encouraging because it shows that the system had some integrity to keep it intact from certain environmental stresses. The basal cover had changed significantly for three of the leaching methods as well as for the sprinkler irrigation method. The sprinkler irrigation method, compared to the other chemical amelioration methods, received the most irrigation water (Section 3.6, Table 3.4). The change in basal cover can most likely be attributed to the fact that the vegetation was not gradually weaned from additional water inputs causing certain mature plants to die off during the drought spell. Under this severe drought condition it is unlikely that new seedlings would survive reducing the basal cover even further.

In the final year, a fire also swept through some of the plots, but the vegetation composition, except for weeds, did not change. Preliminary results from burning vegetation on tailings dams, conducted on PS 6 N tailings dam, indicate that fire influences basal cover negatively. The future drought and fire stress that will be imposed on the vegetation is uncertain. The vegetation on the other dams investigated that were subject to annual burning was dominantly a *Hyparrhenia* community. The younger rehabilitated dams were dominantly either an *Eragrostis* community or a *Chloris* community. At present the leaching plots are dominantly a *Dactylis-Medicago-Eragrostis* community and the chemical amelioration plots are characterised by an *Eragrostis-Medicago-Dactylis* community.

Table 5.4 Statistical significant changes that occur in species frequency and basal cover between the 2001 and 2002 season.

	M1	M2	M3	M4	M5	M6	M7
Cynodon dactylon							**
Medicago sativa						*	**
Melilutus alba							**
Basal cover		**	**	**			*

* P >0.005 <0.025

** P<0.005

M1=Leaching method

M2=Revised leaching method

M3=Elementary amelioration method

M4=Minimum cultivation method

M5=Chemical amelioration method

M6=Chemical amelioration method (drip irrigation)

M7=Chemical amelioration method (sprinkler irrigation)

5.5.2 Change in diversity

Succession is synonymous with community change in composition and structure (Myster & Pickett, 1994). The use of diversity and similarity/dissimilarity indices is a logical way to measure the magnitude of change (Myster & Pickett, 1994). Similarity/dissimilarity indices were developed to detect the degree of association or similarity between samples or communities (Beta-diversity). An important hypothesis, tested by

this method, is that succession should show a decrease in change over years with periodic fluctuations (Myster & Picket, 1994). This is the consequence of the control exerted by late successional species on the community structure through the replacement of annual species by perennial species (Facelli & D'Angela, 1990).

Species diversity indices are related to the population structure in a sample plot according to the number of species (species richness) and their abundances (evenness), and are described as the alpha-diversity of that sample. High species diversity is also considered as an indication of stable ecosystems, but no automatic relationship exists between high diversity or species richness and community stability because community stability will ultimately depend on environmental stability (Kent & Coker, 1994)[high diversity is also associated with communities in a disturbed state where the presence of annual/opportunistic species also skew the data (Baxter, 2002)]. Begon et al. (1990), Brown (1994), and Whalley (1994) questioned the existence of totally stable climax vegetation, as according to them ecosystem stability is more closely related to change in species composition than to diversity of the ecosystem. The Sorensen similarity coefficient and the Shannon diversity index were used to estimate vegetation change over time.

The Sorensen similarity coefficient (Ss) was calculated according to the following equation:

$$Ss = 2a/(2a + b + c)$$

Where:

a = number of species common to both samples

b = number of species in sample 1

c = number of species in sample 2

The Shannon diversity index (Sdi) was calculated according to the following equation:

$$Sdi = -\sum_{i=1}^{S} p_i \ln p_i$$

Where:

S = the number of species (species richness)

p_i = the proportion of individuals or the abundance of the i_{th} species

The values for these two indices are summarised in Table 5.5.

Table 5.5 Shannon diversity index and Sorensen similarity coefficient for the different rehabilitation methods over the study period

Index	period	MI	M2	M3	M4	M5	M6	M7
	2000	1.534	1.55	1.492	1.324	1.138	1.444	1.66
Shannon	2001	1.142	1.264	1.385	1.251	1.583	1.01	1.132
	2002	1.56	1.57	1.445	1.859	1.646	1.973	1.797
	1:2	0.38	0.4	0.4	0.43	0.38	0.38	0.44
Sorensen	1:3	0.34	0.38	0.32	0.39	0.34	0.38	0.33
	2:3	0.41	0.42	0.32	0.4	0.4	0.4	0.39

1:2 = similarity between first and second year

1:3 = similarity between first and third year

2:3 = similarity between second and third year

M1=Leaching method

M2=Revised leaching method

M3=Elementary amelioration method

M4=Minimum cultivation method

M5=Chemical amelioration method

M6=Chemical amelioration method (drip irrigation)

M7=Chemical amelioration method (sprinkler irrigation)

The Shannon diversity index is the highest at the end of the study period because of the colonisation by annual weeds more than anything else. If the ruderal species are ignored then the diversity index has actually decreased over time. The species diversity of the chemical amelioration method has increased mainly because Dactylis glomerata and Lolium perenne, absent in the original seed mixture, colonised these plots. The experimental plots were on the south-facing slope, causing the plots to be colder and wetter, which is beneficial for temperate grasses such as, Dactylis glomerata and Lolium perenne, with C3-pathway photosynthesis. The similarity in vegetation according to the Sorensen coefficient is the lowest between the first and third year and the highest between the second and third year indicating a change in composition, and that the rate of change is decreasing.

5.5.3 Condition assessment

The ultimate aim of every rehabilitation program is to provide a sustainable landscape (Fox & Tacey, 1994). Rehabilitation is, therefore, a critical test of the understanding of ecological principles that rule disturbed ecosystems (Jordan, et al. 1996). By observing community attributes of ecosystems during progressive stages of succession an understanding can be gained of what promotes and enables the selfsustainability in an ecosystem. Vegetation during early stages of succession consists predominantly of annual species, which are replaced under increasing environmental stability by competitive perennial species (Robinson, 1994). The ability of new colonisers to establish themselves depends on the prevailing habitat conditions and the adaptability of colonisers to these conditions (Bradshaw, 1983). To determine if progressive ecosystem development is taking place in an area, it is imperative to assess whether or not the theory of succession applies (Smyth, 1997). The most commonly employed method for assessment of rehabilitation success is the comparison of the vegetation composition between reconstructed communities and the original community (Ewel, 1987). No vegetation surveys were conducted on the surrounding natural veld. However, Morgenthal et al. (1999) indicated that the use of nearby natural grasslands as benchmarks in the assessment of rehabilitation success is not compatible due to the large differences in the species composition and habitat between the two regions.

For this study it was decided to assess rehabilitation success by determining if the plant succession, for the rehabilitation methods evaluated, is progressing towards plant communities occurring on tailings dams, with a good vegetative cover, rehabilitated in the past.

The Hyparrhenia. Eragrostis, and Chloris communities that dominate on some of the dams indicate that these species must be well adapted to the environmental characteristics of rehabilitated tailings. Hyparrhenia reveals resistance to a high fire frequency (East Chamdo'r burnt annually) and relatively high Al contents (the pH value of the tailings of Fleurhof, with a good vegetation cover, was 4.1). The stability of these communities though high (some of the dams were rehabilitated 40 years ago) may lack some resilience due to the low diversity. However, if the vegetation of the rehabilitation methods is progressing towards one of these communities then it should indicate a degree of success.

Hyparrhenia hirta did not occur in the original seed mixtures and the Hyparrhenia hirta present on the experimental plots was established through hand plants. Chloris gayana disappeared almost completely from the site. The frequency of Eragrostis curvula for the different methods over the study period is presented in figure 5.9.

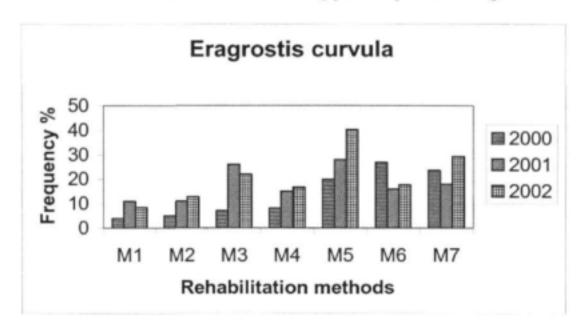


Figure 5.9 Change in abundance of Eragrostis curvula over the study period for the different rehabilitation methods

M1=Leaching method

M2=Revised leaching method

M3=Elementary amelioration method

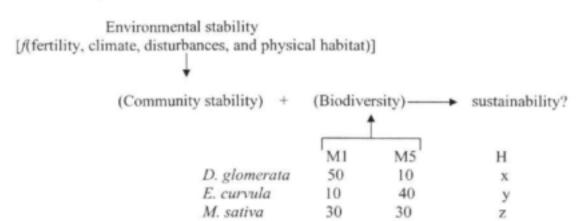
M4=Minimum cultivation method

M5=Chemical amelioration method

M6=Chemical amelioration method (drip irrigation)

M7=Chemical amelioration method (sprinkler irrigation)

Encouraging is that *Eragrostis curvula* steadily increased over the study period for most of the methods (Figure 5.9). *Eragrostis curvula* is more dominant on the chemical amelioration plots. However, the question remains of how to give a value to the sustainability of the vegetation cover? From the preceding discussion and results the following can be deducted:



If one compares only the leaching method (M1) and the chemical method (M5) over the study period then in general:

- The fertility of the tailings between the two methods did not differ significantly.
- For both methods the physical habitat (aspect) had eliminated Chloris gayana
 and the three dominant species remaining were Dactylis glomerata, Eragrostis
 curvula and Medicago sativa, (the frequency of species differed between the
 methods depending on whether sown or colonising)
- Disturbance due to drought and fire may cause shifting in the frequency of the species (although not statistically significant) with Dactylis and Medicago decreasing and Eragrostis increasing for the leaching method while Eragrostis and Dactylis increased and Medicago decreased for the chemical method.

If both communities under continued cycles of disturbance converge to the hypothetical (H) dominant *Eragrostis* community, on what grounds can it be stated that the community of one method is presently more sustainable than the other? Another important question is, will a community consisting mainly of three species be viewed as sustainable?

It is premature to conclude at this stage (3 years after rehabilitation) that the chemical amelioration method is more successful than the leaching method because it has a higher frequency of *Eragrostis curvula*. Only time will tell if future changes in chemical attributes do occur between the different methods that negatively influence plant performance. It is also not possible at this stage to conclude that the vegetation will converge to a stable *Eragrostis* community nor is it certain if such a community will be viewed as sustainable by regulators.

If the different methods are evaluated according to the five pillars of sustainability the following can be said:

Productivity/services

Apart from the sustainable production of plant material and to control wind and water erosion, other services expected from re-vegetated areas, include water and gas partitioning, wildlife habitat, biodiversity reservoir and aesthetic retreat. The vegetation cover established under all the rehabilitation methods is producing plant material and controlling wind and water erosion/pollution. The re-vegetated tailings dam can be classified as a wilderness area according to the Chamber of Mines land capability classification system. A wilderness area complies with the closure requirement that a tailings dam complex should be rehabilitated to a predetermined and agreed standard of land use.

Security/resilience/risk

To ensure that the re-vegetated system had resilience (the ability of the system to return to normal following a period of stress or disturbance) genetic variability was introduced to accommodate for environmental variability and change. The established plant community as such had not yet stabilised as a secondary succession community. Extreme variation in growing medium properties was prevented, by incorporating additional lime into the tailings to counter act any potential acidity developing through further oxidation of pyrite, or to leached free acids and salts from the tailings.

The rehabilitation methods comply with the closure objective that the physical and chemical stability of a tailings dam should be such that the risk to the environment is not increased by naturally occurring forces to the extent that such increased risk cannot be handeled by the installed measures.

Protection

A good vegetative cover dramatically reduces the potential for surface erosion by wind and water. A vegetative surface dramatically increases infiltration and reduces runoff and any sediments and contaminants it may carry. The protection of the surface against erosion complies with the closure requirement that environmental damage or residual environmental impacts should be minimised to such an extent that it is acceptable to all involved parties.

Viability

A wilderness area is the most sustainable land use for a rehabilitated tailings dam with least cost and risk. Although re-vegetation is not a walk-a-way solution, a tailings dam with an established vegetation cover in a good condition will require the minimum of after-care. Viability complies with the closure requirement that mines should be closed efficiently and cost effectively.

Acceptability

A vegetating tailings dam is aesthetically pleasing and any procedure abating dust nuisance from wind erosion is usually acceptable for the nearby communities.

Although the sustainability criteria are more or less met by the different rehabilitation methods it does not imply that the present vegetation cover is sustainable. The management of a re-vegetated dam should be such that it can be tested and monitored against these sustainability criteria. At present the management of re-vegetated tailings dams is made difficult if the final secondary succession community is unknown. The optimal tailings condition for a specific final succession community is also not yet determined. Hopefully, if monitoring can become part of the whole rehabilitation process enough data will be gathered to improve our understanding of re-vegetated gold tailings dams. However, as long as proper tenure systems are not in place the risk of failure of any rehabilitation method will remain.

5.6 Conclusion

The results obtained in this study indicate that the initial "artificial" vegetation community imposed on the ameliorated tailings follows an organizing process where annuals disappear and certain perennials remain and that opportunistic species can colonise the site if environmental factors reduce the competitive edge of the perennial species. The difference between natural successions and the succession on rehabilitated tailings is that the former has more predictable consequences while the latter is on an "un-destined road". For this study it was assumed that the destination is either towards a dominantly Hyparrhenia, or Eragrostis or Chloris community. The results indicate that the most probable destination for the chemical amelioration methods is towards an Eragrostis community. All the leaching methods could be on

that road as well and at this stage of the journey (3 years) it is impossible to say which method had produced the most sustainable vegetation cover.

In future differences in plant communities between the chemical ameliorated and leaching methods may arise because as mentioned in the previous chapter, the tailings will become probably more saline for the chemical amelioration methods while for the leaching methods the tailings will become probably more acidic. The vegetation has to adapt to these changes and climate can be the decisive factor. The tailings for the chemical amelioration methods would have a neutral pH and a higher salt content (compared to the leaching methods), which fits in with soils in dry climates and therefore colonisation of grasses from the adjacent veld is more likely for the chemical amelioration plots, than for the leaching plots. Vice versa, in wetter climates (like the Rand) the somewhat acidic nature and lower salt content of the tailings resulted from a leaching approach would be more favourable for grasses from the immediate vicinity to colonise the tailings, than if a chemical amelioration method was followed.

If the present stable communities, on older rehabilitated tailings dams, *Hyparrhenia*, *Eragrostis*, and *Chloris*, are not viewed as sustainable due to lack of diversity then there is a need to find more species adaptable to the conditions prevailing on tailings dams, to improve diversity.

5.7 Summary

Monitoring is very important but should not be viewed only as the regular surveillance of the conditions (or assessments) of the tailings or the vegetation cover but rather as a control tool to manage or regulate the rehabilitation system. Assessments of quality require some standard of comparison or benchmark against which system function is assessed. What exactly constitutes a good tailings quality or a healthy re-vegetated tailings ecosystem may be debatable, but must be stated clearly at the outset of any assessment. To manage the system one has to understand the processes and the forces that are driving the system. Ecosystem management has been defined as "management driven by explicit goals, executed by policies, protocols, and practices, and made adaptable by monitoring and research based on our best understanding of the ecological interactions and processes necessary to sustain ecosystem composition, structure and function" (Ecological Society of America, 1995). Technically the concern is whether we have at present the insight required to manage re-vegetated tailings ecosystems. Ongoing work on re-vegetated tailings ecosystem complexity, biodiversity, stability, and resilience will be crucial to understanding the sustainability of re-vegetated tailings ecosystems and tailings quality.

