Assessment of Cover Design, Construction and Aging on Percolation, Oxygen Ingress and Acid Mine Drainage for Coal Discard Facilities for Mpumalanga Highveld

Part A
Soil Covers Assessment and Modelling

Technical report to the
Water Research Commission

by

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The publication of this report emanates from a project entitled *Assessment of Cover Design, Construction and Aging on Percolation, Oxygen Ingress and Acid Mine Drainage for Coal Discard Facilities for Mpumalanga Highveld* (WRC Project No. K5/2759/3).

This report forms part of a set of two reports. The other report is *Assessment of Cover Design, Construction and Aging on Percolation, Oxygen Ingress and Acid Mine Drainage for Coal Discard Facilities for Mpumalanga Highveld. Part B. Best Practice Guideline on Soil Covers to Mitigate Acid Mine Drainage and Seepage Impact*. (WRC Report No. 2759/2/22)

EXECUTIVE SUMMARY

Acid Mine Drainage and related seepage impact are an environmental concern in the Mpumalanga Highveld. The proper design and construction of soil covers on rehabilitated coal discard facilities plays an important role in minimising rainwater and oxygen ingress into coal discard, which in turn minimise geochemical processes that produces AMD.

While soil covers are recognised to minimise AMD production and seepage into groundwater for rehabilitated coal mines, the long-term performance of suitable and well-designed covers is poorly documented and no systematic study has been conducted in the coalfields of South Africa to assess how the hydraulic properties of cover materials change over time.

The study aimed to:

- Identify trial sites for the field investigation of cover material properties and vegetation characteristics for a rainshedding cover, and for poorly- and well-constructed store-and-release covers,
- Determine the effect of cover type, standard of cover construction and cover aging on rainwater percolation and oxygen ingress, and AMD production for coal discard facilities for the Mpumalanga Highveld, and
- Develop a Best Practice Guideline (BPG) for soil cover design, construction and after-care for soil covers on discard facilities of coal mines in the Mpumalanga Highveld.

This research study was undertaken to determine the material hydraulic properties, vegetation characteristics and predict the cover performance of mature (older than 20 years) covers. Assessments of net cover percolation, rainwater and oxygen ingress into investigated coal discard facilities, and AMD production is based on in-field measurement of cover material hydraulic properties, laboratory tests and analyses of material properties and vegetation characteristics measured at a range of trial sites.

Suitable research sites on mature, rehabilitated coal discard facilities in the Mpumalanga Highveld were identified to determine in-field material hydraulic properties and vegetation characteristics for covers with a lengthy exposure to climatic conditions and environmental processes. Particular attention was paid to establishing paired trial sites, where different sections of a discard facility or different facilities on the same mine had different cover designs, or the soil cover materials received differing treatments.

The field investigation included cover characterisation that includes determining cover configuration (cover layering), characterising material properties for the various cover layers, determining root penetration depth and extent of root development, and determining extent and characteristics of preferential flow paths if present. In-field permeability tests were conducted to determine in-field hydraulic conductivities of various material layers and the discard below the soil covers.

Saturated hydraulic conductivity (K_{sat}) for highly compacted cover layers is higher than expected. This may be ascribed to preferential flows through fine, isolated (tension) cracks in the compacted cover layers that were observed during the field investigation. K_{sat} determined from samples remoulded to these compacted densities could be more than an order of magnitude lower as it only accounts for flows through soil matrix and not through cracks. This will result in an over-optimistic predicted cover percolation, rainwater ingress and seepage rates if higher rain infiltration through these cracks are not accounted from.

The determined K_{sat} of highly compacted layers does not meet the in-field K_{sat} for a barrier layer, except for one layer which only marginally meet this criterion. This further confirms that a lower reduction in K_{sat} for highly compacted layers can be expected for mature covers, as confirmed by international studies.

Leaf area indices (LAIs) measured on the mature discard facilities are noticeably lower than values expected in natural areas in the region that have similar soils. While compaction clearly plays a role and severely restricts plant growth, it is also clear that a limited range of fine-bladed grasses do not provide the best vegetation cover. More emphasis needs to be placed on establishing a good quality vegetative cover to maximise plant transpiration rates with an aim to minimise rainwater ingress and associated seepage rates.

Predicted percolation rates at the 90th percentile is significantly higher than the mean annual values due to significantly higher percolations rates for wet years that include a series of consecutive rainy days, cloudy conditions and low potential evaporation rates. Target acceptable value of 5% of MAP for semi-arid climates can be achieved for 90 cm and thicker covers with sandy clay loam or sandy clay water retention layer (2nd layer) and root development throughout the cover. The target value can also be achieved for the highly compacted cover if good vegetation conditions can be achieved. Mean annual net percolation rates with poor vegetation conditions exceed target rates, except for the 90 cm thick covers. This emphasises the importance of vegetative vigour and high leaf area indices to maximise plant transpiration with the aim of minimising moisture ingress rates and groundwater impacts.

Geochemical numerical modelling at trial sites indicates that soil covers should be thicker than a metre to be effective in reducing oxygen ingress to an extent that Acid Mine Drainage development is restricted to manageable level. The focus of soil covers to mitigate AMD and related seepage impacts should, therefore, be on minimising net cover percolation and rainwater ingress into the discard.

International research studies have demonstrated the importance of water retention curves and unsaturated flow modelling to optimise cover designs in semi-arid climate conditions. In South Africa these elements traditionally receive less attention. The complex interactions between rainfall, runoff and infiltration, or between seepage, soil water storage and plant water demand, that take place within a soil cover are best analysed within a numerical model. Unsaturated flow models allow iterative testing of design options to refine the design to meet specific performance objectives.

The apedal soils that dominate the hillslopes throughout the Mpumalanga Highveld do provide suitable material for effective and sustainable soil covers on coal discard facilities.

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ACRONYMS

ABA	Acid-Base Accounting
ACAP	Alternative Cover Assessment Programme
AEL	Acceptable environmental limit
AMD	Acid Mine Drainage
AP	Acid potential
AUC	Average Upper Crust
Aus-ACAP	Waste Management Association of Australia Alternative Cover Assessment Programme
BPG	Best Practice Guideline
CoC	Constituent of concern
CQA	Construction Quality Assurance
DSS	Decision Support System
DWAF	Department of Water Affairs and Forestry
EBS	Engineered barrier system
ET_0	Reference potential evaporation
GARD	Global Acid Rock Drainage Guide
INAP	International Network for Acid Prevention
IMWM	Integrated Mine Water Management
IWWM	Integrated Water and Waste Management
K_{sat}	Saturated hydraulic conductivity
K_{unsat}	Unsaturated hydraulic conductivity
LAI	Leaf area index
MAE	Mean annual potential evaporation
MAP	Mean annual precipitation
MRF	Mine residue facility
NAG	Net acid generation
NMD	Neutral mine drainage
NNP	Net neutralisation potential
NP	Net percolation
NP	Neutralisation potential
PAW	Plant available water
PI	Plasticity index
SMD	Saline Mine Drainage
SPR	Source-Pathway-Receptor
SWCC	Soil water characteristic curve
USCS	Unified Soil Classification System
USDA	United States Department of Agriculture
US-ACAP	United States Alternative Cover Assessment Programme
US-EPA	United States Environmental Protection Agency
WMAA	Waste Management Association of Australia
WRC	Water retention curve
WRC	Water Research Commission of South Africa
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence

1. INTRODUCTION

1.1 Background

1.1.1 Acid Mine Drainage

Acid Mine Drainage (AMD) and the release of chemical contaminants into the water resources is an environmental concern in the Mpumalanga Highveld. The consequences of AMD and its impacts on water quality and aquatic life in the Loskop Dam and the Olifants River Catchment represent a concern both public and governmental. AMD production in these catchments is mainly a function of the geochemistry of mine residues and the amount of rainwater and oxygen ingress into pyrite-containing mine residue.