Chapter 6

General discussion, conclusions, recommendations, and summary

The objective of this project was to identify the rehabilitation method, which would produce the most sustainable vegetation cover at the end of the rehabilitation period. A secondary objective was to quantify the amount of water applied for each rehabilitation method investigated. The extent to which each of these aims was achieved will be discussed.

6.1. Rehabilitation methods and the sustainability of the vegetation cover

Discussion

Seven rehabilitation methods were evaluated. Three of these dealt with the leaching method and variations thereof and three with the chemical amelioration method and variations thereof. The other method evaluated was the elementary amelioration method. There were no drastic differences in the chemical attributes of the tailings, between the different rehabilitation methods, at the end of the study period. The fertility of the experimental sites at the end of the study period were higher when compared with the fertility of tailings dams that were rehabilitated in the past and which presently sustain a good vegetation cover but actual fertility of these dams just after rehabilitation is unknown. If the present chemical attributes can be maintained in future, then the ameliorated tailings should be capable of sustaining a stable vegetation cover. However, high fertility can prolonged the existence of certain species and to maintain that species composition high fertility and high maintenance inputs will be required. The management of re-vegetated tailings dams will be more successful if the final secondary succession community is known as well as the response curve of each species of that community for every environmental factor. The lack of diversity of the secondary succession community (Hyparrhenia hirta) on old re-vegetated tailings dams is either an indication that we have not yet identify other species with similar requirements for existence (with Hyparrhenia hirta) in terms of environmental factors or the species with similar requirements (as Hyparrhenia hirta) do not share the ability with Hyparrhenia hirta to tolerate frequent burning.

The similarity of the chemical attributes of the tailings for the different rehabilitation methods was exceptional. Potassium was found to be the most difficult nutrient to rectify through amelioration. Very high application rates (chemical amelioration method) do not improve the potassium content significantly indicating that the potassium either leached out or was fixed (probably in the formation of jarosite). The leaching of potassium can be a reason for the abundance of *Medicago sativa* on the experimental plots because with its deep root system it could benefit from the potassium leached lower down. The chemical amelioration methods were also leaching methods although to a lesser extent than the actual leaching methods.

With regard to the questions of whether limed and/or leached tailings become reacidified over time, and whether ameliorated tailings will be able to function as a "normal" soil in terms of nutrient cycling, thus allowing the perpetuation of a selfsustaining vegetation community, no clear cut answers could be given. The main reason for this being that the time span of three years is too short and because certain important parameters (e.g., acid-base accounting and organic matter content) were not measured. With regard to acid-base accounting Day (1994) pointed out that the quantity of lime required to prevent acid mine drainage in perpetuity would be at least twice that determined by conventional acid-base accounting. With regard to organic matter it was found that the compost added decomposed rapidly (measured against changes in CEC) and it is also unlikely that high soil organic matter (SOM) can be built up in the tailings because of the low clay content (Rowell, 1995). This is in spite of the fact that in the early stages of ecosystem development, primary production exceeds respiration, resulting in the accumulation of C in the ecosystem (Schlesinger, 1991; Johnson, 1995).

The initial seeding involved the sowing of a mixture of 16 species for the leaching methods and the sowing of a mixture of 8 species for the chemical amelioration methods (five species were common to both methods). At the end of the study period 8 of the sown species remained of a total number of 39 species that have been identified on the site at the end of the study period. There were large numbers of mice present on the site and in the last season there was a severe infestation of snails.

At the end of the study period, the three dominant plant species for the leaching method were Dactylis glomerata, Medicago sativa, and Eragrostis curvula and for the chemical amelioration method it was Medicago sativa, Eragrostis curvula and Dactylis glomerata (an increase in weeds did occur, which included Conyza bonariensis, Cirsium vulgare and Lactuca serriola).

Conclusion

At this stage no conclusive statement can be made regarding the sustainability of the vegetation cover, at the experimental site, for any of the rehabilitation methods. However, it is clear that the ameliorated tailings are capable of supporting a vegetation cover. Older dams investigated as part of this study had revealed that a stable plant community on tailings material has been obtained by some of the rehabilitation methods studied. Off the different rehabilitation methods the leaching method had the longest track record.

The diversity of the vegetative cover seems high when considering only the number of species present, 39 at the end of the study period, but unfortunately for both the leaching and chemical amelioration methods only three species occur in abundance. Only Dactylis glomerata and Lolium perenne had colonised plots not originally seeded with these species. This could vary on other aspects of the dam. It is postulated that the vegetation must adapt to a change in pH for the leaching method and adapt to a change in salt content for the chemical amelioration method, over time. However, it is anticipated that the vegetation will probable converge to a predominantly Eragrostis curvula community for both methods but grasses from the natural veld, colonising plots of the chemical amelioration method is probably more likely, because the conditions of the chemical amelioration plots with a neutral to alkaline pH and higher salinity resembles more the chemical conditions of soils associated with dry climates.

6.2 Amount of water applied for the different rehabilitation methods

Under a micro-jet irrigation system, the amount of water applied over the study period for a leaching method was about twice as high as that for a chemical amelioration method. The amount of water applied for a chemical amelioration method under a sprinkler system was about the same as that for a leaching method. The amount of water applied was the lowest for the drip irrigation system, about three times less than a leaching method.

The amount of water applied over the study period exceeded the general guidelines for all methods due to a misunderstanding between those who manage the experimental plots and the project leader and rehabilitation ecologist. Irrigation was extended for an extra season.

The successful establishment of vegetation with the elementary amelioration method indicates that the chemical conditions of the specific tailings of the experimental site were benign, and coupled with the wetter conditions of a south facing slope, the actual beneficial usage of water in the rehabilitation of tailings dams were not highlighted in this study.

6.3 Recommendations

During this study some of the problems that became apparent were:

- The sustainability of re-vegetated tailings dams, even with a proven stable plant community in excess of 30 years, are questioned, due to a lack of diversity in the plant community
- The degradation of vegetated tailings dams is driven by a combination of forces such as lack of funds, low biological productivity, lack of knowledge, lack in ability and desire to maintain the biological productivity, and poorly defined or inadequate tenure systems. Unfortunately, any type of failure is used to point out that re-vegetation efforts are unsustainable.

Future research needs to address biological productivity/diversity, and tenure systems. Tenure systems (land management) should be evaluated and tested against the five pillars of sustainability, namely, productivity/services, security/resilience/risk, protection, viability, and acceptability. The following framework (Figure 6.1) was compiled by Hattingh, (2001) essentially from the rehabilitation scheme of Bradshaw & Chadwick (1980) and the FESLM of Dumanski & Smyth (1993) in an attempt to provide a framework that can be used as a rehabilitation scheme for the end land use of a tailings dam, as defined in the EMPR, and finally for sustainable land management of the rehabilitated site.

The framework can only be used effectively if the necessary support information system (models) for rehabilitation can be expanded and an effective monitoring programme for water, air, vegetation, tailings, and environmental hazards can be implemented. The problem experienced over the years is that once vegetation has been established, the mining companies see little value in monitoring, and are not prepared to pay for these as part of the rehabilitation process.

Recommendations with regard to future research are:

- 1) Models: If the ACRU-model and the Salmine-model, or any other water balance model and geochemical model, can be modified and integrated then it will become an important tool in the rehabilitation of tailings dams for:
- Estimate the water needs for leaching and vegetation establishment
- Estimate the amount of erosion under different plant covers
- Estimate the effect of different rainfall scenarios on vegetation performance
- Estimate the runoff from vegetated tailings for determining the size of paddock structures and return water structures
- Estimate the chemical attributes of the tailings for different rehabilitation methods and climatic scenarios
- "What if" scenarios, and
- Risk assessments.
- 2) Monitoring: Monitoring is an important aspect but is a relative new endeavour (at least for tailings material) and the necessary indicators, minimum data sets, procedures, thresholds, and standards have to be developed.

Re-vegetation monitoring on the other hand comes a long way (Dawson, 2002) but no long-term monitoring was conducted and the exact vegetation parameters and goals (ecological condition assessment, pro-active management systems, evaluation of the rehabilitation process, etc) have yet not been defined.

Monitoring of environmental impacts should also be addressed.

3) Other research:

- Methods to effectively build up potassium to favourable levels in tailings should be investigated
- Soil organic matter dynamics in tailings and their relationship with other chemical/physical attributes should also be investigated
- Methods to address the physical limitations of tailings need urgent attention
- The fate of additional lime to counteract potential acidity should be investigated over a long period
- Vegetation succession or state and transition models for rehabilitated gold tailings have to be developed because the models are essential for land management of re-vegetated systems and to make more conclusive statements regarding sustainability when applying for closure.
- A thorough understanding of the chemistry and mineralogy of iron-bearing minerals such as pyrite, jarosite, schwermannite, ferrihydrite, and goethite, is essential to understand the chemical behaviour of gold tailings.

 Certain standard methods of soil chemical analysis should be modified to ensure that the results are more applicable for the chemical amelioration of gold tailings.

6.4 Summary

The core economy of South Africa has developed around the mining industry. Mining, however, is not an infinite business because the ore is a finite quantity. As the viability of mines begins to decline, mine closure becomes more and more of a reality, as do the liabilities associated with mine closure. One of the liabilities is the rehabilitation of areas disturbed by mining or associated mining activities. Although the successful rehabilitation of gold tailings dams goes back as far as the early 1960's there is still uncertainty if the present established vegetation communities, dominated either by Hyparrhenia, Eragrostis or Chloris, on gold tailings dams will be viewed as sustainable because of the low diversity of these plant communities. Sustainability is an important closure requirement. Furthermore, the actual vegetation succession on rehabilitated tailings dams is not well documented mainly because monitoring of vegetation on rehabilitated tailings dam was not continued over long time spans. The successful land management of re-vegetated tailings dams is dependent on a good understanding of succession and the factors influencing/controlling it. A study period of three years is far too short to give answers regarding sustainability and, therefore, monitoring must be done over long periods and for that reason should be a combined effort between mining houses, tertiary and research institutes and rehabilitation companies to ensure that closure certificates can be obtained.

The following quotation from Hammer (1992) "Growing public concern and awareness of the role of man and his environment will likely ensure that surface mining and other resource utilization activities will continue to be regulated by law...The research scientist, the agronomist, the engineer, the reclamation specialist, and the regulators have to meet at the mutual interface of their disciplines. All share a common goal-learning to wisely and economically utilize our finite resources in such a way that the land we bequeath to our children and grandchildren will sustain them in health and happiness. We must work together to apply what we know in environmentally and economically sound ways. The keys to our successes lie in recognising our mutually shared objectives and in approaching the reclaimed landscape as an ecological system in which the substrate is the dynamic interface between the biotic and the abiotic components" reflects the role of scientists and rehabilitation specialists to constructively contribute to new environmental legislation in South Africa.

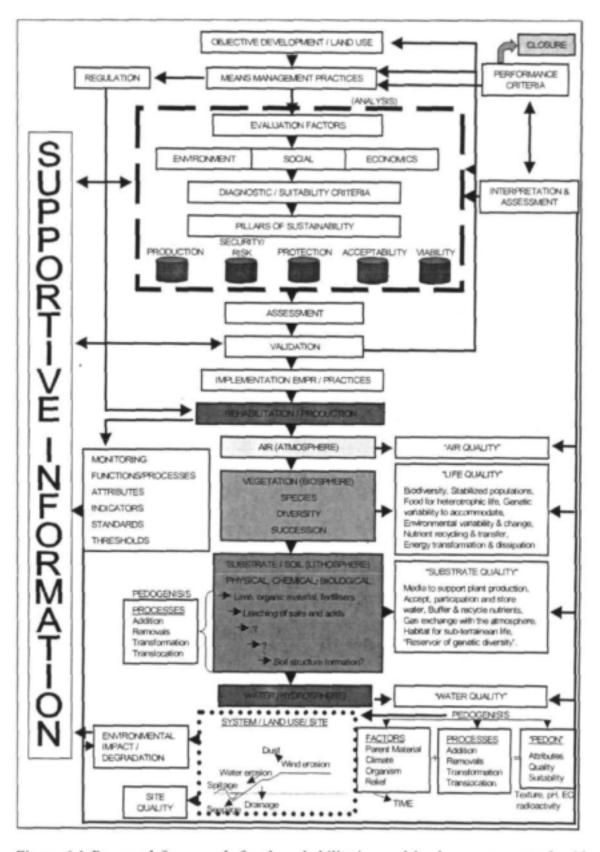


Figure 6.1 Proposed framework for the rehabilitation and land management of gold tailings dams (Hattingh, 2001)

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APPENDIX A: CHEMICAL ANALYSIS OF THE TAILINGS

Analytical data of tailings before and after amelioration

Method 1:Leaching

Plot 4	Be	fore ameli	After amelioration			
Attribute	0-150	150-300	300-600	0-150	150-300	300-600
pH	3.6	3.7	3.4	6.7	4.1	3.4
EC (mS/m)	467	489	481	301	492	526
Na (cmol+/kg)	0.17	0.31	0.46	0.11	0.33	0.42
K (cmol+/kg)	0.10	0.14	0.09	0.20	0.18	0.09
Mg (cmol+/kg)	1.05	0.88	0.99	1.83	0.98	1.09
Ca (cmol+/kg)	7.8	5.4	7.0	18.4	14.4	7.3
Al (cmol+/kg)	1.33	1.19	1.28	0	1.19	1.31
CEC (cmol+/kg)	2.42	1.06	1.68	2.80	1.36	1.49
P (mg/kg)	4	4	3	24	6	7
SO ₄ (mg/kg)	743	747	734	688	704	789
Cl (mg/kg)	65	88	86	62	81	94

Plot 11	Bef	ore ameli	oration	After amelioration			
Attribute	0-150	150-300	300-600	0-150	150-300	300-600	
pH	3.6	3.7	3.5	7.2	5.2	4.2	
EC (mS/m)	383	349	371	366	295	286	
Na (cmol+/kg)	0.23	0.31	0.33	0.19	0.22	0.30	
K (cmol+/kg)	0.28	0.32	0.55	0.48	0.19	0.48	
Mg (cmol+/kg)	0.37	0.25	0.36	1.28	1.40	0.36	
Ca (cmol+/kg)	9.98	8.40	7.50	15.5	13.1	5.7	
Al (cmol+/kg)	1.20	1.21	1.27	0	0.16	1.24	
CEC (cmol+/kg)	1.64	1.27	1.91	1.90	1.19	1.78	
P (mg/kg)	4	7	5	20	6	4	
SO ₄ (mg/kg)	637	621	693	540	626	693	
Cl (mg/kg)	53	54	61	50	56	64	

Plot 13	Bef	ore amelio	ration	After amelioration			
Attribute	0-150	150-300	300-600	0-150	150-300	300-600	
pH	3.4	3.5	3.2	7.2	4.0	3.6	
EC (mS/m)	371	412	471	349	367	415	
Na (cmol+/kg)	0.22	0.34	0.22	0.21	0.37	0.27	
K (cmol+/kg)	0.32	0.29	0.16	0.48	0.33	0.16	
Mg (cmol+/kg)	0.19	0.32	0.20	1.08	0.24	0.26	
Ca (cmol+/kg)	9.58	10.69	8.50	14.5	10.1	8.2	
Al (cmol+/kg)	1.33	1.12	1.17	0	1.11	1.24	
CEC (cmol+/kg)	1.66	1.28	1.84	1.92	1.24	1.83	
P (mg/kg)	4	4	5	18	3	3	
SO ₄ (mg/kg)	629	679	743	600	672	738	
Cl (mg/kg)	55	59	71	49	60	79	

Plot 21	Bef	ore ameli	oration	After amelioration			
Attribute	0-150	150-300	300-600	0-150	150-300	300-600	
pH	3.9	3.6	3.7	7.7	3.4	3.6	
EC (mS/m)	306	376	382	378	389	378	
Na (cmol+/kg)	0.15	0.23	0.09	0.15	0.11	0.21	
K (cmol+/kg)	0.19	0.26	0.14	1.22	0.15	0.28	
Mg (cmol+/kg)	0.12	0.17	0.29	1.16	0.79	0.34	
Ca (cmol+/kg)	4.6	9.3	5.68	13.5	12.7	5.5	
Al (cmol+/kg)	1.22	1.24	1.14	0	1.01	1.14	
CEC (cmol+/kg)	1.71	1.69	1.03	1.43	1.65	1.18	
P (mg/kg)	5	3	5	24	15	3	
SO ₄ (mg/kg)	658	733	701	698	749	738	
Cl (mg/kg)	51	69	76	56	62	71	

Method 2: Revised leaching

Bef	ore ameli	oration	After amelioration			
0-150	150-300	300-600	0-150	150-300	300-600	
3.6	3.4	3.4	8.7	7.0	3.4	
331	362	482	349	359	425	
0.32	0.40	0.22	0.22	0.42	0.15	
0.23	0.26	0.17	0.48	0.29	0.23	
0.21	0.28	0.26	4.18	1.24	0.27	
9.6	10.22	7.00	19.50	20.60	6.30	
1.20	1.19	1.15	0	1.11	1.34	
1.62	1.67	1.56	2.90	1.72	1.45	
4	4	5	33	7	4	
629	621	744	541	592	672	
50	67	64	59	66	68	
	0-150 3.6 331 0.32 0.23 0.21 9.6 1.20 1.62 4 629	0-150 150-300 3.6 3.4 331 362 0.32 0.40 0.23 0.26 0.21 0.28 9.6 10.22 1.20 1.19 1.62 1.67 4 4 629 621	3.6 3.4 3.4 331 362 482 0.32 0.40 0.22 0.23 0.26 0.17 0.21 0.28 0.26 9.6 10.22 7.00 1.20 1.19 1.15 1.62 1.67 1.56 4 4 5 629 621 744	0-150 150-300 300-600 0-150 3.6 3.4 3.4 8.7 331 362 482 349 0.32 0.40 0.22 0.22 0.23 0.26 0.17 0.48 0.21 0.28 0.26 4.18 9.6 10.22 7.00 19.50 1.20 1.19 1.15 0 1.62 1.67 1.56 2.90 4 4 5 33 629 621 744 541	0-150 150-300 300-600 0-150 150-300 3.6 3.4 3.4 8.7 7.0 331 362 482 349 359 0.32 0.40 0.22 0.22 0.42 0.23 0.26 0.17 0.48 0.29 0.21 0.28 0.26 4.18 1.24 9.6 10.22 7.00 19.50 20.60 1.20 1.19 1.15 0 1.11 1.62 1.67 1.56 2.90 1.72 4 4 5 33 7 629 621 744 541 592	

Plot 16	Befe	ore amelio	ration	After amelioration			
Attribute	0-150	150-300	300-600	0-150	150-300	300-600	
pH	3.9	3.6	3.6	7.7	7.4	3.2	
EC (mS/m)	356	358	382	334	379	378	
Na (cmol+/kg)	0.19	0.25	0.29	0.15	0.19	0.10	
K (cmol+/kg)	0.10	0.12	0.11	0.22	0.17	0.14	
Mg (cmol+/kg)	0.23	0.27	0.18	1.56	1.40	0.16	
Ca (cmol+/kg)	4.7	5.22	6.38	18.50	11.50	6.50	
Al (cmol+/kg)	1.19	1.21	1.19	0	1.18	1.24	
CEC (cmol+/kg)	1.91	2.00	1.31	1.93	1.87	0.98	
P (mg/kg)	2	5	3	40	4	3	
SO ₄ (mg/kg)	614	700	731	683	701	745	
Cl (mg/kg)	49	61	78	64	67	75	

Plot 33	Befo	re amelio	ration	After amelioration			
Attribute	0-150	150-300	300-600	0-150	150-300	300-600	
pH	3.8	3.4	3.3	5.8	3.9	3.4	
EC (mS/m)	258	381	394	241	360	371	
Na (cmol+/kg)	0.15	0.30	0.16	0.36	0.12	0.17	
K (cmol+/kg)	0.29	0.41	0.26	0.48	0.46	0.25	
Mg (cmol+/kg)	0.43	0.57	0.38	0.85	0.56	0.40	
Ca (cmol+/kg)	6.72	5.4	7.60	9.39	6.20	7.30	
Al (cmol+/kg)	1.01	1.37	1.31	0.31	1.26	1.22	
CEC (cmol+/kg)	1.06	0.93	0.85	0.92	0.79	1.05	
P (mg/kg)	4	7	6	18	5	4	
SO ₄ (mg/kg)	651	692	733	692	728	741	
Cl (mg/kg)	49	59	63	49	58	69	

Plot 36	Befe	ore amelio	ration	After amelioration			
Attribute	0-150	150-300	300-600	0-150	150-300	300-600	
pH	3.8	3.3	3.2	7.2	4.1	3.3	
EC (mS/m)	303	349	391	421	374	391	
Na (cmol+/kg)	0.23	0.21	0.16	0.13	0.12	0.23	
K (cmol+/kg)	0.09	0.21	0.24	0.82	0.36	0.21	
Mg (cmol+/kg)	0.43	0.22	0.34	1.58	0.72	0.31	
Ca (cmol+/kg)	7.94	5.44	7.23	19.40	6.93	6.34	
Al (cmol+/kg)	0.96	1.13	1.34	0	0.96	1.24	
CEC (cmol+/kg)	2.02	1.27	1.04	2.00	1.10	1.03	
P (mg/kg)	3	3	5	28	5	3	
SO ₄ (mg/kg)	672	685	712	620	717	769	
Cl (mg/kg)	43	57	68	49	72	74	

Method 3: Elementary amelioration

Plot 1 Attribute	Be	fore ameli	oration	Aft	ration	
	0-150	150-300	300-600	0-150	150-300	300-600
pH	3.7	3.8	3.8	8.3	4.8	4.2
EC (mS/m)	343	312	298	212	279	374
Na (cmol+/kg)	0.13	0.22	0.56	0.22	0.22	0.15
K (cmol+/kg)	0.09	0.13	0.1	0.21	0.18	0.15
Mg (cmol+/kg)	0.67	0.2	0.12	1.65	0.18	0.14
Ca (cmol+/kg)	10.56	6.98	6.72	15.2	6.58	6.99
Al (cmol+/kg)	1.26	1.13	1.44	0	0.74	1.42
CEC (cmol+/kg)	1.3	1.14	1.06	1.44	1.21	1.25
P (mg/kg)	3.3	3.8	4.1	31.3	4.4	3.1
SO ₄ (mg/kg)	439	655	745	443	728	739
Cl (mg/kg)	69	72	89	65	91	83

Plot 3	Before amelioration			After amelioratio		
Attribute	0-150	150-300	300-600	0-150	150-300	300-600
pH	3.8	3.8	3.9	6.7	4.1	3.8
EC (mS/m)	491	475	483	301	454	473
Na (cmol+/kg)	0.16	0.22	0.48	0.18	0.23	0.37
K (cmol+/kg)	0.09	0.12	0.09	0.29	0.18	0.09
Mg (cmol+/kg)	1.01	0.76	0.84	1.83	1.17	0.89
Ca (cmol+/kg)	8.9	5.8	6.9	18.4	6.4	7.3
Al (cmol+/kg)	1.01	0.95	0.97	0	0.93	0.96
CEC (cmol+/kg)	2.13	1.45	1.11	2.8	1.44	1.32
P (mg/kg)	5	4	5	14	6	7
SO ₄ (mg/kg)	756	729	735	718	754	739
Cl (mg/kg)	67	90	80	62	88	84

Plot 17 Attribute	Be	fore ameli	ioration	A	oration	
	0-150	150-300	300-600	0-150	150-300	300-600
pH	3.6	3.4	3.5	7.7	4.1	3.2
EC (mS/m)	312	301	332	367	284	341
Na (cmol+/kg)	0.13	0.05	0.29	0.15	0.11	0.30
K (cmol+/kg)	0.10	0.11	0.15	0.20	0.15	0.08
Mg (cmol+/kg)	0.17	0.25	0.29	1.56	0.69	0.14
Ca (cmol+/kg)	5.7	7.1	6.56	13.8	7.4	6.5
Al (cmol+/kg)	1.24	1.24	1.35	0	1.34	1.24
CEC (cmol+/kg)	1.29	1.39	1.10	1.00	1.58	1.15
P (mg/kg)	4	3	3	19	4	3
SO ₄ (mg/kg)	613	683	703	648	745	735
Cl (mg/kg)	57	55	73	57	59	77

Plot 18 Attribute	Be	fore ameli	oration	After ameliorati		
	0-150	150-300	300-600	0-150	150-300	300-600
pH	3.5	3.5	3.4	7.7	4.1	3.2
EC (mS/m)	376	378	372	358	394	380
Na (cmol+/kg)	0.17	0.11	0.29	0.15	0.13	0.19
K (cmol+/kg)	0.14	0.16	0.13	0.34	0.19	0.18
Mg (cmol+/kg)	0.24	0.31	0.23	0.96	0.49	0.24
Ca (cmol+/kg)	7.70	8.15	7.82	18.50	7.4	7.5
Al (cmol+/kg)	1.22	1.27	1.25	0	1.17	1.13
CEC (cmol+/kg)	1.89	1.78	1.14	1.60	1.84	1.13
P (mg/kg)	4	3	5	30	5	3
SO ₄ (mg/kg)	681	756	757	701	716	738
Cl (mg/kg)	60	63	79	68	67	79

Method 4: Minimum cultivation

Plot 7	Befor	re amelior	ation	ion After amelioration		
Attribute	0-150	150-300	300-600	0-150	150-300	300-600
pH	3.7	3.5	3.4	6.7	3.4	3.6
EC (mS/m)	481	444	438	301	456	483
Na (cmol+/kg)	0.17	0.16	0.32	0.22	0.23	0.32
K (cmol+/kg)	0.09	0.13	0.12	0.39	81.0	0.09
Mg (cmol+/kg)	1.10	0.96	0.94	1.84	0.78	0.59
Ca (cmol+/kg)	8.60	5.60	6.60	11.40	6.40	6.30
Al (cmol+/kg)	1.26	1.14	1.27	0	1.19	1.31
CEC (cmol+/kg)	1.13	1.46	1.31	2.84	1.29	1.47
P (mg/kg)	6	4	5	16	6	5
SO ₄ (mg/kg)	481	444	438	301	456	483
Cl (mg/kg)	59	68	82	53	89	86

Plot 12 Attribute	Befe	ore amelio	ration	Af	ration	
	0-150	150-300	300-600	0-150	150-300	300-600
pH	3.6	3.7	3.5	7.2	3.6	3.6
EC (mS/m)	634	681	692	329	645	793
Na (cmol+/kg)	0.22	0.34	0.24	0.23	0.28	0.17
K (cmol+/kg)	0.15	0.17	0.16	0.32	0.19	0.18
Mg (cmol+/kg)	0.20	0.24	0.30	1.70	0.24	0.28
Ca (cmol+/kg)	6.68	7.49	6.50	14.70	7.25	6.80
Al (cmol+/kg)	1.29	1.23	1.17	0	1.01	1.24
CEC (cmol+/kg)	1.61	1.24	1.06	3.18	1.07	1.14
P (mg/kg)	4	7	5	18	6	4
SO ₄ (mg/kg)	634	681	692	329	645	793
Cl (mg/kg)	47	67	69	37	60	64

Plot 20 Attribute	Before amelioration			After amelioration		
	0-150	150-300	300-600	0-150	150-300	300-600
pH	3.4	3.5	3.7	7.7	4.1	3.2
EC (mS/m)	349	332	385	378	395	360
Na (cmol+/kg)	0.22	0.05	0.39	0.25	0.11	0.15
K (cmol+/kg)	0.23	0.08	0.18	0.52	0.15	0.18
Mg (cmol+/kg)	0.26	0.35	0.18	1.46	1.54	1.14
Ca (cmol+/kg)	5.70	9.02	7.45	22.50	10.40	6.50
Al (cmol+/kg)	1.26	1.13	1.05	0	1.02	1.24
CEC (cmol+/kg)	1.91	1.29	1.34	2.09	1.64	1.45
P (mg/kg)	4	5	4	36	3	3
SO ₄ (mg/kg)	643	731	758	346	729	748
Cl (mg/kg)	50	56	72	36	67	74

Plot 30	Before amelioration			After amelioration		
Attribute	0-150	150-300	300-600	0-150	150-300	300-600
pH	3.2	3.4	3.6	6.8	3.9	3.6
EC (mS/m)	358	391	482	207	339	402
Na (cmol+/kg)	0.15	0.29	0.09	0.12	0.33	0.18
K (cmol+/kg)	0.09	0.10	0.16	0.79	0.19	0.14
Mg (cmol+/kg)	0.53	0.82	1.40	1.84	0.81	1.20
Ca (cmol+/kg)	9.92	10.40	8.60	19.02	9.05	8.30
Al (cmol+/kg)	1.36	1.23	1.30	0	1.07	1.23
CEC (cmol+/kg)	1.05	1.29	1.45	2.49	1.40	1.05
P (mg/kg)	3	6	5	19	5	5
SO ₄ (mg/kg)	771	745	710	492	629	783
Cl (mg/kg)	48	53	63	31	59	72