The proper design and construction of soil covers on rehabilitated coal discard facilities plays an important role in minimising rainwater and oxygen ingress into coal discard, which in turn inhibits geochemical processes that results in AMD production. Effective soil covers ultimately reduce the volume and quality of seepage that enters the groundwater. Well-designed and constructed soil covers are one of the most important passive measures that can be implemented on a mine residue facility to minimise AMD production and seepage, and constituents of concern (CoCs) flux into the receiving vadose zone and groundwater.

1.1.2 Motivation for investigating mature/old soil covers

The Alternative Cover Assessment Programmes of the United States Environmental Protection Agency (US-ACAP) and the Waste Management Association of Australia (Aus-ACAP) illustrated the importance of well-constructed covers and of good cover designs. The ACAP studies showed that changes in the material hydraulic properties can occur with the aging of soil covers that are constructed in arid and semi-arid climates. A similar result should be expected for equivalent cover designs in the semi-arid summer rainfall areas of South Africa. It was concluded from the ACAP studies that the long-term cover performance should be considered when designing covers or assessing the post closure impacts of discard facilities. Soil cover design should consider material properties that represent the cover material properties impacted by cover aging (Benson and Albright, 2012).

In South Africa, design standards and guidelines for the design of soils covers have largely not accounted for the effects of cover aging. While soil covers are recognised to minimise AMD production and seepage into groundwater for rehabilitated coal mines, the *long-term performance of suitable and well-designed covers is undocumented and no systematic study has been conducted in the coalfields of South Africa to assess how the hydraulic properties of cover materials change over time*. Accuracy of analysis may be limited by the shortage of data on appropriate input parameters for cover soils and other barrier materials that were exposed to climatic conditions and environmental processes for a considerable time period.

1.1.3 Creating a shared understanding of soil cover design, construction and care

When it comes to the design of soil covers over mine residue facilities, mining and civil engineers, geochemists, hydrologists and soil scientists all need to collaborate in an integrated study. Design processes have evolved that use advanced algorithms and theory developed in isolation for specific conditions and disciplines and then apply them across this particular minefield.

There is growing evidence from a wide range of research studies conducted across the globe that traditional approaches to soil cover design do not often produce sustainable covers with lasting designed functions. The hydraulic properties of materials used in cover layers change over time. While laboratory tests of cover material samples might indicate a reduction in oxygen ingress into the sample only when the sample is saturated or near-saturated, in the field it seems that some other process also has an effect and some reduction in oxygen ingress is measured below thick layers of unsaturated soils. The most important consideration when trying to understand what happens in a soil cover is that no single system or element is static, but dynamic changes occur.

Within this field of dynamically changing conditions within a soil cover, there are clear knowledge gaps. Past design approaches have often failed to provide sustainable soil cover designs. The hypothesis is that by directly measuring what happens in mature (older) soil cover layers and analysing these measurements in a multi-disciplinary team, we should at least be able to define issues to be able to refine design processes to produce more effective and sustainable soil covers. This research study should, however, be viewed as starting the process. Issues will be identified and further research studies could focus on these issues and further refine design processes. The single largest short-term benefit of this study will, however, lie in establishing a shared appreciation of the challenges faced across all specialist disciplines, which should facilitate more focussed interdisciplinary interactions.

1.2 Study design

A research study was undertaken to assess the material hydraulic properties, vegetation characteristics and cover performance of mature (older than 20 years) covers that have been exposed to climatic conditions and environmental processes for a long period. This assessment of rain percolation, rainwater and oxygen ingress into coal discard facilities, and AMD production for coal discard facilities is based on in-field measurement of cover material hydraulic properties, laboratory tests and analyses of material properties and vegetation characteristics measured at a range of trial sites.

The study aimed to:

- Identify trial sites for the field investigation of cover material properties and vegetation characteristics for a rainshedding cover, and for poorly- and well-constructed store-and-release covers,
- Determine the effect of cover type, standard of cover construction and cover aging on rainwater percolation and oxygen ingress, and AMD production for coal discard facilities for the Mpumalanga Highveld, and
- Develop a Best Practice Guideline (BPG) for soil cover design, construction and after-care for soil covers on discard facilities of coal mines in the Mpumalanga Highveld.

Particular attention was paid to establishing paired trial sites, where different sections of a discard facility or different facilities on the same mine had different cover designs, or the soil cover materials received differing treatments.

2. LITERATURE STUDY

2.1 Cover types

A classification of soil covers is shown in Figure 1. The discussion on cover types is based on literature from Vermaak, Wates, Bezuidenhout and Kgwale (2004), International Network for Acid Prevention (INAP), (2009) and Waste Management Association of Australia (WMAA), 2011. The terms, cover(s), cap(s) and capping, as used in the literature, is interchangeable. The term cover(s) will be used in this report, but also represents the terms cover(s), cap(s) and capping.

2.1.1 Water and wet covers

A water cover entails flooding of the mine residue, whereas a wet cover is designed to maintain near-saturation conditions to prevent oxygen ingress into the residue. These covers can be very effective in minimising AMD production and associated seepage of constituents of concern (CoCs) from residue due to the large reduction in oxygen availability. These covers are best suited for climates where the precipitation is higher than potential evaporation, and are therefore not suitable for the coalfields in South Africa (SA).

2.1.2 Alkaline- and organic covers

An *alkaline cover* is designed to increase the alkalinity of rain water that infiltrates into the mine residue, thereby providing a pH control. Alkaline water that infiltrates into mine residue may react with – and generate a surface coating on sulphide bearing materials that isolates sulphide minerals in the mine residue. An alkaline cover can be constructed with power station fly ash or limestone.

An *organic/reactive cover* consists of a layer of organic material such as compost or sludge on, or close to the ground surface, which create a large biological oxygen demand to consume atmospheric oxygen in the cover before it enters the mine residue. Its limitation being that the organic reactive layer replenishes.

2.1.3 Soil covers

Soil/earthen covers can consist of soil, weathered (soft) overburden and/or non-carbonaceous mine residue materials. The covers are best suited to climates where the precipitation is lower than the potential evaporation, such as at the coalfields in SA. Soil covers should be designed to minimise rainwater ingress (also referred to as net rain infiltration, net percolation or rain recharge) into mine residue, rather than to prevent oxygen ingress. The covers can be designed to provide suitable growth medium for vegetation growth and the design of stable landforms that will lead to low erosion.

A *net neutral sulphide-bearing cover* consists of material that contain sulphide (pyrite) minerals, as well as excess neutralisation to prevent net acid production. The cover can be constructed with soft or pulverised overburden or fine-textured mine residue materials when limited volume of soil material is available for cover construction. The cover may result in high sulphate, total dissolved solids and iron concentrations leaching from the residue due to pyrite oxidation.