Method 5: Chemical amelioration

Befor	e ameliora	ation	After amelioration		
0-150	150-300	300-600	0-150	150-300	300-600
3.6	3.7	3.5	8.2	7.0	4.6
381	312	471	309	341	415
0.25	0.31	0.13	0.29	0.40	0.17
0.12	0.29	0.16	0.18	0.39	0.18
0.17	0.22	0.30	1.08	1.24	0.26
9.68	10.49	8.60	14.50	12.10	12.20
1.41	1.58	1.38	0	0	0.99
1.66	1.28	1.95	4.92	3.14	2.54
4	7	5	9	7	4
625	649	703	529	602	693
57	60	65	48	51	68
	0-150 3.6 381 0.25 0.12 0.17 9.68 1.41 1.66 4 625	0-150 150-300 3.6 3.7 381 312 0.25 0.31 0.12 0.29 0.17 0.22 9.68 10.49 1.41 1.58 1.66 1.28 4 7 625 649	3.6 3.7 3.5 381 312 471 0.25 0.31 0.13 0.12 0.29 0.16 0.17 0.22 0.30 9.68 10.49 8.60 1.41 1.58 1.38 1.66 1.28 1.95 4 7 5 625 649 703	0-150 150-300 300-600 0-150 3.6 3.7 3.5 8.2 381 312 471 309 0.25 0.31 0.13 0.29 0.12 0.29 0.16 0.18 0.17 0.22 0.30 1.08 9.68 10.49 8.60 14.50 1.41 1.58 1.38 0 1.66 1.28 1.95 4.92 4 7 5 9 625 649 703 529	0-150 150-300 300-600 0-150 150-300 3.6 3.7 3.5 8.2 7.0 381 312 471 309 341 0.25 0.31 0.13 0.29 0.40 0.12 0.29 0.16 0.18 0.39 0.17 0.22 0.30 1.08 1.24 9.68 10.49 8.60 14.50 12.10 1.41 1.58 1.38 0 0 1.66 1.28 1.95 4.92 3.14 4 7 5 9 7 625 649 703 529 602

Plot 14 Attribute	Before amelioration			After amelioration		
	0-150	150-300	300-600	0-150	150-300	300-600
pH	3.7	3.5	3.5	8.2	7.0	3.7
EC (mS/m)	481	461	483	349	358	489
Na (cmol+/kg)	0.24	0.33	0.15	0.25	0.32	0.17
K (cmol+/kg)	0.16	0.24	0.19	0.19	0.29	0.28
Mg (cmol+/kg)	0.21	0.25	0.33	1.38	1.24	0.36
Ca (cmol+/kg)	9.59	10.25	8.27	19.50	17.10	12.30
Al (cmol+/kg)	1.13	1.18	1.17	0	0	0.74
CEC (cmol+/kg)	1.62	1.69	1.63	3.92	3.18	1.59
P (mg/kg)	3	3	4	26	9	4
SO ₄ (mg/kg)	644	693	748	527	656	698
Cl (mg/kg)	56	71	67	50	56	60

Plot 19 Attribute	Before amelioration			After amelioration		
	0-150	150-300	300-600	0-150	150-300	300-600
pH	3.4	3.5	3.3	7.7	7.1	4.2
EC (mS/m)	316	268	303	308	344	320
Na (cmol+/kg)	0.17	0.21	0.20	0.14	0.15	0.26
K (cmol+/kg)	0.12	0.06	0.17	0.30	0.21	0.24
Mg (cmol+/kg)	0.23	0.25	0.29	1.56	1.49	0.34
Ca (cmol+/kg)	5.70	9.40	6.50	18.50	15.40	6.70
Al (cmol+/kg)	1.21	1.28	1.13	0	0.11	1.12
CEC (cmol+/kg)	1.91	1.77	1.54	3.10	2.98	1.39
P (mg/kg)	4	3	4	24	13	3
SO ₄ (mg/kg)	697	745	735	673	704	731
Cl (mg/kg)	69	78	80	61	62	87

Plot 22	Before amelioration			After amelioration		
Attribute	0-150	150-300	300-600	0-150	150-300	300-600
pH	3.9	3.6	3.7	7.7	7.1	4.2
EC (mS/m)	296	278	282	358	294	350
Na (cmol+/kg)	0.16	0.15	0.19	0.15	0.11	0.10
K (cmol+/kg)	0.09	0.06	0.10	0.20	0.15	0.08
Mg (cmol+/kg)	0.16	0.20	0.19	0.56	0.49	0.14
Ca (cmol+/kg)	4.70	9.12	6.92	13.50	12.40	6.50
Al (cmol+/kg)	1.28	1.23	1.15	0	0	1.14
CEC (cmol+/kg)	1.92	1.99	1.03	3.07	3.38	1.08
P (mg/kg)	4	3	4	19	13	3
SO ₄ (mg/kg)	667	701	721	646	729	713
Cl (mg/kg)	56	59	78	60	67	77

Method 6: Chemical amelioration under drip irrigation

Plot 2	Befor	re amelior	ation	After amelioration			
Attribute	0-150	150-300	300-600	0-150	150-300	300-600	
pH	3.5	3.5	3.3	6.7	5.9	4.7	
EC (mS/m)	491	439	456	313	404	433	
Na (cmol+/kg)	0.25	0.32	0.39	0.21	0.30	0.32	
K (cmol+/kg)	0.26	0.05	0.09	0.59	0.21	0.28	
Mg (cmol+/kg)	1.04	1.34	0.94	2.57	2.30	2.10	
Ca (cmol+/kg)	6.40	6.90	5.80	19.30	11.60	8.40	
Al (cmol+/kg)	1.04	1.05	1.19	0	0	0.13	
CEC (cmol+/kg)	1.60	1.60	1.40	1.90	2.30	1.29	
P (mg/kg)	5	4	6	19	10	5	
SO ₄ (mg/kg)	751	772	749	459	624	741	
Cl (mg/kg)	67	69	77	52	58	62	

Plot 5 Attribute	Befor	e amelior:	ation	After amelioration		
	0-150	150-300	300-600	0-150	150-300	300-600
рН	3.6	3.4	3.7	6.2	4.8	3.7
EC (mS/m)	482	432	476	313	444	473
Na (cmol+/kg)	0.23	0.28	0.44	0.21	0.31	0.42
K (cmol+/kg)	0.16	0.15	0.14	0.49	0.28	0.18
Mg (cmol+/kg)	1.51	1.43	0.97	2.56	2.30	0.89
Ca (cmol+/kg)	7.40	5.70	5.90	14.40	10.50	5.20
Al (cmol+/kg)	1.01	1.00	1.09	0	0	0.83
CEC (cmol+/kg)	1.67	1.42	1.15	2.96	2.81	1.12
P (mg/kg)	4	4	5	18	8	7
SO ₄ (mg/kg)	743	762	755	721	785	769
Cl (mg/kg)	61	79	86	52	88	89

Plot 6	Before amelioration			After amelioration		
Attribute	0-150	150-300	300-600	0-150	150-300	300-600
pH	3.4	3.6	3.0	6.7	4.8	3.8
EC (mS/m)	467	439	399	301	454	473
Na (cmol+/kg)	0.19	0.25	0.46	0.28	0.43	0.32
K (cmol+/kg)	0.11	0.14	0.10	0.49	0.28	0.09
Mg (cmol+/kg)	0.96	0.86	0.75	1.83	1.18	0.73
Ca (cmol+/kg)	7.3	5.3	6.8	10.4	9.4	7.3
Al (cmol+/kg)	1.19	1.10	1.36	0	0	0.80
CEC (cmol+/kg)	1.90	1.08	1.25	3.8	3.5	1.38
P (mg/kg)	5	5	5	14	6	7
SO ₄ (mg/kg)	734	779	728	638	754	739
Cl (mg/kg)	66	79	69	52	88	84

Plot 9	Before amelioration			After amelioration		
Attribute	0-150	150-300	300-600	0-150	150-300	300-600
pH	3.6	3.7	3.5	7.9	7.1	4.3
EC (mS/m)	348	352	461	376	358	433
Na (cmol+/kg)	0.25	0.21	0.15	0.23	0.20	0.15
K (cmol+/kg)	0.14	0.29	0.16	0.48	0.35	0.18
Mg (cmol+/kg)	0.25	0.24	0.29	1.46	1.31	0.31
Ca (cmol+/kg)	8.59	9.58	7.60	16.50	13.20	11.70
Al (cmol+/kg)	1.13	1.26	1.14	0	0	0.63
CEC (cmol+/kg)	1.83	1.50	1.73	3.95	2.16	2.31
P (mg/kg)	5	7	4	18	5	4
SO ₄ (mg/kg)	643	604	751	541	668	693
Cl (mg/kg)	56	71	92	50	63	78

Method 7: Chemical amelioration under sprinkler irrigation

Plot 25 Before amelioration After amelioration Attribute 0-150 150-300 300-600 0 - 150150-300 300-600 pH 3.7 3.6 3.4 7.7 6.1 4.2 EC (mS/m) 307 335 369 388 384 399 Na (cmol+/kg) 0.10 0.05 0.12 0.11 0.11 0.15 K (cmol+/kg) 0.13 0.25 0.12 0.72 0.45 0.28 Mg (cmol+/kg) 0.34 0.37 0.21 1.46 1.36 0.24 5.7 7.31 6.49 15.60 16.20 6.40 Ca (cmol+/kg) Al (cmol+/kg) 1.08 1.23 1.04 0 0 1.04 3.30 2.76 2.53 CEC (cmol+/kg) 1.51 1.58 1.60 P (mg/kg) 4 3 41 28 3 3 SO₄ (mg/kg) 659 757 771 669 758 792 53 71 65 69 Cl (mg/kg) 43 75

Plot 26 Attribute	Before amelioration			After amelioration		
	0-150	150-300	300-600	0-150	150-300	300-600
pH	3.9	3.7	3.5	.7.7	5.9	3.7
EC (mS/m)	337	382	451	368	359	392
Na (cmol+/kg)	0.16	0.12	0.09	0.27	0.17	0.18
K (cmol+/kg)	0.19	0.15	0.13	0.44	0.35	0.08
Mg (cmol+/kg)	0.36	0.29	0.29	1.13	1.39	0.34
Ca (cmol+/kg)	4.90	7.14	5.62	15.50	10.30	6.50
Al (cmol+/kg)	1.16	1.13	1.12	0	0	1.02
CEC (cmol+/kg)	1.61	1.87	1.67	3.67	2.44	1.35
P (mg/kg)	4	3	4	16	13	3
SO ₄ (mg/kg)	605	756	731	692	758	746
Cl (mg/kg)	51	69	75	65	65	78

Plot 27	Bef	ore amelio	ration	After amelioration		
Attribute	0-150	150-300	300-600	0-150	150-300	300-600
pH	3.9	3.6	3.1	7.7	6.1	4.0
EC (mS/m)	329	381	373	240	324	380
Na (cmol+/kg)	0.06	0.35	0.13	0.10	0.21	0.15
K (cmol+/kg)	0.20	0.08	0.31	0.74	0.55	0.38
Mg (cmol+/kg)	0.16	0.34	0.20	1.49	1.07	0.14
Ca (cmol+/kg)	3.70	4.38	5.61	20.60	12.90	6.50
Al (cmol+/kg)	0.96	1.23	1.35	0	0	1.17
CEC (cmol+/kg)	1.45	1.67	1.83	3.23	2.83	1.94
P (mg/kg)	4	3	4	35	11	4
SO ₄ (mg/kg)	749	726	789	686	702	781
Cl (mg/kg)	47	41	79	36	57	75

Plot 28 Attribute	Befo	re amelio	ration	After amelioration			
	0-150	150-300	300-600	0-150	150-300	300-600	
pH	3.9	3.2	3.7	6.7	5.1	3.5	
EC (mS/m)	381	362	397	348	381	340	
Na (cmol+/kg)	0.36	0.21	0.09	0.25	0.20	0.11	
K (cmol+/kg)	0.20	0.09	0.14	0.42	0.31	0.18	
Mg (cmol+/kg)	0.35	0.40	0.25	1.38	1.29	0.34	
Ca (cmol+/kg)	5.90	7.17	6.48	17.50	13.50	6.20	
Al (cmol+/kg)	1.01	1.33	0.94	0	0.18	1.12	
CEC (cmol+/kg)	1.67	1.04	1.05	3.76	2.12	1.02	
P (mg/kg)	3	3	5	31	9	3	
SO ₄ (mg/kg)	648	729	748	703	728	759	
Cl (mg/kg)	41	55	63	38	49	60	

Soil analysis 2000: 0-30 cm layer

Attribute	M1	M2	M3	M4	M5	M6	M7
pH	7.3	7.3	7.4	7.3	7.5	6.9	7.5
EC (mS/m)	249	252	233	236	231	269	235
Na (cmol+/kg)	0.16	0.13	0.12	0.07	0.13	0.24	0.12
K (cmol+/kg)	0.16	0.07	0.18	0.08	0.15	0.12	0.11
Mg (cmol+/kg)	0.58	0.31	0.39	0.33	0.59	0.52	0.52
Ca (cmol+/kg)	4.77	3.73	8.33	7.34	8.48	14.47	7.93
Al (cmol+/kg)							
CEC (cmol+/kg)	2.2	2.75	2.12	2.33	1.22	1.35	2.52
P (mg/kg)	18	17	14	16	25	11	18
SO ₄ (mg/kg)							
Cl (mg/kg)	21	27	20	16	16	29	19

Soil analysis 2001: 0-30 cm layer

Attribute	M1	M2	M3	M4	M5	M6	M7
pH	7.7	7.6	7.6	7.6	7.7	7.6	7.7
EC (mS/m)	234	247	302	319	327	355	324
Na (cmol+/kg)	0.24	0.28	0.27	0.38	0.28	0.45	0.37
K (cmol+/kg)	0.08	0.15	0.16	0.17	0.12	0.08	0.07
Mg (cmol+/kg)	0.92	1.05	0.82	1.07	1.15	1.01	0.80
Ca (cmol+/kg)	2.03	2.91	4.46	4.32	4.62	6.09	6.09
Al (cmol+/kg)				0.102		0.08	
CEC (cmol+/kg)	2.07	2.33	1.88	2.21	2.58	1.90	2.14
P (mg/kg)	15	9	13	25	25	17	8
SO ₄ (mg/kg)	376	588	664	722	643	703	678
Cl (mg/kg)	160	56	123	184	140	287	230

Method 1: Leaching analysis at end of study period

PH EC (mS/m) Na (cmol+/kg) K (cmol+/kg) Mg (cmol+/kg) Ca (cmol+/kg) Al (cmol+/kg) CEC (cmol+/kg) P (mg/kg)		0 - 30 c	m layer		30 - 60 cm layer				
Attribute	P4	P11	P13	P21	P4	P11	P13	P21	
рН	7.3	6.7	7.4	8.2	7.4	5.2	7.2	7.8	
EC (mS/m)	469	321	181	62	550	393	417	98	
Na (cmol+/kg)	1.07	0.50	0.20	0.09	1.27	0.70	0.53	0.16	
K (cmol+/kg)	0.30	0.16	0.14	0.14	0.12	0.10	0.05	0.06	
Mg (cmol+/kg)	1.34	0.67	0.59	0.76	0.43	0.19	0.25	0.47	
Ca (cmol+/kg)	3.88	3.47	1.16	1.89	6.75	8.74	0.95	0.91	
Al (cmol+/kg)									
CEC (cmol+/kg)	2.29	1.15	4.52	1.78	4.90	2.60	5.49	1.25	
P (mg/kg)	48	9	27	43	8	3	7	17	
SO ₄ (mg/kg)	1171	867	216	21	1396	1280	796	67	
Cl (mg/kg)	443	208	109	19	440	225	231	59	

Method 2: Revised leaching

EC (mS/m) Na (cmol+/kg) K (cmol+/kg) Mg (cmol+/kg) Ca (cmol+/kg) Al (cmol+/kg) CEC (cmol+/kg) P (mg/kg)		0-30	m layer	-	30-60 cm layer				
DH EC (mS/m) Na (cmol+/kg) K (cmol+/kg) Mg (cmol+/kg) Ca (cmol+/kg) Al (cmol+/kg) CEC (cmol+/kg) P (mg/kg)	P10	P16	P33	P36	P10	P16	P33	P36	
pH	7.3	7.5	7.8	7.8	7.1	6.5	7.5	7.3	
EC (mS/m)	286	338	61	141	360	383	204	339	
Na (cmol+/kg)	0.46	0.44	0.10	0.15	0.58	0.49	0.23	0.32	
K (cmol+/kg)	0.18	0.10	0.08	0.13	0.10	0.06	0.04	0.05	
Mg (cmol+/kg)	1.24	0.74	0.59	1.44	0.14	0.22	0.10	0.18	
Ca (cmol+/kg)	3.65	2.02	1.31	2.21	8.14	2.97	0.87	2.86	
Al (cmol+/kg)									
CEC (cmol+/kg)	3.24	1.30	1.08	2.90	1.98	1.60	1.10	2.23	
P (mg/kg)	26	25	26	19	3	8	5	6	
SO ₄ (mg/kg)	647	705	40	114	1172	864	380	724	
Cl (mg/kg)	196	153	16	64	137	144	52	108	

Method 3: Elementary amelioration

PH EC (mS/m) Na (cmol+/kg) K (cmol+/kg) Mg (cmol+/kg) Ca (cmol+/kg) Al (cmol+/kg) CEC (cmol+/kg)		0-30 c	m layer		30-60 cm layer				
Attribute	P 1	P 3	P 17	P 18	P 1	P 3	P 17	P 18	
рН	6.8	7.1	7.6	7.3	6.6	6.7	6.8	6.2	
EC (mS/m)	539	362	232	258	438	335	314	305	
Na (cmol+/kg)	1.31	0.64	0.25	0.22	1.00	0.56	0.31	0.29	
K (cmol+/kg)	0.15	0.18	0.14	0.09	0.08	0.10	0.09	0.05	
Mg (cmol+/kg)	0.40	0.98	0.56	0.84	0.26	0.23	0.08	0.15	
Ca (cmol+/kg)	9.08	6.12	1.24	2.22	9.16	11.54	8.71	4.18	
Al (cmol+/kg)									
CEC (cmol+/kg)	1.37	2.69	1.23	1.64	2.00	2.44	1.29	1.40	
P (mg/kg)	9	25	16	12	3	4	5	3	
SO ₄ (mg/kg)	1507	1347	305	617	1427	1232	793	854	
Cl (mg/kg)	566	217	126	57	254	122	63	73	

Method 4: Minimum cultivation with topsoil

		0-30 c	m layer			30-60 c	m layer	
EC (mS/m) Na (cmol+/kg) K (cmol+/kg) Mg (cmol+/kg) Ca (cmol+/kg) Al (cmol+/kg)	P 7	P 12	P 20	P 30	P 7	P 12	P 20	P 30
рН	7.4	7.6	7.7	7.3	5.7	6.3	7.5	7.3
EC (mS/m)	406	238	165	391	424	378	375	301
Na (cmol+/kg)	0.82	0.47	0.16	0.44	0.91	0.42	0.38	0.24
K (cmol+/kg)	0.17	0.20	0.13	0.14	0.12	0.06	0.04	0.06
Mg (cmol+/kg)	1.04	1.46	1.05	0.40	0.32	0.30	0.23	0.10
Ca (cmol+/kg)	4.50	3.64	2.43	2.75	11.99	4.24	2.92	8.69
Al (cmol+/kg)								
CEC (cmol+/kg)	2.19	2.63	1.29	1.64	2.68	4.98	1.78	1.42
P (mg/kg)	21	22	34	18	3	3	6	6
SO ₄ (mg/kg)	1029	451	135	906	1395	802	692	225
Cl (mg/kg)	314	162	84	225	255	122	149	52

Method 5: Chemical amelioration

pH EC (mS/m) Na (cmol+/kg) K (cmol+/kg) Mg (cmol+/kg) Ca (cmol+/kg) Al (cmol+/kg) CEC (cmol+/kg) P (mg/kg)		0-30	m layer		30-60 cm layer				
Attribute	P 8	P 14	P 19	P 22	P 8	P 14	P 19	P 22	
pH		7.8	7.8	7.7		7.5	7.5	7.5	
EC (mS/m)		97	112	146		317	392	387	
Na (cmol+/kg)		0.12	0.13	0.20		0.48	0.43	0.35	
K (cmol+/kg)		0.14	0.28	0.10		0.03	0.06	0.02	
Mg (cmol+/kg)		1.27	1.06	1.19		0.54	0.55	0.13	
Ca (cmol+/kg)		2.09	1.77	1.98		1.59	1.77	4.40	
Al (cmol+/kg)									
CEC (cmol+/kg)		6.10	1.66	1.23		1.91	1.53	1.86	
P (mg/kg)		38	27	27		5	8	5	
SO ₄ (mg/kg)		47	36	147		555	578	718	
Cl (mg/kg)		45	59	92		167	208	159	

Method 6: Chemical amelioration under drip irrigation

pH EC (mS/m) Na (cmol+/kg) K (cmol+/kg) Mg (cmol+/kg) Ca (cmol+/kg) Al (cmol+/kg) CEC (cmol+/kg)		0-30 c	m layer		30-60 cm layer			
Attribute	P 2	P 5	P 6	P 9	P 2	P 5	P 6	P 9
рН	7.6	5.7	7.5	7.3	7.2	4.6	6.5	6.2
EC (mS/m)	288	548	399	499	328	421	498	485
Na (cmol+/kg)	0.18	1.21	0.51	0.78	0.46	0.72	0.96	0.89
K (cmol+/kg)	0.14	0.18	0.13	0.14	0.07	0.09	0.10	0.09
Mg (cmol+/kg)	2.01	0.62	1.94	1.87	0.79	0.02	1.03	1.19
Ca (cmol+/kg)	6.63	9.94	7.62	11.44	6.26	18.22	11.53	11.68
Al (cmol+/kg)								
CEC (cmol+/kg)	2.25	1.29	1.50	2.95	3.32	5.01	3.72	2.16
P (mg/kg)	23	5	18	12	5	2	4	4
SO ₄ (mg/kg)	1070	1553	1187	1224	1105	1331	1481	1620
Cl (mg/kg)	97	457	217	480	139	250	291	295

Method 7: Chemical amelioration under sprinkler irrigation

DH EC (mS/m) Na (cmol+/kg) K (cmol+/kg) Mg (cmol+/kg) Ca (cmol+/kg) Al (cmol+/kg) CEC (cmol+/kg)		0-30 c	m layer			m layer		
Attribute	P 25	P 26	P 27	P 28	P 25	P 26	P 27	P 28
pH	7.9	7.3	7.5	7.5	7.4	5.6	6.9	7.4
EC (mS/m)	122	373	582	292	558	581	430	457
Na (cmol+/kg)	0.19	0.26	0.96	0.41	1.00	1.01	0.67	0.83
K (cmol+/kg)	0.08	0.15	0.15	0.16	0.05	0.09	0.06	0.04
Mg (cmol+/kg)	0.71	0.71	0.91	0.84	0.40	0.46	0.30	0.33
Ca (cmol+/kg)	1.16	2.70	3.20	2.57	6.81	9.11	8.53	6.35
Al (cmol+/kg)								
CEC (cmol+/kg)	2.00	1.78	2.87	2.16	1.07	1.87	3.26	1.65
P (mg/kg)	13	20	28	27	4	5	5	5
SO ₄ (mg/kg)	64	684	875	383	924	1022	946	993
Cl (mg/kg)	62	143	453	193	316	320	193	234

APPENDIX B: VEGETATION SURVEY DATA

President Steyn Gold Mine Tailings Dam no. 6

Table B 1. Species composition and basal cover for the experimental methods: 2000

Species	M1	M2	M3	M4	M5	M6	M7
Chloris gayana	36.6	45.4	48.4	59.2	62.8	36.7	37.9
Cynodon dactylon	0.7	3.9	3.2	3.4	7.2	25.2	7.7
Dactylis glomerata	35.6	25	25.1	15.6			
Eragrostis cuvula	3.9	5.1	7.1	8.2	20	26.9	23.6
Eragrostis tef	2.3		0.7	*	6.3	6	12.6
Lolium perenne	9.1	11.4	7.4	7.5			1.2
Festica elatior	9.7	3.6	5.7	4.1			
Polypogon monspeliensis					1.5	2.6	2.8
Medicago sativa	1.5	2.8	*	2	1.5	1.7	11.9
Melilutus alba					0.7	0.9	2.3
Atriplex semibaccata	*		*	*	*	*	*
Conyza bonariensis	*	*	*	*			
Brassica napus	*	*	*	*			
Basal cover %	6.2	7.3	6.1	5.4	4.6	4.9	4.1

^{*&}lt; 0.7 %

Table B2 Species composition and basal cover for the experimental methods: 2001

Specie	M1	M2	M3	M4	M5	M6	M7
Chloris gayana	1				*		2
Cynodon dactylon	2	3	1	2	5	2	10
Dactylis glomerata	55	60	38	41	6	5	*
Eragrostis curvula	11	11	26	15	28	16	18
Hyparrhenia hirta	1				5		
Lolium perenne	*	6	7	2	2	1	1
Poa pratensis	*	*	1				
Polypogon monspeliensis	*	2	*	*	1	7	*
Medicago sativa	27	15	24	33	41	69	65
Melilutus alba	1	2	*	2	9	*	2
Atriplex semibaccata	*	*	1	*	1	*	1
Atriplex nimmularia			2	3		*	-
Basal cover (%)	6.3	7.5	6.8	7.5	5.5	5	7.3

^{* &}lt; 1 %

Table B3: Species composition and basal cover results for the 36 research plots (D1 – D36) on the southern slope (first lift) of President Steyn Mine tailings Dam no 6. March 2002

Species					Plots				
	D 01	D 02	D 03	D04	D 05	D 06	D 07	D 08	D 09
Eragrostis cuvula (Weeping lovegrass)	20	24	14	5	8	8	14	41	31
Dactylis glomerata (Rough cocksfoot)	34	13	59	68	*	4	49	8	5
Lolium perenne (Perennial ryegrass)									
Cynodon dactylon (Couch grass)				3	12	5	2		16
Ploypogon monspeliensis (Rabbit's foot)						6			5
Chloris gayana (Rhodes grass)									
Agrostis tenius (Colonial bentgrass)				7			10	*	
Medicago sativa (Lucern)	29	23	16	11	23	44	8	29	24
Melilutus alba (Sweet clover)	12	8	10		7		1		
Atriplex semibacata (Creeping salt bush)	1						3		
Conyza bonariensis (Flax-leaf fleabane)		7			11	10	5	10	9
Cirsium vulgare (Scotch thistle)		9		3	19	5	4	4	2
Lactuca serriola (Wild lettuce)	4	15	1_	3	18	18	4	7	8
Basal cover	3	2	3	4	3	2	4	3	3

Legend:

 Species is present but the botanical composition consist of less than 1% of the species.

Plots - Species abundance in the different plots (%)

Species					Plots				
	D 10	D 11	D 12	D 13	D 14	D 15	D 16	D 17	D 18
Eragrostis cuvula (Weeping lovegrass)	9	9	12	4	26	49	19	27	27
Dactylis glomerata (Rough cocksfoot)	59	46	48	48	8	6	49	51	43
Lolium perenne (Perennial ryegrass)							*		*
Cynodon dactylon (Couch grass)	*	1	2		1	9	2		5
Ploypogon monspeliensis (Rabbit's foot)						4		*	
Hyparrhenia hirta (Common thatching grass)					1				
Chloris gavana (Rhodes grass)									*
Agrostis tenuis (Colonial bentgrass)	9	9	7	12	٠	٠	7	5	3
Medicago sativa (Lucern)	20	29	22	19	52	14	11	13	14
Melilutus alba (Sweet lucern)					8		2		4
Atriplex semibaccata (Creeping salt bush)						8			
Conyza bonariensis (Flax-leaf fleabane)	*	4	2	9	2	7	2		1
Cirsium vulgare (Scotch thistle)	*	1	4	5	1	3	5	3	1
Lactuca serriola (Wils lettuce)	1	1	3	2	1	1	2	*	2
Basal cover	3	4	3	3	4	5	3	3	2

Species					Plots				
	D 19	D 20	D 21	D 22	D 23	D24	D 25	D 26	D 27
Eragrostis cuvula (Weeping lovegrass)	33	19	16	61	51	41	22	22	27
Dactylis glomerata (Rough cocksfoot)	16	34	44		6	12	1	1	*
Lolium perenne (Perennial ryegrass)				2					
Cynodon dactylon (Couch grass)		2	*	6	2	4	2	2	
Ploypogon monspeliensis (Rabbit's foot)	*								
Hyparrhenia hirta (Common thatching grass)									
Chloris gayana (Rhodes grass)			14	2					
Agrostis tenius (Colonial bentgrass)	2	1	1		7	16	4	2	1
Digitaria eriantha (Smuts vingergrass)						2			
Medicago sativa (Lucern)	19	21	8	11	6	10	39	32	19
Melilutus alba (Sweet lucern)	9	6	1	4	1	1	8	7	12
Atriplex semibacata (Creeping salt bush)					14	5	1		
Conyza honariensis (Flax-leaf fleabane)	12	11	5	9	7	3	11	24	31
Cirsium vulgare (Scotch thistle)	5	4	4	2	3	2	2	2	2
Lactuca serriola (Wild lettuce)	3	1	6	1	2	3	9	8	7
Basal cover	4	3	4	5	4	3	2	3	3

Species					Plots				
	D 28	D 29	D 30	D 31	D 32	D 33	D 34	D 35	D 36
Eragrostis cuvula (Weeping lovegrass)	46	44	22	47	44	9	46	71	14
Dactylis glomerata (Rough cocksfoot)	9	7	29	4	25	65	24	5	36
Lolium perenne (Perennial ryegrass)		7	5	4	3	4	3	1	4
Cynodon dactylon (Couch grass)	2	5	5	15	8		14	6	5
Ploypogon monspeliensis (Rabbit's foot)				6				3	2
Hyparrhenia hirta (Common thatching grass)	1				1				
Chloris gavana (Rhodes grass)	2	1	2		2				1
Agrostis tenius (Colonial bentgrass)	2	21				6			2
Digitaria eriantha (Smuts vingergrass)					3	_			
Medicago sativa (Lucern)	21	4	12	8	2	9	7	6	22
Melilutus alba (Sweet lucern)	4	1		3		3	2	1	2
Atriplex semibaccata (Creeping salt bush)		4	5	3	4		*		
Conyza bonariensis (Flax-leaf fleabane)	8	3	11	5	4	3	2	5	9
Cirsium vulgare (Scotch thistle)	2	1	3	3	2			1	2
Lactuca serriola (Wild lettuce)	3		5	2	1	1	1		1
Basal cover	5	3	1	4	3	2	3	3	3

Species composition

The research plots are covered by a large variety of other species, which include numerous natural volunteer species. These species are:

Amaranthus viridus (Slender amaranth)

Aristida canescens (Pale Three-awn)

Atriplex nimmularia (Old man salt bush)

Berkeya setifera (Dissel thorn)

Bromus catharticus (Rescue grass)

Bidens bipinnata (Spanish blackjack)

Chenopodium album (White goosefoot)

Convza albida (Tall fleabane)

Convza bonariensis (Flax-leaf fleabane)

Conyza podocephala (Common Conyza)

Cynodon nlemfuensis (Star grass)

Cyperus rotundus (Purple nutsedge)

Dactyloctenium giganteum (Giant crowfoot)

Eragrostis lehmanniana (Lehmann's grass)

Eragrostis trichophora (Hairy lovegrass)

Hypochoeris radicata (Hairy wild lettuce)

Panicum schinzi (Sweet grass)

Paspalum dilatatum (Common paspalum)

Pennisetum macrourum (Hippo grass)

Phragmites australis (Common reed)

Poa pratensis (Kentucky blue)

Pseudognaphalium luteo-album (Jersey cudweed)

Scenecio latifolius (Ragworth)

Tagetes minuta (Tall khaki weed)

Tamarix gallica (Tamarix)

Tribulus terrestris (Common dubbeltjie)

Verbena officinalis (European verbena)

Numerous anomalies were identified during the survey.