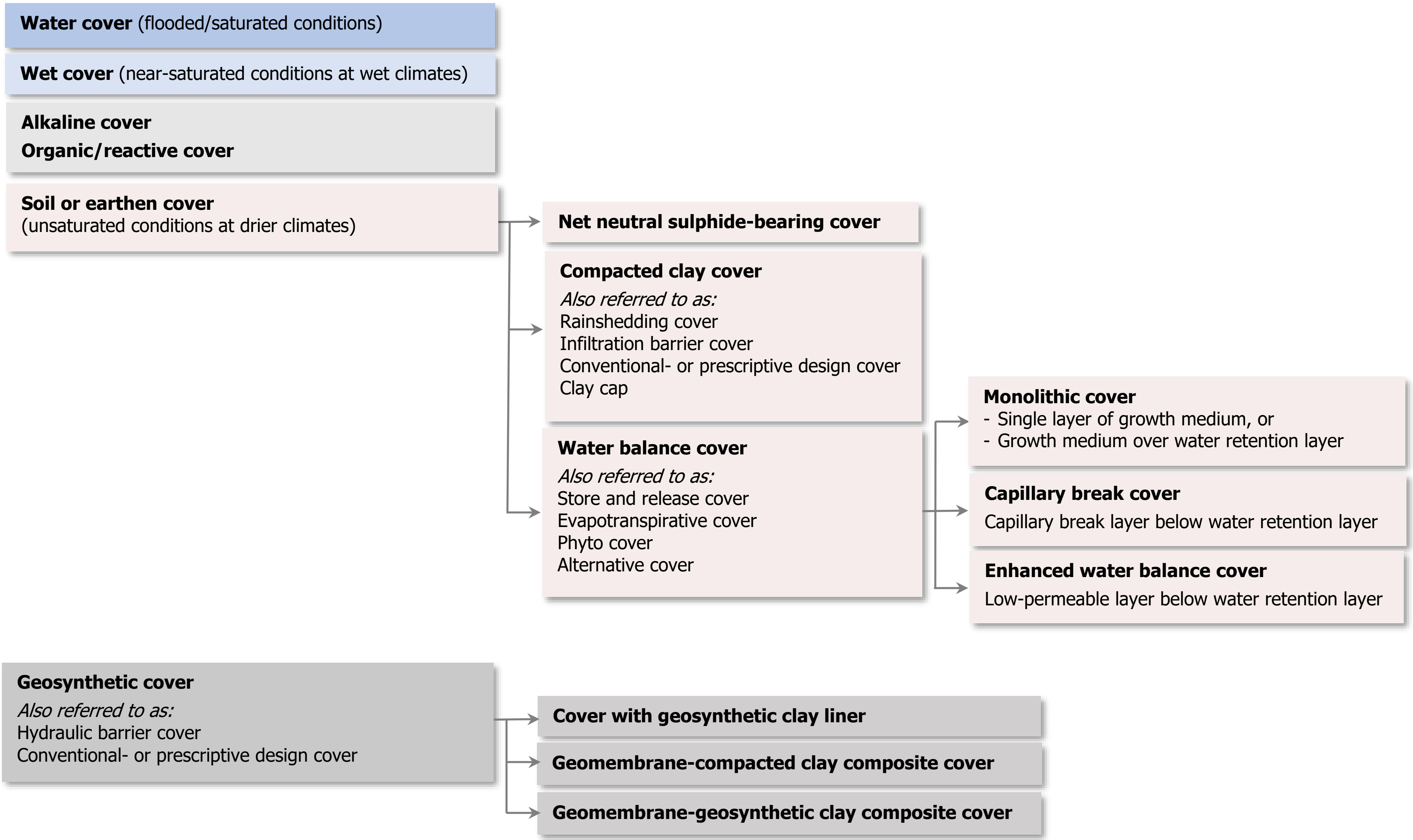


Figure 2-1: Cover types.

A *compacted clay cover* consists of a compacted clay layer that provides a low-permeable barrier to minimise rain infiltration and water ingress into mine residue. The cover typically consists of a compacted clay layer below a thin growth medium. The cap design specified in the Minimum Requirements for Waste Disposal by Landfill (DWAF, 1998) is an example of a compacted clay cover. Additional layers such as desiccation protection-, drainage- and capillary breaker layers can be required for long-term functioning of these covers. A compacted clay cover is also referred to as a rainshedding-, infiltration barrier-, conventional- or prescriptive design cover.

A *water balance cover* is best suited to arid and semi-arid climates where the climate is characterised by distinct wet and dry seasons and the annual potential evaporation is at least double the annual precipitation, such as at the coalfields in SA. A SRC are also referred to as a water balance-, evapotranspirative-, phyto- or alternative cover.

A *monolithic water balance cover* consists typically of a growth medium over a fine-textured water retention layer with a high silt, clay and very fine sand contents. A monolithic cover can also consist of a single (thick) layer of growth medium. The water retention layer can be constructed from fine-textured subsoil, weathered (soft) overburden, non-carbonaceous mine residue or other material with a high silt and/or clay contents.

A *capillary break cover* consists of a layer of uniformly graded medium or coarse sand or very fine gravel below the fine-textured water retention layer to create a capillary break effect. The capillary break can further reduce rainwater ingress rates from a monolithic cover and it prevent upward movement of salts and acid into the root zone. The function and design of a capillary break cover depends on a significant contrast between the hydraulic properties of the fine-textured water retention layer and underlying coarse-textured capillary break layer.

An *enhanced water balance cover* consists of a low-permeable layer below the water retention layer to further reduce rainwater ingress rates from a monolithic cover. The low-permeable layer can be constructed from fine-textured subsoils, weathered overburden, mine residue or material with a high silt and/or clay content, or by compacting the surface of the mine residue.

2.1.4 Geosynthetic covers

A geosynthetic cover includes a geosynthetic clay layer and/or a geomembrane to provide a low-permeable barrier to intercept infiltrated rain that would have percolated into the mine residue. A geosynthetic cover usually consists of multiple layers that include a (thin) growth media, geomembrane liner and compacted clay layer or geosynthetic liner. A geosynthetic cover usually also include a drainage- and desiccation protection layers. According to INAP (2017, 2009), the use of geosynthetic covers for mine residue facilities are in most cases prohibitive expensive even though it is recommended as a default design. A geosynthetic cover is also referred to as a hydraulic barrier-, conventional- or prescriptive design cover.

2.2 Cover layers

The various types of cover layers are shown in Figure 2-2. The discussion on cover layers is based on literature from INAP (2017) and Vermaak *et al*. (2004).

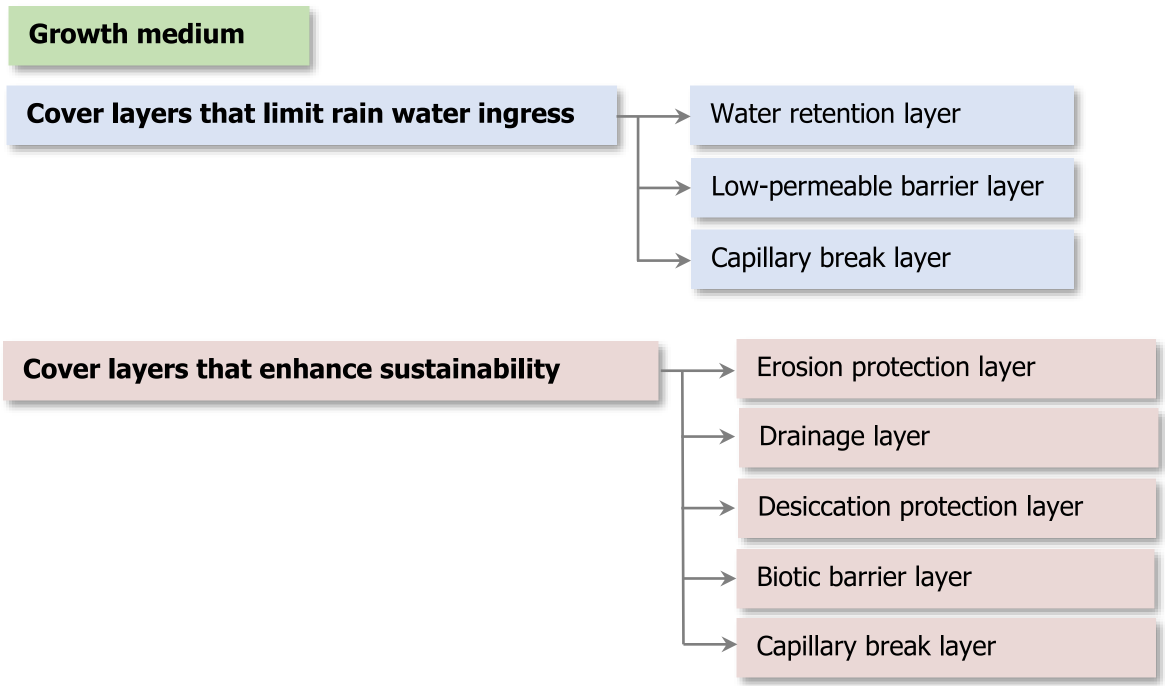


Figure 2-2: Cover layers.

2.2.1 Growth medium

A layer of topsoil provides growth medium for vegetation. Placement of even a thin growth medium on mine residue enhances germination and survival of vegetation, and biomass production.

The functions of a growth medium are to:

- Provide a medium to establish and sustain vegetation on rehabilitated mined land;
- Retain soil water and provide storage capacity for water for plant growth;
- Provide a medium for plant nutrient uptake;
- Enhance evapotranspiration as part of a water balance cover;
- Minimise run-off generation and erosion, and promote controlled run-off; and
- Re-establish sustainable ecosystems for post-closure land use.

The growth medium typically comprises the nutrient-rich A soil horizon, but can also include the apedal B soil horizons which is stripped ahead of mining and stockpiled. The Rehab-BPG emphasises that growth medium should not be compacted to the extent that could restrict root penetration and development.

2.2.2 Cover layers that minimise rainwater ingress

The *water retention layer* is the primary layer for the effective functioning of a water balance cover.

The functions of the water retention layer are to:

- Retain infiltrated rain and provide sufficient water storage capacity during wet periods and rainfall events to minimise rainwater ingress into mine residue;
- Facilitate removal of infiltrated rain from the cover by means of evapotranspiration;
- Mitigate generation and seepage of AMD by minimising rainwater ingress;
- Reduce oxygen ingress into the mine residue, thereby reducing AMD production and potential for spontaneous combustion of carbonaceous mine residue; and
- Retain soil water and provide storage capacity for plant available water.

Materials with high water retention should be used for the water retention layer. These include subsoils, weathered overburden and non-carbonaceous materials (softs) with high silt, clay and very fine sand contents.

Three types of *low-permeable barrier layers* are used for covers; namely compacted clay layer, geomembrane- and geosynthetic clay liners. The main functions of barrier layers are:

- Minimise rainwater ingress into the mine residue through increased runoff and/or intercepting and diverting infiltrated rain laterally to a drain;
- Mitigate generation and seepage of AMD by minimising rainwater ingress; and
- Reduce oxygen ingress into the mine residue, thereby reducing AMD production and potential for spontaneous combustion of carbonaceous mine residue;

The effectiveness of a compacted clay layer as a low-permeable barrier is proportional to the field hydraulic conductivity (permeability) of the layer, which depends largely on the quality assurance during construction. Low-permeable barrier layers are also called infiltration-, hydraulic- or resistive barrier layers. According to INAP (2009), the use of geomembrane- and geosynthetic clay liners are prohibitively expensive for most mine residue facilities (INAP, 2009). A compacted clay layer has the advantage of being cost-effective if suitable material is available at site or locally.

A *capillary break layer* can be used to retain percolation (deep drainage) from the water retention layer during relatively wet short-duration periods or large rain events where the water storage capacity of the overlying water retention layer is exceeded. The functioning of a capillary break layer relies on a considerable contrast between the hydraulic properties of the coarse-textured capillary breaker layer and overlying fine-textured water retention layer. A capillary break layer of uniformly graded medium/coarse sand or very fine gravel layer must be overlain by a fine-textured water retention layer to create a capillary break at the boundary of these layers. Unlike a compacted clay layer that rely solely on a low-permeable barrier to restrict rainwater ingress into the mine residue, processes that increase the hydraulic conductivity such as desiccation do not necessarily decrease the effectiveness of a capillary break layer.

2.2.3 Cover layers that advance sustainable cover functioning

An *erosion protection layer* will be required where poor- or sparse vegetation is expected, steep- or long slopes need to be covered, and/or the surface material is highly erodible. This layer is also referred to as a rock armour layer or rock armouring. More cost-effective erosion protection layers can be provided by mixing non-carbonaceous rock into the growth medium at the surface, however, the rock content should not exceed about 35-40% by volume to be effective in minimising rainwater ingress. Rainwater ingress rates from rock cladding, where a cover is constructed with rock with no vegetation, will be too high to have an effect on AMD production and seepage.

A *drainage layer* that comprises of coarse sand, gravel or geosynthetic material is usually included above a geomembrane, geosynthetic clay liner and/or compacted clay layer to:

- Drain the intercepted water that has percolated through the growth medium or water retention layer; and
- Reduce pore-water pressures within the cover that may have developed along the water retention- and low-permeable barrier interface to improve slope stability.

A *desiccation protection layer* can be constructed from a thick (e.g. ≥0.7 m) water retention layer to protect the compacted clay layer or geosynthetic clay liner against desiccation, the development of desiccation cracks and increased rainwater ingress due to preferential flows through the cracks.

A thin (e.g. 0.3 m) *biotic protection layer* of gravel and/or rock could be used to inhibit root penetration and animal burrowing into low-permeable barrier- and capillary breaker layers that will be rendered ineffective due to preferential flows through the conduits, leading to increased rainwater ingress.

Mine residue with a high AMD potential could result in acidification and salinisation of the root zone to the extent that vegetation growth could be negatively affected due to the upward movement of acid and salt into the root zone. A *capillary break layer* can be included above the mine residue to minimise the upward movement of acid and salt into the root zone through capillary action.

2.3 Soil cover performance

For the coal mining industry, a simple, cost-effective cover design is needed because of the large areas covered. Covers that contain geomembrane- and geosynthetic clay liners require high construction standards, good quality assurance and will have to be maintained over areas that are considerably larger than landfill/hazardous waste facilities. According to INAP (2009), soil covers are preferred as covers for the mine residue facilities since the use of geomembrane- and geosynthetic clay liners can be prohibitively expensive for larger facilities. Simple soil covers, such as monolithic water balance covers or shallow compacted clay covers without desiccation- and biotic barrier protection layers may not be effective for coal discard facilities that have a high potential for Acid Mine Drainage and which might require a more sophisticated cover (Vermaak *et al*., 2004).

2.3.1 Effect of cover degradation

The design and long-term functioning of soil covers are complicated by environmental factors that cause cover degradation over time. Vermaak *et al*. (2004) described various factors that influence the degradation of covers over time as follows:

- Cyclical wetting and drying and temperature changes;
- Root and burrow penetration into barrier- or capillary breaker layers;
- Wind and water erosion;
- Differential settlement caused by consolidation of underlying mine residue;
- Slips or creep of cover layers; and
- Vehicular movement on haul roads that traverse the cover.

Short to medium term soil cover degradation that is likely to be caused by:

- *Plant roots*. As vegetation is established on newly rehabilitated land, root systems may develop that penetrate, or grow through the soil cover. Dead plant roots create macro-pores and increase the potential for preferential flow paths that will result in increased moisture and oxygen ingress. Plant roots will abstract water up the growth medium above any shallow compacted clay layer, which will result in desiccation of the compacted clay layer. Desiccation cracks will develop, and preferential flow paths will occur through the low-permeability barrier layer, resulting in increased moisture and oxygen ingress.
- *Burrowing animals*. As a natural ecosystem is re-established on rehabilitated land, burrowing animals may be re-inhabit the land, providing preferential flow paths through the water retention-, compacted clay and/or capillary breaker layer, which will result in an increase in rainwater and oxygen ingress. Few species are, however, known to burrow to depths greater than approximately 1 m.
- *Drought*. Periods of drought may induce the development of desiccation cracks that may have otherwise not occurred. The development of desiccation cracks through the low-permeability compacted clay- or moisture retention layer will result in increased rainwater and oxygen ingress through preferential flow paths.
- *Erosion*. Erosion can be a significant short-term problem if covers are poorly constructed, inadequate surface drainage features are provided, or where vegetation has not been re-established.

In the long term, cover degradation may be dominated by erosion processes. Short-term erosion could be prevented with (best practice) planned erosion prevention measures, but long-term erosion is more difficult to address. Post-rehabilitation soil loss will occur, albeit at a low rate. The rate at which soil loss occurs should be predicted or determined. An erosion protection layer should be included where applicable.