- Eragrostis curvula (Weeping love grass) was more abundant on the top half of the slope while Medicago sativa (Lucerne), Dactylis glomerata (Rough cocksfoot) and Agrostis tenius (Colonial bentgrass) dominated the bottom half of the slope. Atriplex semibaccata (Creeping salt bush) and Tamarix gallica (Tamarix) were also more abundant on the bottom half of the slope.
- Species with bigger seed that were used for rehabilitation are also found in the toe paddocks eg. Bromus catharticus (Smooth brome).
- Very few seedlings were encountered during the survey.

- There is a high amount of dead biomass covering the slimes material, which could be one of the reasons for the few seedlings.
- Pennisetum macrourum (Hippo grass) is still abundant on the boundaries of the research plots.
- The botanical physiognomy of the different plots is evident of the different seed mixtures and amelioration that was applied.

Remarks regarding surveys of the previous year.

- Chloris gayana (Rhodes grass) did not penetrate the plots to a great extent.
- Medicago sativa (Lucerne) decreased substantially in most of the plots.
- Dactylis glomerata (Rough cocksfoot), Eragrostis curvula (Weeping lovegrass) and Medicago sativa (Lucerne) are the most abundant species of those that were used in the seed mixture.
- There are an increase in weeds in the plots, which include Conyza bonariensis
 (Flax-leaf fleabane), Cirsium vulgare (Scotch thistle) and Lactuca serriola (Wild lettuce).
- The basal cover also decreased to a great extent.

Table B4 The mean and standard deviations in species frequency

Method 1	leaching		200	1		
	d4	d11	d13	d21	avg	stdv
E.curvula	3	5	5	32	11.25	13.87
D. glomerata	74	65	38	42	54.75	17.5
L. perenne	0	0	0	0	0	0
C. dactylon	0	2	3	4	2.25	1.71
P. monspeliences	0	0	0	0	0	0
H.hirta	0	0	4	0	1	2
C.gayana	0	0	2	2	1	1.15
P.pratensis	0	0	0	0	0	0
A. tenius	0	0	0	0	0	0
M.sativa	21	28	48	12	27.25	15.31
M.alba	0	0	0	6	1.5	3
A. semibaccata	0	0	0	0	0	0
C. bonariensis	0	0	0	0	0	0
C. vulgara	0	0	0	0	0	0
L. serriola	0	0	0	0	0	0
basal cover	6	8	7	4	6.25	1.71

Table B5 The mean and standard deviations in species frequency

Method 1	leaching	200	2			
	d4	d11	d13	d21	avg	stdv
E.curvula	5	9	4	16	8.5	5.45
D. glomerata	68	46	48	44	51.5	11.12
L. perenne	0	0	0	0	0	0
C. dactylon	3	1	0	0	1	1.41
P. monspeliences	0	0	0	0	0	0
H.hirta	0	0	0	0	0	0
C.gayana	0	0	0	14	3.5	7
P.pratensis	0	0	0	0	0	0
A. tenius	7	9	12	1	7.25	4.65
M.sativa	11	29	19	8	16.75	9.39
M.alba	0	0	0	1	0.25	0.5
A. semibaccata	0	0	0	0	0	0
C. bonariensis	0	4	9	5	4.5	3.7
C. vulgara	0	1	5	4	2.5	2.38
L. serriola	3	1	2	6	3	2.16
basal cover	4	4	3	4	3.75	0.5

Table B6 The mean and standard deviations in species frequency

Method 2	revised lea	aching		2001			
	d10	d16	d33	d36	avg	stdv	
E.curvula	5	14	12	12	10.75	3.95	
D. glomerata	78	70	58	34	60	19.18	
L. perenne	0	6	6	12	6	4.9	
C. dactylon	2	2	4	4	3	1.15	
P. monspeliences	0	2	2	4	2	1.63	
H. hirta	0	0	0	0	0	0	
C.gayana	0	0	0	0	0	0	
P pratensis	0	0	0	0	0	0	
A. tenius	0	0	0	0	0	0	
D. eriantha	0	0	0	0	0	0	
M.sativa	13	2	18	26	14.75	10.05	
M.alba	0	0	0	6	1.5	3	
A. semibaccata	0	0	0	0	0	0	
C. bonariensis	0	0	0	0	0	0	
C. vulgara	0	0	0	0	0	0	
L. serriola	0	0	0	0	0	0	
basal cover	9	7	8	6	7.5	1.29	

Table B7 The mean and standard deviations in species frequency

Method 2	revised le	aching	2002			
	d10	d16	d33	d36	avg	stdv
E.curvula	9	19	9	14	12.75	4.79
D. glomerata	59	49	65	36	52.25	12.69
L. perenne	0	0	4	4	2	2.31
C. dactylon	0	2	0	5	1.75	2.36
P. monspeliences	0	0	0	2	0.5	1
H. hirta	0	0	0	0	0	0
C.gayana	0	0	0	1	0.25	0.5
P pratensis	0	0	0	0	0	0
A. tenius	9	7	6	2	6	2.94
D. eriantha	0	0	0	0	0	0
M.sativa	20	11	9	22	15.5	6.45
M.alba	0	2	3	2	1.75	1.26
A. semibaccata	0	0	0	0	0	0
C. bonariensis	0	2	3	9	3.5	3.87
C. vulgara	0	5	0	2	1.75	2.36
L. serriola	1	2	1	1	1.25	0.5
basal cover	3	3	2	3	2.75	0.5

Table B8 The mean and standard deviations in species frequency

Method 3	elementar	y ameliora	tion	2001			
	d1	d3	d17	d18	avg	stdv	
E.curvula	38	10	32	22	25.5	12.26	
D. glomerata	12	70	46	24	38	25.56	
L. perenne	0	2	12	12	6.5	6.4	
C. dactylon	0	0	0	4	1	2	
P. monspeliences	0	0	0	0	0	0	
H.hirta	0	0	0	0	0	0	
C.gayana	0	0	0	4	1	2	
P pratensis	0	0	0	4	1	2	
A. tenius	0	0	0	0	0	0_	
M.sativa	46	15	10	26	24.25	15.97	
M.alba	0	0	0	0	0	0	
A. semibaccata	0	0	0	0	0	0	
C. bonariensis	0	0	0	0	0	0	
C. vulgara	0	0	0	0	0	0	
L. serriola	0	0	0	0	0	0	
Basal cover	8	6	6	7	6.75	0.96	

Table B9 The mean and standard deviations in species frequency

Method 3	Elementary	amelio	ration	20	02	
	d1	d3	d17	d18	Avg	stdv
E.curvula	20	14	27	27	22	6.27
D. glomerata	34	59	52	43	47	10.86
L. perenne	0	0	0	0	0	0
C. dactylon	0	0	0	5	1.25	2.5
P. monspeliences	0	0	0	0	0	0
H.hirta	0	0	0	0	0	0
C.gayana	0	0	0	0	0	0
P pratensis	0	0	0	0	0	0
A. tenius	0	0	5	3	2	2.45
M.sativa	29	16	13	14	18	9.19
M.alba	12	10	0	4	6.5	1.41
A. semibaccata	1	0	0	0	0.25	0.71
C. bonariensis	0	0	0	0	0	0
C. vulgara	0	0	3	. 1	1	1.41
L. serriola	4	1	0	2	1.75	2.12
Basal cover	3	3	3	2	2.75	0.5

Table B10 The mean and standard deviations in species frequency

Method 4	minimu	ım cultivatio	n		2001		
	d7	d12	d20	d30	avg	stdv	
E.curvula	8	3	14	36	15.25	14.55	
D. glomerata	38	60	38	28	41	13.52	
L. perenne	0	5	0	4	2.25	2.63	
C. dactylon	4	0	2	2	2	1.63	
P. monspeliences	0	0	0	0	0	0	
H. hirta	0	0	0	0	0	0	
C.gayana	0	0	6	0	1.5	3	
P.pratensis	0	0	0	0	0	0	
A. tenius	0	0	0	0	0	0	
D. eriantha	0	0	0	0	0	0	
M.sativa	44	32	36	20	33	10	
M.alba	0	0	0	10	2.5	5	
A. semibaccata	0	0	0	0	0	0	
C. bonariensis	0	0	0	0	0	0	
C. vulgara	0	0	0	0	0	0	
L. serriola	0	0	0	0	0	0	
basal cover	7	8	9	6	7.5	1.29	

Table B 11 The mean and standard deviations in species frequency

Method 4	minimun	cultivation	with top so	il 2002	2	
	d7	d12	d20	d30	avg	stdv
E.curvula	14	12	19	22	16.75	4.57
D. glomerata	49	48	34	29	40	10.03
L. perenne	0	0	0	5	1.25	2.5
C. dactylon	2	2	2	5	2.75	1.5
P. monspeliences	0	0	0	0	0	0
H. hirta	0	0	0	0	0	0
C.gayana	0	0	0	2	0.5	1
P.pratensis						
A. tenius	10	7	1	0	4.5	4.8
D. eriantha	0	0	0	0	0	0
M.sativa	8	22	21	12	15.75	6.85
M.alba	1	0	6	0	1.75	2.87
A. semibaccata	3	0	0	5	2	2.45
C. bonariensis	5	2	11	11	7.25	4.5
C. vulgara	4	4	4	3	3.75	0.5
L. serriola	4	3	1	5	3.25	1.71
basal cover	4	3	3	1	2.75	1.26

Table B12 The mean and standard deviations in species frequency

Method 5	chemica	l ameliorati	on	2001			
	d8	d14	d19	d22	avg	stdv	
E.curvula	26	28	12	46	28	13.95	
D. glomerata	18	0	8	0	6.5	8.54	
L. perenne	0	2	4	2	2	1.63	
C. dactylon	2	4	2	14	5.5	5.74	
P. monspeliences	0	2	0	2	1	1.15	
H. hirta	0	0	0	10	2.5	5	
C.gayana	0	0	0	0	0	0	
P. pratensis	0	0	0	0	0	0	
A. tenius	0	0	0	0	0	0	
D. eriantha	0	0	0	0	0	0	
M.sativa	40	56	52	16	41	18	
M.alba	8	2	22	6	9.5	8.7	
A. semibaccata	0	0	0	2	0.5	1	
C. bonariensis	0	0	0	0	0	0	
C. vulgara	0	0	0	0	0	0	
L. serriola	0	0	0	0	0	0	
basal cover	6	7	5	4	5.5	1.29	

Table B13 The mean and standard deviations in species frequency

Method 5	chemical amelioration 2002							
	d8	d14	d19	d22	avg	stdv		
E.curvula	41	26	33	61	40.25	15.13		
D. glomerata	8	8	16	0	8	6.53		
L. perenne	0	0	0	2	0.5	1		
C. dactylon	0	1	0	6	1.75	2.87		
P. monspeliences	0	0	0	0	0	0		
H. hirta	0	1	0	0	0.25	0.5		
C.gayana	0	0	0	2	0.5	1		
P. pratensis								
A. tenius	0	0	2	0	0.5	1		
D. eriantha	0	0	0	0	0	0		
M.sativa	29	52	19	11	27.75	17.76		
M.alba	0	8	9	4	5.25	4.11		
A. semibaccata	0	0	0	0	0	0		
C. bonariensis	10	2	12	_ 9	8.25	4.35		
C. vulgara	4	1	5	2	3	1.83		
L. serriola	7	1	3	1	3	2.83		
basal cover	3	4	4	5	4	0.82		

Table B14 The mean and standard deviations in species frequency

Method 6	drip in	rigation		200	1	
	d2	d5	d6	d9	avg	stdv
E.curvula	45	5	4	10	16	19.51
D. glomerata	4	0	9	6	4.75	3.77
L. perenne	0	3	0	0	0.75	1.5
C. dactylon	0	2	2	2	1.5	1
P. monspeliences	0	3	0	24	6.75	11.59
H.hirta	0	0	0	0	0	0
C.gayana	0	0	0	0	0	0
P. pratensis	0	0	0	0	0	0
A. tenius	0	0	0	0	0	0
M.sativa	51	87	85	54	69.25	19.4
M.alba	0	0	0	0	0	0
A. semibaccata	0	0	0	4	1	2
C. bonariensis	0	0	0	0	0	0
C. vulgara	0	0	0	0	0	0
L. serriola	0	0	0	0	0	0
basal cover	7	4	4	5	5	1.41

Table B15 The mean and standard deviations in species frequency

Method 6	drip in	rigation	2002	2		
	d2	d5	d6	d9	avg	std
E.curvula	24	8	8	31	17.75	11.61
D. glomerata	13	0	4	5	5.5	5.45
L. perenne	0	0	0	0	0	0
C. dactylon	0	12	5	16	8.25	7.14
P. monspeliences	0	0	6	5	2.75	3.2
H.hirta	0	0	0	0	0	0
C.gayana	0	0	0	0	0	0
P. pratensis	0	0	0	0	0	0
A. tenius	0	0	0	0	0	0
M.sativa	23	23	44	24	28.5	10.34
M.alba	8	7	0	0	3.75	4.35
A. semibaccata	0	0	0	0	0	0
C. bonariensis	7	11	10	9	9.25	9.25
C. vulgara	9	19	5	2	8.75	7.41
L. serriola	15	18	18	8	14.75	4.72
basal cover	2	3	2	3	2.5	0.58

Table B16 The mean and standard deviations in species frequency

Method 7	impact spr	inklers	200	1		
	d25	d26	d27	d28	avg	stdv
E.curvula	16	14	20	22	18	3.65
D. glomerata	0	0	0	0	0	0
L. perenne	2	2	0	2	1.5	1
C. dactylon	8	8	12	12	10	2.31
P. monspeliences	0	0	0	0	0	0
H. hirta	0	0	0	0	0	0
C.gayana	2	4	0	0	1.5	1.91
P.pratensis	0	0	0	0	0	0
A. tenius	0	0	0	0	0	0
D. eriantha	0	0	00	0	0	0
M.sativa	66	70	62	64	65.5	3.41
M.alba	2	0	6	0	2	2.83
A. semibaccata	4	2	0	0	1.5	1.91
C. bonariensis	0	0	0	0	0	0
C. vulgara	0	0	0	0	0	0
L. serriola	0	0	0	0	0	0
basal cover	8	7	8	6	7.25	0.96