The effect of cover degradation should be considered in the cover design and will affect post closure care and maintenance. The following aspects need to be considered:

- *Select appropriate covers for long-term cover performance*. Compacted clay covers are, in general, more prone to the development of desiccation cracks in a semi-arid climate such as the Mpumalanga Highveld. Preferential flow paths created in compacted clay layers by desiccation cracks will have significant negative impacts on permeability of the layer.
- *Include layers that advance sustainable cover function where necessary.* Layer(s) that advance sustainable cover function, such as erosion protection-, desiccation protection-, biotic barrier- and capillary breaker layers may, sometimes be required. Generally, compacted clay covers require more likely of these layers.
- *Design and construct thicker covers*. A thicker water retention layer will reduce the risk of desiccation of underlying layers, likelihood and/or intensity of root and burrow penetration through the cover, and the effect preferential flow paths created by desiccation, roots and burrows on moisture and oxygen ingress. A thicker water retention layer will also reduce any impacts that frequent and/or intense droughts are likely to have on vegetation covers.
- *Conduct modelling to optimise cover design for long-term cover performance*. Erosion modelling should be conducted to design long-term erosional stable landforms in addition to the engineered erosion control measures that will be effective in the shorter term. Unsaturated flow/cover water balance modelling should be conducted to determine the optimum cover configuration and thickness(es) after considering the likely effect of cover degradation.
- *Appropriate model input data on material properties* that represent the (hydraulic) properties of cover materials that were exposed to climatic conditions and environmental processes over a considerable period (long-term conditions).
- *Quality assurance* of cover design-, construction-, rehabilitation- and post rehabilitation care and maintenance.

2.3.2 Effect of cover aging

Macro-pores in the cover material develop due to environmental processes that occur after cover construction and rehabilitation. These include processes such as wetting and drying cycles, root growth and death, and burrowing of worms, insects and animals. The macro-pores alter the hydraulic properties of the cover material and the hydrology of the cover. Temporal changes in cover material properties are assumed or inferred for long-term conditions in the modelling of the cover hydrology (unsaturated flow modelling) because a lack of data exists that explains how hydraulic properties change over time (Benson *et al.,* 2007; Benson *et al.,* 2012).

Test sections from ten field sites of the US-EPA Alternative Cover Assessment Program (US-ACAP) were selected to determine changes in material properties with cover aging for a broad range of environmental conditions. Field observations and measurements, in-field permeability tests, laboratory tests and analysis of results were conducted at the test sections four to nine years after cover construction. Data collected on the material properties at the time of construction and four to nine years after construction were compared to assess how the hydraulic properties of cover materials changed over time as a result of exposure to climatic and field conditions. The methodologies and results of the study are discussed in detail by Benson *et al.* (2011).

The following inferences can be made from the comparative study results between the properties with cover construction (as built) and four to nine years after cover construction:

- Changes in material hydraulic properties, such as the saturated hydraulic conductivity (K_{sat}), water retention curve (WRC) characteristics, structure development and volume changes, occurred in all the covers;
- Changes in material hydraulic properties were most significant for compacted clay covers, and for arid and semi-arid climates;
- Larger changes occur for denser or more plastic fine-textured (higher clay content) materials;
- The changes in material hydraulic properties were most significant for K_{sat}.
  - The K_{sat} of compacted clay covers older than about 5 years were typically more than two orders of magnitude higher than the as-built K_{sat}. This was ascribed to preferential flows through cracks that developed in compacted clay layers with seasonal wetting and drying cycles,
  - The K_{sat} of water balance covers older than 5 years were between typically one to two orders of magnitude higher than the as-built K_{sat},
- Larger changes in the water retention curve characteristics occurred for the compacted clay covers than for water balance covers;
- Hydraulic properties of cover materials converge toward common values over time, eliminating many of the differences that exist in the as-built condition produced by compaction and differences in soil composition.

The following practical implications are inferred from the study results:

- Water balance covers are more resilient to changes in material hydraulic properties for arid and semi-arid climates than compacted clay covers;
- The long-term performance of cover materials should be considered when designing covers and for assessing the post closure impacts of covers;
- Cover materials that are less prone to volume change and development of preferential flow paths in response to wetting and drying should be selected for cover design as far as possible;
- Water content should be controlled during cover construction to ensure that cover materials are placed under conditions that minimise changes in soil structure, such as pulverising or remoulding of clods, to limit changes in material hydraulic properties;

- An approach to determine a realistic long-term dry density is to measure the dry density of natural vegetated in-situ soils of a similar type in the vicinity of the facility;
- An indication of conditions expected in aged covers can be obtained by inspecting existing natural soil profiles (in the borrow source) that have similar composition and layering.

Water balance covers that are designed and constructed using these principles are less likely to exhibit large changes in hydraulic properties. In addition, vegetation is more readily established and maintained when cover materials are placed with less compaction and the soil structure is preserved.

2.3.3 Field performance monitoring of soil covers

Compacted clay covers have traditionally been constructed as covers over coal discard facilities to minimise rainwater ingress, AMD production and seepage. Compacted clay covers have the advantage of being relatively cost-effective if suitable material is available locally for the compacted clay barrier layer. The performance of compacted clay barrier layers relies on very low permeability to limit moisture ingress.

Compacted clay covers are most suitable in wet climates that keep the clay layer saturated or near saturated to prevent desiccation. A critical problem for compacted clay covers is the development of desiccation cracks and associated preferential flows resulting in increased rainwater ingress in the long-term. Albrecht and Benson (2001) and Albright *et al.* (2003) reported that once cracks develop in the clay layer, resulting in preferential flows, the cover can significantly lose its function to minimise rainwater ingress.

Water balance covers are widely used in arid, semi-arid and dry sub-humid climates that are characterised by distinct wet and dry seasons. Water balance covers are, however, a relatively new technology to rainwater ingress and AMD production. Until recently they have lacked the standard procedures for cover design, monitoring and evaluation that are needed to insure reliable cover performance (INAP, 2009; WMAA, 2011). Water balance covers rely on the water storage capacity of the cover and on evapotranspiration to minimise rainwater ingress into mine residues. International research and commercial experience for semi-arid climates, such as Mpumalanga Highveld have, during the past decade, demonstrated that (depending on site characteristics of the mine residue facility) correctly designed and constructed water balance covers can potentially provide several performance-, cost- and environmental benefits. Water balance covers may also provide construction and maintenance cost advantages and can allow use of a wider range of soils within the cover profile (WMAA, 2011).

Water balance cover performance is sensitive to covers being designed for site-specific conditions. Cover performance depends on climate, soils available for cover construction and vegetative growth vigour (WMAA, 2011). The long-term integrity of water balance covers must consider the effects of climate and extreme climatic events, cover hydrology, vegetation establishment and vigour, and biogeochemistry (INAP, 2009).

The *Environmental Protection Agency of the United States (EPA)* initiated an *Alternative Covers Assessment Program* (US-ACAP) in 1998. US-ACAP was the first large-scale quantitative trial of the comparative performance of conventional covers (geosynthetic- and compacted clay covers) and water balance covers. The program included twelve trial sites in eight states.

Field-scale lysimeters were used in the study to determine percolation rates for the following covers and site characteristics:

- Cover types:
  - Geosynthetic covers (referred to as composite covers in US-ACAP reports),
  - Compacted clay covers (referred to as soil barrier covers in US-ACAP reports),
  - Monolithic store-and-release (evapotranspirative) covers, and
  - Capillary breaker water balance covers;
- Climates ranging from arid to humid;
- Cover thicknesses of 0.8 to 2.9 m; and
- Vegetation types:
  - Grasses,
  - Grasses and shrubs, and
  - Grasses, shrubs and poplar trees.

The study included some side-by-side comparisons of geosynthetic-, compacted clay- and water balance covers using field-scale lysimeters for which data were collected over four to five years.

The following inferences are made from the results of the ACAP trials in the United States:

- *Geosynthetic covers* perform well in all climates. Cover percolation rates are very low (≤1 mm/yr) for arid, semi-arid and sub-humid climates. Cover percolation was high (± 50 mm/yr) at a site where the geomembrane was damaged during construction.
- Cover percolation of *compacted clay covers* is initially low (0.8-3.3 % of rainfall) for arid and semi-arid climates. The performance of compacted clay covers decreases due to preferential flow through macro-pore features related to desiccation and root penetration.
- Cover percolation of *monolithic water balance covers* varies from very low to moderately high (0.0-13.1 % of rainfall) for arid and semi-arid climates. Two covers performed below expectation (11.8 and 13.0 % of rainfall) as a result of insufficient water storage and lower than expected plant transpiration. Cover percolation is very low (0-0.9 % of rainfall) for the other monolithic covers monitored. This indicates the importance of design for monolithic water balance covers, with enough water storage capacity and good vegetation to attain high water losses through plant transpiration.
- Cover percolation of *capillary breaker covers* varies from very low to moderate (0.0-7.3 % of rainfall) for arid and semi-arid climates. The cover with the highest cover percolation can be ascribed to poor vegetation conditions resulting in lower than anticipated plant transpiration. Cover percolation also differs significantly with cover thickness (7.7 % of rainfall for 0.76 m thick and 3.7 % of rainfall for 1.05 m thick

covers). This indicates the importance water balance covers with enough water storage capacity to capture and store rainfall. Cover percolation is low (0-3.7 % of rainfall) for capillary breaker water balance covers designed with enough moisture storage capacity and good vegetative growth vigour.

It should be noted that the results of the cover percolation expressed as a % of precipitation is based on rainfall amount that excludes the effect of snow melt.

The *Waste Management Association of Australia (WMAA) initiated an Alternative Covers Assessment Program* (Aus-ACAP) in 2003. The aim of the project was to determine quantitatively whether phytocaps (water balance covers) can meet performance criteria for landfill covers more cost effectively and sustainably than conventional covers (geosynthetic- and compacted clay covers).

Field-scale lysimeters were used in the study to determine percolation rates for the following covers and site characteristics:

- Cover types:
  - Compacted clay covers (referred to as conventional caps in ACAP reports),
  - Monolithic water balance covers (referred to as phytocaps in ACAP reports), and
  - Enhanced water balance cover (referred to as a conventional cap in ACAP reports);
- Climates ranging from semi-arid (Mediterranean) to humid (subtropical – no dry season);
- Ten soil types;
- Cover thicknesses of 0.8 to 1.5 m;
- Slope gradients of 5-25%;
- Six vegetation communities for the following vegetation types:
  - Grasses,
  - Native grasses,
  - Grass, shrubs and native trees.

The study included three side-by-side comparisons of compacted clay- and water balance covers using field-scale lysimeters for which data were collected over 2 to 4 years.

The following key inferences are made from the ACAP trials in Australia:

- Cover percolation of *compacted clay covers* is initially low (0.6-2.3 % of rainfall), and is comparable to cover percolation determined for the ACAP trials in the United States. The lateral flows that have occurred above the compacted clay layer (1.0-1.3 % of rainfall) are comparable to the cover percolation. Higher than average cover percolation was measured during the last year of the trials, in contrast to lower or similar cover percolation measured for the water balance covers. This can be an indication of the effect of preferential flows through the desiccation cracks that had developed in the compacted clay layer.

- Cover percolation of *monolithic water balance covers* is low (1.6-2.7 % of rainfall) and comparable to cover percolation determined for the ACAP trials in the United States for monolithic covers with enough water storage capacity and good vegetative growth. The high cover percolation (15.8% of rainfall) measured at a site is the result of very high cover percolation (36% of rainfall) measured in the first year. This can be ascribed to the fact that the cover is constructed with sandy soil and the grass failed to establish in the first year. Cover percolation decreased as the vegetation became established (WMAA, 2011). This indicates the importance of good vegetative growth to attain high moisture losses through plant transpiration and that cover material with good moisture retention being used for water balance covers.
- Cover percolation of an *enhanced water balance covers* is very low (0.1% of rainfall) and low compared to the paired monolithic water balance cover with cover percolation of 1.6% of rainfall. The lateral flow above the compacted clay layer is also very low (0.4% of rainfall). This indicates the potential of recent developments in water balance cover designs (enhanced water balance covers) in minimising rainwater ingress.

The *Water Research Commission (WRC) and Coaltech of South Africa initiated a research project* entitled "Performance of natural soil covers in rehabilitating opencast mines and mine residue dumps in South Africa" in 1993. The aim of the project was to assess the performance of different soil cover configurations in terms of limiting leachate generation into coal discard. This project (Phase 1) was followed-up with a second (Phase 2) project entitled "The evaluation of soil covers used in rehabilitation of coal mines" (Vermaak *et al.*, 2004).

The study included ten side-by-side comparisons of uncovered fine coal discard and soil cover options using field-scale lysimeters that were fully instrumented to monitor percolation (rainwater ingress), oxygen concentration (oxygen ingress) and leachate qualities (acid mine drainage production) for the cover options over nine years for the following covers and site characteristics:

- Cover types:
  - Uncovered fine coal discard,
  - Monolithic water balance covers (referred to as soil covers in WRC reports):
    - Single layer (growth medium and water retention layer combined in a single layer),
    - Double layer (growth medium underlain by water retention layer), and
    - Double layer – sloped (10 and 20% slope gradient);
- Two soil types (Avalon and Escort);
- Cover thicknesses of 0.3, 0.5 and 1.0 m;
- Vegetation cover being only grasses.

After a run-in period, in-field double ring infiltrometers test results on compacted soil layers showed higher infiltration than the maximum infiltration rate of 0.5 m/yr ($1.5x10^{-8}$ m/s) specified by the Minimum Requirements for Waste Disposal by Landfill (DWAF, 1998) for a low-permeability compacted clay layer. Consequently, all the soil covers were re-classified as monolithic water balance covers rather than compacted clay covers. The experiment site is situated close to the old Kilbarchan Colliery, approximately 10 kilometres south-east of the town Newcastle, in KwaZulu-Natal.

The following key inferences are made from the study results in the report by Vermaak *et al.* (2004), based on the data and information obtained:

- *Water content*: Avalon soils are characterised by cycles of wetting and drying, but Estcourt soils remained moist throughout the rainy season. This is an indication that Avalon soils demonstrated store and release mechanisms required by water balance covers, whereas Escort soils did not function effectively as a water balance cover.
- *Percolation rates (rainwater ingress; referred to as outflow rates in WRC reports)*.
  - The differences in percolation rates for compacted and uncompacted fine coal discard are small, indicating that the effect of compaction of coal discard is not significant on percolation rates for uncovered discard surfaces;
  - Percolation rates through soil covers are considerably lower than for uncovered discard. The reduction in percolation rates gained by compacting fine coal discard is insignificant compared with providing the discard with a soil cover;
  - Percolation rates are related to cover thickness with high rates measured for the 0.3 and 0.5 m covers and lower rates for the 1.0m covers;
  - Percolation rates are lower for double layered covers compared to single layered;
  - Mean annual percolation rate for the 1.0 m thick double layered cover with Avalon soil is less than 5% of MAP, which meets the criteria for rainwater ingress-limiting covers. The mean annual percolation rate for the cover is about a tenth of that of uncovered fine discard, which confirms the effectiveness of water balance covers for the KwaZulu-Natal coalfields;
- *Oxygen and carbon dioxide concentration (oxygen ingress, oxygen and carbon dioxide concentration measured at base of 3 m discard profile):*
  - Oxygen concentration of uncovered fine discard cells approaches atmospheric concentrations. The carbon dioxide concentrations are low, indicating that carbon dioxide, generated by sulphide oxidation processes, is unrestricted in diffusing into the atmosphere,
  - Oxygen concentrations are related to soil cover thickness with high rates measured for the 0.3 and 0.5 m covers and lower rates for the 1.0m covers,
  - Oxygen concentrations are high for the 0.3 m cover, indicating that oxygen ingress is not significantly reduced by 0.3 m thick covers,
  - Moderately low oxygen concentrations were measured for the 1.0 m thick covers, indicating that the 1.0 m thick covers reduce, but do not prevent oxygen ingress. This confirms international experience that the design of water balance covers for semi-arid climates such as the coalfields of South Africa should aimed to rainwater ingress-ingress, with a secondary effect to reduce oxygen ingress;