Table B17 The mean and standard deviations in species frequency

Method 7	impact spr	inklers	2002	2		
	d25	d26	d27	d28	avg	stdv
E.curvula	22	22	27	46	29.25	11.41
D. glomerata	1	1	0	9	2.75	4.19
L. perenne	0	0	0	0	0	0
C. dactylon	2	2	0	2	1.5	1
P. monspeliences	0	0	0	0	0	0
H. hirta	0	0	0	1	0.25	0.5
C.gayana	0	0	0	2	0.5	1
P.pratensis						
A. tenius	4	2	1	2	2.25	1.26
D. eriantha	0	0	0	0	0	0
M.sativa	39	32	19	21	27.75	9.43
M.alba	8	7	12	4	7.75	3.3
A. semibaccata	1	0	0	0	0.25	0.5
C. bonariensis	11	24	31	8	18.5	10.85
C. vulgara	2	2	2	2	2	0
L. serriola	9	8	7	3	6.75	2.63
basal cover	2	3	3	5	3.25	1.26

APPENDIX C

General information of dams rehabilitated in the past using different rehabilitation methods

Name / no of dam	East Champ D'or 1L1
Locality	Northern aspect
Owner	(Presently DME dam)
Who rehab	Chamber of mines
When rehab	Early 1960's
Rehab method	Leaching (with cultivation)
Time of leaching	
Type of water	
Maintenance time	
Type of	
maintenance	
Average slope 0	36
Average slope	50 m
length	
Est Veg cover	The original 20 species with seed and 5 species hand plants
Dominant species	Hyperhinia hirtha (90%+), Cynodon dactylon (5%). Medicago sativa, Cortaderia selloana, Eragrostis curvula,
	(Photo 1)
Root depth	60 cm
Signs of erosion	Limit to pathways and beneath seepage line
Surrounding veg	
Sample no	1 (0-30 cm)
Sample no	2 (30-60cm)
Sample no	
Remarks	Highly leached S-value< T- value, P-very high, Seems if organic cycle in place (Ca, Mg and K highest in top layer). Relative good buffer capacity CEC = 5

Attribute	0-30 cm	30-60 cm	Attribute	0-30 cm	30-60 cm
pН	7.4	6.5	Na (cmol+/kg)	0.12	0.12
EC (mS/m)	24	27	K (cmol+/kg)	0.05	0.03
P (mg/kg)	52	8	Mg (cmol+/kg)	0.57	0.02
SO ₄ (mg/kg)	14	50	Ca (cmol+/kg)	2.34	0.32
Cl (mg/kg)	3	2	CEC (cmol+/kg)	4.93	6.23

Name / no of dam	Fleurhof 2L3					
Locality	West facing slope					
Owner	Consolidated Main Reef					
Who rehab	Rand Mines					
When rehab	1969					
Rehab method	Leaching					
Time of leaching						
Type of water						
Maintenance time						
Type of maintenance						
Average slope 0	25					
Average slope length	86 m					
Est Veg cover	Original seed mix and hand plants					
Dominant species	Hyperenia hirta (90%+), Cynodon dactylon, Medicago sativa, Cynodon plestotachyus, Pennisetum macrounum, Cortaderia selloana					
	Photo 2 & 3					
Root depth	45 cm					
Signs of erosion	Only near trees (shade)					
Surrounding veg						
Sample no	3 (0-30 cm)					
Sample no	4 (30 – 60 cm)					
Sample no						
Sample no						
Sample no						
Sample no						
Remarks	Low pH in lower layer indicate Al problems, roots 45 cm- Hyparrhenia well adapted. CEC reasonably good. Excess salts- reflected in EC and S-values					

Attribute	0-30 cm	30-60 cm	Attribute	0-30 cm	30-60 cm
рН	6.8	4.1	Na (cmol+/kg)	0.25	0.37
EC (mS/m)	261	354	K (cmol+/kg)	0.07	0.02
P (mg/kg)	14	2	Mg (cmol+/kg)	0.56	0.80
SO ₄ (mg/kg)	1439	1913	Ca (cmol+/kg)	11.13	10.08
Cl (mg/kg)	29	55	CEC (cmol+/kg)	4.71	8.54

Name / no of dam	Wemmer pan 3L44			
Locality	West facing slope			
Owner				
Who rehab	Chamber of Mines			
When rehab	Late 1960's (east slope vegetated in 1995-97, N17 road cut)			
Rehab method	Leaching			
Time of leaching				
Type of water				
Maintenance time				
Type of maintenance				
Average slope 0	39			
Average slope length				
Est Veg cover	Original seed mix and hand plants			
Dominant species	Hyperhinia hirta (95%), Cynodon dactylon, Erogristus curvila			
	Medicago sativa			
	Photo 4 & 5			
Root depth	45 cm			
Signs of erosion	Along drain pipe failure, motor cycles			
Surrounding veg				
Sample no	5 (0-30 cm)			
Sample no	6 (30 – 60 cm)			
Sample no				
Remarks	Low pH in lower layer, Hyparrhenia well adapted to the high Al. CEC of top layer fairly good			

Attribute	0-30 cm	30-60 cm	Attribute	0-30 cm	30-60 cm
pH	6.3	3.7	Na (cmol+/kg)	0.20	0.15
EC (mS/m)	170	285	K (cmol+/kg)	0.10	0.02
P (mg/kg)	8	2	Mg (cmol+/kg)	0.36	0.38
SO ₄ (mg/kg)	67	1375	Ca (cmol+/kg)	9.27	5.21
Cl (mg/kg)	13	19	CEC (cmol+/kg)	4.7	2.64

Name / no of dam	EMPR 4L48		
Locality			
Owner	East facing slope		
Who rehab	ERPM		
When rehab	1994		
Rehab method	Leaching and the use of oxi-humate		
Time of leaching			
Type of water			
Maintenance time			
Type of			
maintenance			
Average slope ⁰	31		
Average slope	46		
length			
Est Veg cover	Original seed mix and hand plants (Chamber of Mines)		
Dominant species	Hyperhinia hirta, Cynodon ethiopus, Erogrostis curvila,		
	Chloris gayna (Populas)		
	Photo 7 & 8		
Root depth	45 cm		
Signs of erosion	Gullies stabilised with star grass		
Surrounding veg			
Sample no	7 (0 – 30 cm)		
Sample no	8 (30 – 60 cm)		
Sample no			
Remarks	pH on the low side, P and K on low side, CEC good for top layer		
	Seems good OM cycle.		

Attribute	0-30 cm	30-60 cm	Attribute	0-30 cm	30-60 cm
рН	5.3	3.4	Na (cmol+/kg)	0.18	0.24
EC (mS/m)	287	316	K (cmol+/kg)	0.04	0.02
P (mg/kg)	2	2	Mg (cmol+/kg)	0.94	0.26
SO ₄ (mg/kg)	1422	1563	Ca (cmol+/kg)	7.58	4.53
Cl (mg/kg)	20	37	CEC (cmol+/kg)	5.45	1.77

Name / no of dam	ERPM Dam 4 4L50					
Locality	South east facing slope					
Owner						
Who rehab	Chamber of Mines					
When rehab	1994					
Rehab method	Leaching					
Time of leaching						
Type of water						
Maintenance time						
Type of						
maintenance						
Average slope 0	30					
Average slope	40					
length						
Est Veg cover	Original seed mix and hand plants					
Dominant species	Eragrostis curvula, Hyparrhenia hirta, Cortaderia selloana,					
	Cynodon plestostachyus, Medicago sativa, Carpobrotus edulis					
	Photo 8 & 9					
Root depth	55					
Signs of erosion	(Many bare patches around Carpobrotus edulis)					
Surrounding veg						
Sample no	9 (0 – 30 cm)					
Sample no	10 (30 – 60 cm)					
Sample no						
Sample no						
Sample no						
Sample no						
Remarks	pH very low, CEC, K & Mg on low side.					

Attribute	0-30 cm	30-60 cm	Attribute	0-30 cm	30-60 cm
pH	4.5	3.7	Na (cmol+/kg)	0.16	0.19
EC (mS/m)	191	259	K (cmol+/kg)	0.06	0.03
P (mg/kg)	28	3	Mg (cmol+/kg)	0.27	0.20
SO ₄ (mg/kg)	881	1167	Ca (cmol+/kg)	2.64	10.51
Cl (mg/kg)	7	10	CEC (cmol+/kg)	2.73	2.43

Name / no of dam	Stilfontein no 5				
Locality	Stilfontein				
Owner	Durban Roodepoot Deep (Mine waste solution)				
Who rehab	Envirogreen				
When rehab	1994/95				
Rehab method	Chemical amelioration (30 ton lime/ha, 30 m ³ compost/ha, 1000kg supers/ha, 1000kg KCl/ha, 300 kg LAN				
Time of leaching	none				
Type of water	Good, irrigated for two years				
Maintenance time	Up to				
Type of maintenance	Normal 200 kg 4:3:4/ha/year				
Average slope ⁶	31				
Average slope length					
Est Veg cover	Mother crop, followed with Eragrostis curvula, Chloris gayana, Cynodon dactylon, Digitaria eriantha, Cenchrus ciliaris, Medicago sativa				
Dominant species	Eragrostis curvula, Cynodon dactylon, (Hyparrhenia hirta, Pampas)				
Root depth	45 cm				
Signs of erosion	Few at crest and toe				
Surrounding veg					
Sample no	No 11 (0-30 cm)				
Sample no	No 12 (30-60 cm)				
Sample no					
Sample no					
Sample no					
Sample no					
Remarks	pH of sub-horizon low, K low, CEC low				

Attribute	0-30 cm	30-60 cm	Attribute	0-30 cm	30-60 cm
pН	7.4	4.6	Na (cmol+/kg)	0.17	0.28
EC (mS/m)	250	267	K (cmol+/kg)	0.08	0.06
P (mg/kg)	9	7	Mg (cmol+/kg)	0.52	0.13
SO ₄ (mg/kg)	1102	1258	Ca (cmol+/kg)	13.45	27.92
Cl (mg/kg)	16	25	CEC (cmol+/kg)	3.3	2.43

Name / no of dam	DRD 2L 24
Locality	Krugersdorp
Owner	DRD
Who rehab	Chamber of mines but not for the full time (water problems), Envirogreen presently
When rehab	Envirogreen 2000
Rehab method	Chemical amelioration, 90 ton lime/ha, 60 m3 compost
Time of leaching	none
Type of water	fair
Maintenance time	
Type of maintenance	
Average slope 0	18
Average slope length	
Est Veg cover	
Dominant species	Cynodon aethiopicas, Eragrostis curvula, Pampas, vygies
Root depth	45-60
Signs of erosion	Toe slump – excess drainage water
Surrounding veg	-
Sample no	No 13 (0-30 cm)
Sample no	No 14 (30-60)
Sample no	
Remarks	PH of sub-horizon very low, K & CEC low, Low pH associated with high Ca and sulphate

Attribute	0-30 cm	30-60 cm	Attribute	0-30 cm	30-60 cm
pH	6.3	3.0	Na (cmol+/kg)	0.02	0.15
EC (mS/m)	281	383	K (cmol+/kg)	0.03	0.05
P (mg/kg)	35	2	Mg (cmol+/kg)	0.43	0.09
SO ₄ (mg/kg)	744	3190	Ca (cmol+/kg)	3.72	25.38
Cl (mg/kg)	13	21	CEC (cmol+/kg)	2.85	1.90

Name / no of dam	DRD 2L24
Locality	Krugersdorp
Owner	DRD
Who rehab	Chamber of mines
When rehab	
Rehab method	Leaching
Time of leaching	
Type of water	poor
Maintenance time	
Type of maintenance	
Average slope 0	28
Average slope length	
Est Veg cover	Conventional seed mixture
Dominant species	Hyparrhenia hirta, Cynodon aethiopicus, Medicago sativa, Pampas
Root depth	45
Signs of erosion	Below seepage line
Surrounding veg	
Sample no	No 15 (0-30) cm
Sample no	No 16 (30-60 cm)
Sample no	
Remarks	pH low, K & CEC low in top layer

Attribute	0-30 cm	30-60 cm	Attribute	0-30 cm	30-60 cm
pН	5.2	4.5	Na (cmol+/kg)	0.14	0.13
EC (mS/m)	253	233	K (cmol+/kg)	0.03	0.02
P (mg/kg)	35	3	Mg (cmol+/kg)	0.40	0.00
SO ₄ (mg/kg)	1984	1166	Ca (cmol+/kg)	4.62	3.79
Cl (mg/kg)	16	11	CEC (cmol+/kg)	2.77	5.50

Name / no of dam	PS 5				
Locality	Welkom (western aspect)				
Owner	Anglogold (Harmony)				
Who rehab	Envirogreen				
When rehab	1998				
Rehab method	Chemical amelioration				
Time of leaching	none				
Type of water	fair				
Maintenance time	2 years				
Type of maintenance					
Average slope 0	28				
Average slope length	14				
Est Veg cover	Envirogreen Mixture				
Dominant species	Chloris gayana, Cynodon dactylon, Melilutus alba, Eragrostis curvula, Hyparrhenia hirta.				
Root depth	40				
Signs of erosion					
Surrounding veg					
Sample no	No 17 (0-30 cm)				
Sample no	No 18 (30-45 cm)				
Sample no					
Sample no					
Sample no					
Sample no					
Remarks	Phosphate low side, pH low				

Attribute	0-30 cm	30-45 cm	Attribute	0-30 cm	30-45 cm
pH	5.6	3.9	Na (cmol+/kg)	0.96	0.69
EC (mS/m)	441	426	K (cmol+/kg)	0.15	0.04
P (mg/kg)	3	2	Mg (cmol+/kg)	0.71	0.41
SO ₄ (mg/kg)	1589	1352	Ca (cmol+/kg)	10.73	9.28
Cl (mg/kg)	307	197	CEC (cmol+/kg)	2.66	2.82

Name / no of dam	Saaiplaas 4			
Locality	Welkom			
Owner	Harmony			
Who rehab	Envirogreen			
When rehab	1997			
Rehab method	Chemical amelioration			
Time of leaching	none			
Type of water	good			
Maintenance time	None			
Type of maintenance				
Average slope 0				
Average slope length				
Est Veg cover	Envirogreen mixture			
Dominant species	Chloris gayana, Cynodon dactylon, Eragrostis curvula, Pennisetum macrourum			
Root depth	45+ cm			
Signs of erosion				
Surrounding veg				
Sample no	No 19 (0-30 cm)			
Sample no	No 20 (30-45 cm)			
Sample no				
Remarks	pH low in sub-horizon, Cl high, CEC low			

Attribute	0-30 cm	30-45 cm	Attribute	0-30 cm	30-45 cm
рН	7.2	4.7	Na (cmol+/kg)	0.20	0.77
EC (mS/m)	530	364	K (cmol+/kg)	0.23	0.10
P (mg/kg)	14	3	Mg (cmol+/kg)	1.06	0.18
SO ₄ (mg/kg)	1519	859	Ca (cmol+/kg)	6.63	2.28
Cl (mg/kg)	600	296	CEC (cmol+/kg)	1.43	2.49

Name / no of dam	Beatrix
Locality	Theunissen
Owner	Gold fields
Who rehab	Mine
When rehab	1994
Rehab method	Top soil
Time of leaching	
Type of water	good
Maintenance time	
Type of maintenance	
Average slope 0	
Average slope length	
Est Veg cover	Pennisetum clandestinum
Dominant species	Pennisetum clandestinum
Root depth	30
Signs of erosion	Frequent bare patches
Surrounding veg	rrequent bare pateries
Sample no	No 21 (0-30)
Sample no	No 22 (30-45)
Sample no	110 82 (00-10)
Sample no	
Sample no	
Sample no	
Remarks	pH very low, Sulphate extremely high, CEC good, Salt content high

Attribute	0-30 30-4 em em		Attribute	0-30 cm	30-45 cm	
pH	3.6	2.7	Na (cmol+/kg)	0.04	0.00	
EC (mS/m)	862	894	K (cmol+/kg)	0.17	0.02	
P (mg/kg)	30	4	Mg (cmol+/kg)	4.46	1.50	
SO ₄ (mg/kg)	7541	14167	Ca (cmol+/kg)	11.10	3.05	
Cl (mg/kg)	94	97	CEC (cmol+/kg)	5.78	4.30	

Name / no of dam	PS 3				
Locality	Welkom				
Owner	Anglogold (Harmony)				
Who rehab	Industrial landscapers				
When rehab	1996				
Rehab method	Revised leaching				
Time of leaching					
Type of water					
Maintenance time					
Type of					
maintenance					
Average slope 0					
Average slope					
length					
Est Veg cover					
Dominant species	Cynodon dactylon, Vetiver, Chloris gayana, Hyparrhenia, hirta, Silk				
Root depth					
Signs of erosion					
Surrounding veg					
Sample no	No 23 a (0-30 cm) in trench				
Sample no	No 23b (30-45 cm)				
Sample no	No 24 0-30 between trenches				
Sample no					
Sample no					
Sample no					
Remarks	Conditions between trenches poor. Sulphate and chlorine on the high side, Phosphate high.				

Attribute	cm cm between			Attribute	0-30 cm	30-45 cm	0-30 cm between	
pH			Na (cmol+/kg)	1.66	1.32	0.64		
EC (mS/m)	645	626	432	K (cmol+/kg)	0.12	0.12	0.02	
P (mg/kg)	126	7	4	Mg (cmol+/kg)	0.91	0.64	0.29	
SO ₄ (mg/kg)	3489	1558	1318	Ca (cmol+/kg)	7.60	7.98	13.24	
Cl (mg/kg)	694	469	186	CEC (cmol+/kg)	3.81	2.98	1.79	

Name / no of dam	Oryx
Locality	Theunissen
Owner	Goldfields
Who rehab	Envirogreen
When rehab	1998
Rehab method	Chemical amelioration
Time of leaching	none
Type of water	good
Maintenance time	2 years
Type of maintenance	
Average slope 0	
Average slope length	
Est Veg cover	Envirogreen mixture
Dominant species	Chloris gayana, Hyparrhenia hirta, Cynodon dactylon, Eragrostis curvula
Root depth	45+ cm
Signs of erosion	
Surrounding veg	
Sample no	No 152 (0-15 cm)
Sample no	No 153 (15-30 cm)
Sample no	No 154 (30-45 cm)
Sample no	
Sample no	
Sample no	
Remarks	Phosphate high, pH of sub-horizon low side

Attribute	0-15 15-30 30-45 cm cm cm		30-45 cm	Attribute	0-15 cm	15-30 cm	30-45 cm	
pH	7.6	7.3	4.8	Na (cmol+/kg)	0.17	0.26	0.08	
EC (mS/m)	C (mS/m) 308 316 265 K (cmol+/kg)		0.14	0.10	0.05			
P (mg/kg)	90	48	47	Mg (cmol+/kg)	0.87	0.63	0.12	
SO ₄ (mg/kg)				Ca (cmol+/kg)	18.51	20.75	13.57	
Cl (mg/kg)				CEC (cmol+/kg)	2.80	4.53	2.86	

APPENDIX D: PENETRATION RESULTS

PENETRATION VALUES IN kPa (avg of 16 sets of penetrations for each method)

epth			Metho	d 2	Metho	d 3	Method 4	
cm	AVG	Stdev	AVG	Stdev	AVG	Stedy	AVG	Stdev
1	26.7	28.5	26.4	22.2	23.4	24.9	46.0	62
2	253.5	97.0	169.4	141.4	212.4	143.2	196.0	97
3	546.4	206.8	428.7	344.0	536.6	388.5	441.4	255
4	783.9	300.4	647.5	496.5	715.6	458.7	628.0	412
5	1047.2	425.1	823.3	616.9	888.2	552.	795.2	510
6	1305.3	490.2	956.8	631.1	1103.1	639.5	922.5	628
7	1448.2	484.6	1076.3	621.3	1228.8	662.1	942.8	584
8	1629.4	604.7	1181.0	603.2	1336.6	795.1	996.8	545
9	1815.1	688.3	1241.2	599.7	1495.3	795.7	1060.1	432
10	1983.9	694.3	1318.6	588.3	1600.7	673.9	1144.5	436
11	2119.6	720.3	1463.9	600.4	1761.6	623.7	1251.5	530
12	2144.6	725.8	1492.0	565.7	1891.3	653.4	1321.8	564
13	2183.9	715.9	1574.0	530.3	1948.4	658.3	1370.3	603
14	2253.5	752.9	1655.3	488.9	2039.8	727.8	1438.2	699
15	2283.9	841.9	1709.1	459.0	2132.0	731.7	1474.9	769
16	2250.0	924.3	1769.3	536.5	2239.8	821.1	1517.1	799
17	2276.7	960.3	1863.1	636.4	2284.3	887.1	1605.4	788
18	2258.9	1024.5	1942.0	672.9	2274.1	879.8	1722.6	801
19	2291.0	1144.3	1985.8	751.7	2375.7	972.4	1778.8	920
20	2327.6	1169.7	2100.6	743.6	2454.6	1008.4	1859.3	997
21	2426.7	1202.4	2195.1	817.0	2485.9	1056.0	1910.9	1030
22	2492.8	1266.2	2225.6	837.0	2513.2	1104.5	1968.0	1090
23	2518.7	1317.8	2195.1	769.9	2582.0	1121.2	1990.5	1145
24	2635.7	1337.7	2189.0	737.1	2710.0	1160.2	1974.9	1249
25	2750.0	1372.4	2190.4	761.3	2915.5	1224.7	2071.0	1292
26	2805.3	1363.6	2232.6	770.1	3049.1	1193.7	2115.5	1332
27	2919.6	1403.5	2335.8	852.9	3150.7	1185.4	2176.4	1382
28	3116.0	1388.2	2474.8	916.6	3315.6	1204.2	2248.3	1408
29	3150.8	1306.9	2699.1	987.7	3488.9	1238.8	2296.0	1403
30	3296.4	1407.7	2842.8	949.7	3634.3	1149.6	2367.9	1434
31	3356.2	1455.1	2959.2	1034.6	3741.3	1109.8	2413.1	1440
32	3426.7	1434.4	3018.6	1083.7	3825.0	1100.7	2452.2	1411
33	3451.7	1418.9	3086.5	1096.4	3937.5	1107.4	2541.3	1405
34	3469.6	1447.8	3178.0	1062.3	4007.8	1108.7	2677.2	1412
35	3500.0	1446.4	3196.0	978.9	4077.3	1069.5	2738.9	1358
36	3566.0	1424.3	3241.2	1044.8	4168.6	1003.5	2843.6	1364
37	3569.6	1436.5	3264.6	1110.2	4225.7	942.4	2924.9	1301
38	3599.0	1404.8	3369.3	1146.6	4250.7	987.3	2965.5	1258
39	3653.5	1375.6	3481.0	1117.5	4164.7	1053.1	3053.0	122
40	3727.6	1347.6	3572.5	1129.9	4194.4	1121.6	3143.6	1261
41	3733.0	1295.7	3668.5	1214.7	4240.5	1123.5	3242.1	1284
42	3787.4	1260.2	3717.0	1298.7	4227.2	1168.3	3371.0	1241
43	3833.9	1179.2	3762.3	1257.6	4293.6	1126.1	3534.3	1202
44	3842.8	1140.6	3806.1	1208.0	4364.7	1078.7	3649.1	1178
45	3875.0	1103.4	3859.2	1219.9	4482.7	949.8	3803.0	1132
46	3905.2	1101.8	3897.5	1285.1	4637.4	818.7	3950.6	1029
47	3870.5	1106.4	3997.5	1291.6	4753.8	578.2	4063.8	976
48	3827.5	1144.5	4103.0	1241.2	4889.8	257.8	4190.5	1005
49	3773.2	1230.0	4187.3	1235.7	4987.4	79.8	4235.7	1000

PENETRATION VALUES IN kPa (avg of 16 penetration sets for each method)

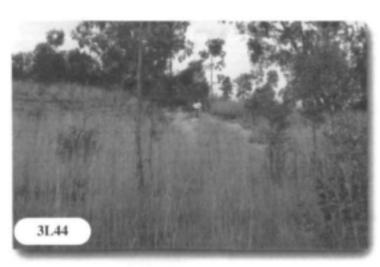
	Metho	d 5	Method	16	Method 7		
Depth cm	AVG	Stdev	AVG	Stdev	AVG Stdev		
1	34.1	35.4	32.4	27.4	27.1	31.	
2	209.1	83.5	215.8	135.7	176.3	71.	
3	420.8	119.8	488.3	205.0	369.7	92.	
4	558.3	163.2	745.0	304.6	532.2	86.	
5	719.1	220.7	1007.4	427.1	639.6	90.	
6	915.0	255.7	1305.8	513.3	811.0	128	
7	1000.0	283.1	1550.0	598.0	971.2	204	
8	1125.8	376.0	1765.0	702.2	1094.0	257	
9	1232.4	416.2	1964.1	807.7	1225.6	300	
10	1311.6	503.9	2162.4	908.8	1351.4	286	
11	1411.6	550.3	2307.4	1066.4	1458.7	272	
12	1483.3	555.5	2450.8	1178.6	1609.4	304	
13	1585.0	594.3	2582.3	1300.1	1735.9	357	
14	1678.3	603.5	2639.1	1379.8	1830.7	404	
15	1793.3	665.9	2678.3	1314.4	1931.5	523	
16	1980.0	737.8	2916.6	1264.0	2079.2	603	
17	2198.3	820.4	4235.8	3919.9	2224.8	666	
18	2375.0	821.5	3310.0	1207.7	2366.1	777	
19	2491.6	836.4	3332.4	1149.2	2452.0	885	
20	2580.0	873.2	3444.1	1111.8	2590.4	920	
21	2716.6	787.7	3420.8	1103.0	2652.8	943	
22	2860.8	723.6	3479.1	1243.3	2724.1	1004	
23	2952.4	662.2	3514.1	1296.7	2794.0	1085	
24	2969.1	636.9	3579.1	1282.2	2902.0	989	
25	3018.3	623.5	3707.4	1282.1	3030.7	949	
26	3137.4	559.9	3790.8	1232.5	3174.0	1015	
27	3305.0	640.1	3892.4	1227.9	3322.7	1024	
28	3419.0	705.2	3940.8	1213.3	3511.6	1154	
29	3526.6	827.4	3994.1	1232.6	3636.5	1174	
30	3572.4	844.2	4096.6	1246.0	3748.3	1201	
31	3593.2	832.9	4130.8	1249.6	3793.2	1203	
32	3647.4	921.0	4134.9	1255.5	3828.5	1172	
33	3719.9	1000.0	4156.6	1251.9	3858.0	1216	
34	3780.8	1066.9	4242.4	1277.6	3903.6	1196	
35	3866.6	1037.3	4316.6	1261.2	3927.1	1195	
36	3934.9	1021.3	4324.1	1223.8	3954.3	1247	
37	4009.1	1056.1	4359.0	1235.5	4033.0	1289	
38	4133.3	1052.7	4316.6	1266.0	4064.6	1333	
39	4314.9	1028.5	4315.8	1269.9	4124.9	1346	
	4414.9	943.7	4348.2	1267.1	4163.9	1316	
40				1250.7			
41	4524.9	900.3	4368.2		4199.9	1307	
42	4569.1	898.4	4369.1	1240.1	4213.9	1300	
43	4635.0	854.5	4401.6	1228.3	4227.1	1268	
44	4689.9	810.2	4435.8	1222.4	4242.5	1266	
45	4700.0	793.7	4467.4	1232.6	4276.4	1313	
46	4687.4	825.0	4464.1	1235.2	4292.5	1308	
47	4685.8	829.1	4490.8	1206.4	4314.6	1293	
48	4710.0	766.2	4494.1	1203.5	4335.1	1311	
49	4694.1	809.3	4500.8	1202.3	4385.9	1250	
50	4680.0	844.6	4519.1	1193.8	4456.5	1202	









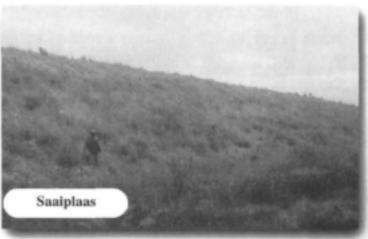


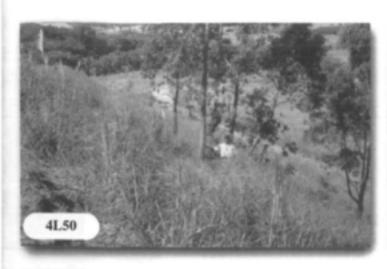














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Hattingh RP • Lake J • Boer RH • Aucamp P • Viljoen C

An earlier preliminary assessment of pollution contained in the unsaturated and saturated zones beneath reclaimed gold-mine dumps, indicated that this pollution can have a significant negative environmental impact on the underlying vadose zone and subsequently the groundwater system. This study identified five alternative rehabilitation strategies to deal with this pollution and modelled their expected impact at three study sites. The strategies were found to represent mainly two opposing alternatives, i.e. those that result in the pollutant remaining within the confines of the residue deposit area, and those in which the pollutants are transported to the deeper aguifer, away from the source. The preferred management option would thus depend on whether containment or dilution and migration of pollutants would be the desired option. The problems associated with reclaimed mine-residue deposits were also assessed by evaluating the various risks that are associated with the source of contamination, the pathway it would follow and the receptor that would be adversely affected by the contaminated substance. Site-specific variation in physical characteristics was found to have a marked influence on the resultant risk assigned to individual aspects. The introduction of a risk assessment approach, a phased and chemically orientated approach to site investigation, and the selection of remediating strategies from a number of technologies, were identified as intrinsic components of the rehabilitation process. This would require that rehabilitation be conducted on a site-specific basis. The basic methodology for this approach is outlined in a companion document to the project report.

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