- *Acid drainage and leachate qualities:*
  - Acid breakthrough occurred at the uncovered discard cells, but the onset of acid drainage was delayed by compaction and treatment of coal discard with lime. Acid breakthrough also occurred for the 0.3 m thick cover. The acid drainage from the uncovered and 0.3 m cover indicate that sulphide oxidation could not be limited due to the relatively high moisture and oxygen ingress rates,
  - Acid drainage was not observed for the 0.5 m cover during the 9-year monitoring period, but an increase in sulphate concentrations indicates increased sulphide oxidation rates This indicates that moisture and oxygen ingress rates for the 0.5 m thick cover could not be reduced to levels that limit sulphide oxidation,
  - Acid drainage was not observed for flat 1.0 m covers during the 9-year monitoring period. Slight decreases in sulphate concentrations indicated that sulphide oxidation rates had decreased since placement of the cover,
  - Acid drainage was observed for the 1.0 m cover with a 20% slope but did not occur for the 10% slope cover. High sulphate concentrations at a 10% slope do, however, indicate increased sulphide oxidation rates. Vermaak *et al.* (2004) theorised that infiltrated rain had flowed laterally downwards along the interface of the compacted 2nd layer and coal discard, resulting in the drying out of the cover layer along the top portions of the cover, thereby increasing ingress of oxygen into the fine coal discard,
  - There is a distinct relationship between oxygen ingress rates and leachate quality. The quality of leachate can be improved by reducing oxygen ingress into sulphide-containing mine residues. Consequently, the design of rainwater ingress-limiting covers for coal discard facilities in South Africa should also focus to reduce (not necessary prevent) oxygen ingress.
- *Unsaturated flow modelling:*
  - Excellent calibration curves could be achieved with unsaturated flow model using in-field measured material hydraulic properties. This indicates that unsaturated flow models can simulate percolation rates for covers accurately, provided that the cover material properties accurately reflect in-field material properties.

3. GUIDELINES ON SOIL COVERS

Guidelines and Best Practice Guidelines (BPG) were reviewed on the use of soil covers to mitigate rainwater ingress- and oxygen ingress and AMD production and seepage in support of groundwater protection for discard facilities; and on the planning, design, construction and maintenance of soil covers.

3.1 South African guidelines

3.1.1 Best practice guideline series of DWS

The Department of Water and Sanitation (former Department of Water Affairs and Forestry) have a series of Best Practice Guidelines (BPGs) for Water Resource Protection in the South African Mining Industry, which are listed in Table 3-1. Only those guidelines relevant to soil covers are discussed in the subsequent sections.

Table 3-1: Series of Best Practice Guidelines of Department of Water and Sanitation

Best Practice Guidelines		Topics covered	Relevance to soil covers
Dealing with aspects of DWAF's water management	H1	Integrated Mine Water Management	**Key importance**
	H2	Pollution Prevention and Minimisation of Impacts	**Key importance**
	H3	Water Reuse and Reclamation	n.a.
	H4	Water Treatment	n.a.
Deal with general water management strategies, techniques and tools	G1	Storm Water Management	n.a.
	G2	Water and Salt Balances	*Important*
	G3	Water Monitoring Systems	n.a.
	G4	Impact Prediction	**Key importance**
	G5	Water Management Aspects for Mine Closure	**Key importance**
Deal with specialised mining activities or aspects	A1	Small-scale Mining	n.a.
	A2	Water Management for Mine Residue Deposits	**Key importance**
	A3	Water Management in Hydrometallurgical Plants	n.a.
	A4	Pollution Control Dams	n.a.
	A5	Water Management for Surface Mines	n.a.
	A6	Water Management for Underground Mines	n.a.

The discussion in subsequent sections focusses only on the aspects relevant to soil covers to rainwater ingress- and oxygen ingress and AMD production and seepage.

H1: Integrated Mine Water Management (IMWM)

The four key principles of IMWM, namely risk-based approach, life-cycle, water management hierarchy and management commitment, are key importance to soil cover design, construction and long-term performance. The risk-based approach is imperative to the design of soil covers that is based on a firm scientific foundation and scientifically-validated environmental and water resource risks. The IMWM also refers to an important aspect of soil covers in improving vegetation to optimise groundwater protection, minimise erosion and improve long-term landform stability and landscape function.

H2: Pollution Prevention and Minimisation of Impacts

The common thread to minimise pollution during decommissioning and closure specific to the soil covers is through the application of planning and design of soil covers to limit AMD production and seepage, and ongoing and effective management and re-evaluation of soil covers. Once the soil cover performance characteristics have been specified, it must be ensured that the soil cover is designed to reduce long-term AMD production and seepage. Soil cover designs to rainwater ingress and oxygen ingress into mine residue is a source directed mitigation measure to mitigate AMD production and seepage into the receiving groundwater.

G2: Water and Salt Balances

Soil cover design to rainwater ingress support the principles of the G2-guideline that detailed rainfall and climate records are used and predictions made for i.e. 10^{th} percentile (dry), 50^{th} percentile (average rainfall) and 90^{th} percentile (wet) as a minimum modelling requirement. Predicted rainwater ingress can be combined with geochemical modelled leachate results to determine contaminant seepage loads into groundwater for worst-, average- and best-case scenarios. Oxygen ingress modelling through soil covers is imperative to predict AMD production in the mine residue and associate seepage into groundwater for post-closure conditions and for concurrent rehabilitation during the operational phase.

G4: Impact prediction

The G4-guideline is the most important guideline of the DWAF BPGs series on soil covers and to mitigate AMD production and seepage. The aspects covered in the G4-guideline, and those relevant to soil covers are listed in Table 3-2.

The ability to make impact prediction of soil cover options, cover construction and rehabilitation standard and long-term post-closure cover performance on the water resource into the future is fundamental to the science of environmental risk assessment and management at mine sites. The risk tools/models included in the quantitative risk-based assessments according to the G4-Guideline are listed in Table 3-3. The inclusion of these tools/models and the status of application are also listed in Table 3-3.

Table 3-2: Chapters of G4 guideline and relevance to soil covers

Chapter	Aspects	Relevance to soil covers	Addressing soil cover aspects
1	Introduction and objectives of this best practice guideline	Relevant	
2	General principles of impact prediction	**Key importance**	Soil cover guideline addresses all principles listed for impact prediction
3	Risk-based approach to impact prediction	**Key importance**	Quantitative risk assessment of soil cover guideline entails source term component of risk-based approach
4	Impact prediction methodology & process	**Key importance**	Soil cover guideline includes similar impact methodology and process of G4-Guideline, except that cover materials balance and hydraulic properties are included
5	Key impact prediction questions	**Key importance**	Soil cover guideline addresses impact prediction questions, but specific to soil covers
6	Impact prediction tools & procedures	**Key importance**	Soil cover guideline includes similar impact prediction tools / models and procedures of G4-Guideline, except that soil cover water balance and vadose zone modelling is included
7	Independent review	**Key importance**	Soil cover guideline addresses principles of independent review
8	Contents of an impact prediction report	**Key importance**	Soil cover guideline includes aspects of impact prediction report of G4-Guideline, except that cover materials balance, hydraulic properties, soil cover water balance modelling, long-term cover performance are included
9	Additional reading	n.a.	
Appendix			
A	Introduction to physical and chemical process involved in impact prediction	**Key importance**	
B	Impact prediction tools and procedures	**Key importance**	
C	Considerations for incorporation into conceptual models	*Important*	
D	Example of conceptual model report for waste disposal facility	Relevant	
E	Example of conceptual model report for tailings disposal facilities, waste rock dumps and reclaimed waste rock dump footprints	Relevant	

Table 3-3: Gap analysis between G4- and international guidelines on soil covers

Risk-based approach components	G4 Guideline Tools / Models	Inclusion in guideline: South African	Inclusion in guideline: International	Application in South Africa
Source term characterisation	Soil cover materials balance	Not included	- INAP[1] Cover design[2] - Aus-ACAP[3] - US-ACAP[4]	Limited application
	Material hydraulic properties sampling and analysis	Not included	- INAP Cover design - GARD[5] - Aus-ACAP - US-ACAP	Limited application
	Geochemical sampling and analysis	- DWAF-BPG[6] - MRF-DSS[7]	- INAP Cover design - GARD - Aus-ACAP - US-ACAP	Standard practise
Source term modelling	Soil cover water balance (rainwater ingress)	Not included	- INAP-Cover design - Aus-ACAP - US-ACAP	Limited application
	Geohydrological (groundwater)	- DWAF-BPG	- Several guidelines	Standard practise
	Water balance (mine water)	- DWAF-BPG - MRF-DSS	- Several guidelines	Standard practise
	Oxygen diffusion (oxygen ingress)	- MRF-DSS	- INAP-Cover design - GARD - Aus-ACAP	Some application
	Geochemical (leachate quality)	- MRF-DSS	- GARD - INAP-Cover design - Aus-ACAP - US-ACAP	Standard practise
Pathway	Vadose zone (unsaturated pathway)	Not included	- US-ACAP	Limited application
	Aquifer (saturated pathway)	- DWAF-BPG	- Several guidelines	Standard practise
	Runoff (hydrologic)	- DWAF-BPG - MRF-DSS	- Several guidelines	Standard practise
	Mining voids	- DWAF-BPG - DSS-MRF	- GARD - INAP Cover design - Aus-ACAP - US-ACAP	Standard practise
Receptor	Groundwater abstracting / user			
	Surface water abstracting / user			
	Aquatic fauna and flora			

[1] INAP: International Network for Acid Protection
[2] INAP Cover design: INAP Global Cover System Design Technical Guidance Document
[3] Aus-ACAP: Waste Management Association of Australian Guideline of Phytocaps
[4] US-ACAP: Guideline on Water Balance Cover for Waste – Principles and Practice
[5] GARD: INAP Global Acid Rock Drainage Guide
[6] DWAF-BPG: Best Practice Guideline Series of Department of Water Affairs and Forestry
[7] MRF-DSS: Decision Support System on Mine Residue Facilities

Application of the quantitative risk assessment of the soil cover guideline (Part B) will provide time series of seepage volumes and quality as it varies from operation to long-term post-closure conditions. This provide more realistic prediction then when a static constant condition is predicted that is unrealistic and is inappropriate for anything than the most basic screening level assessment. Predicted seepage time series from soil cover design is provided as input to the vadose zone and/or groundwater models.

The soil cover guideline (Part B) supports the impact prediction methodology, roles and tasks for stakeholders, as well as the impact prediction tools and procedures included in the G4-Guideline. Similar decision-making trees to that of the G4-Guideline are included specific for predicting the impact of soil cover options, construction and rehabilitation standard, and long-term post-closure cover performance on AMD production and seepage volumes, qualities and loads seeping into the receiving vadose zone and/or groundwater. Even though the decision-making tree of the G4-Guideline is similar than the international soil cover guidelines, specific aspects of soil covers are not included in the G4-guideline, which the soil cover guideline addresses. The soil cover guideline is discussed in Part B of this report.

G5: Water Management Aspects for Mine Closure

The soil cover guideline, discussed in Part B of the report, supports the water-related closure risks and liabilities included in the G5-Guideline. Even though the water management aspects for closure of the G5-Guideline are similar than the international soil cover guidelines, the following aspects of soil covers in the G5-guidelines are *not* included:

- *Closure planning:* Soil covers that are cost-effective;
- *Appropriate tools:* Predicting long-term post-closure performance of soil covers based on risk-based approach, soil cover water balance modelling to predict moisture- and oxygen ingress to limit ARD generation and seepage, determining cover materials balance and hydraulic properties, dedicated design of soil covers to meet ARD seepage and groundwater quality objectives, care and maintenance monitoring for long-term cover performance;
- *Specialists:* Soil scientist with an understanding of soil cover function and mine rehabilitation;
- *Closure objectives:* A clear objective and criteria for soil covers and rehabilitation with the specific aim to rainwater ingress- and oxygen ingress and associate ARD seepage, as well as required monitoring for long-term cover performance;
- *Indicators:* Soil cover construction criteria from dedicated soil cover design, soil cover construction quality assurance, indicators to monitor post-closure aspects of long-term cover performance and corrective care and maintenance required to limit the moisture- and oxygen ingress and ARD generation and seepage.

A2: Water Management for Mine Residue Deposits

Water management of the disposal of mine residue is critical important for the design, operational management and closure of any mine facilities. The A2-guideline focuses on the details on the recommended processes to follow the best practice water management for decommissioning and closure phases of mine residue deposits.

The following aspects related to soil covers are *not* included in the A2-guideline:

- Site-specific and rehabilitation characterisation, such as survey to identify and quantify the soil available at site (cover material balance);
- Soil cover water balance (moisture ingress, net infiltration) modelling;
- Oxygen ingress modelling;
- Soil cover design based on soil cover water balance-, oxygen ingress-, geochemical (leachate quality)- and geohydrological (groundwater) modelling;
- Field trials on soil cover performance.

3.1.2 Decision Support System on mine residue facilities

The Water Research Commission (WRC) initiated in 2004 a study to develop a Decision Support System (DSS) for the sustainable design, operation and closure of metalliferous tailings facilities. The DSS includes several aspects relevant to soil covers, and only the chapters of the DSS relevant to soil covers are discussed.

Decision support guideline for oxidative zone assessment of metalliferous tailings facilities

The oxidation zone can influence the refinement of closure design and mitigation measures (soil cover design), water quality and impact predictions, and rehabilitation planning. The recommended assessment process for oxidation zones includes:

- Material characterisation (sampling and analyses);
- Modelling;
- Field testing; and
- Field verification.

If there are any oxygen consumption rates in the mine residue, an oxygen ingress modelling needs to be performed. The soil cover guidelines discussed in Part B of the report also include oxygen ingress modelling for mine residues, but the oxygen ingress modelling from operation to post-closure conditions for soil covers is included.

Decision support guideline on tailings water balance

It is clear from practical examples of water balances for both operational- and for a closed mine residue disposal facility that water balances cannot be calculated with reliable accuracy if the necessary mine residue (material hydraulic) properties are not known. The characterisation of the material hydraulic properties is an important aspect to be addressed during soil cover modelling and design. According to the decision support guideline, the actual material properties of the mine residue must be determined when a facility has been commissioned. After closure, the water balance must be optimised to minimise seepage rates, AMD production in the mine residue and AMD seepage into the receiving groundwater. The soil cover guidelines discussed in Part B of the report follows similar actions but in addition entail the soil cover water balance modelling based on site-specific characterisation.

Decision support guideline on pore-water quality evolution

The importance of the concept of pore water quality evolution for sustainable design, operation and closure, relates to the difficulty of predicting future water impacts from the mine residue facility. These future water impacts require mitigation measures which liability needs to be defined. The pore water quality evolution based on future risk-based decisions needs to be quantified and expressed. The discussion of this guideline is similar to the discussion of the G4-guideline for soil covers.

3.1.3 Guidelines for the rehabilitation of coal mine facilities/land

The discussion on the guidelines for rehabilitation of coal mined land are based on the 3rd revised guideline entitled "Land Rehabilitation Guidelines for Surface Coal Mines" published by the Land Rehabilitation Society of South Africa (LaRSSA), Coaltech and the Minerals Council of South Africa (2019). The guideline includes the full process from the initial planning and conceptualisation stages, through the actual mining and rehabilitation processes, the development and monitoring of criteria for completion (including post-mining monitoring criteria), up to and including the actions needed to obtain final clearance from the authorities that the rehabilitation process has been completed.

Currently, few mines receive final closure status in South Africa and the key issue hinges on residual risks (pollution effects, suitability and vegetation issues) and how to manage it. While the situation with respect to these residual risks can be closely monitored at the time of application for the closure certificate, the concern of the authorities lies with the potential for post-rehabilitation residual- and latent risks (LaRSSA *et al.,* 2019). The key sections of the guideline relevant to soil covers are listed in Table 3-4.

Section A: Planning

The Guideline's focus is mostly on land rehabilitation and the long-term goal of having resilient vegetation cover, or on reaching long-term viable land use (which has been defined in the planning stages of the mine's life cycle). It is mentioned in Chapter 3.2 that an appropriate cover design needs to be planned and implemented to limit the ingress of water, thereby limiting CoCs seepage to underground water sources. Although this guide deems cover design as necessary, no further detailed guidelines are provided by which covers should be designed to limit the ingress of water and oxygen, as well as limiting AMD production and the leaching thereof.

This study and cover design guideline, in Part B, puts emphasis on the importance of unsaturated flow modelling and provides a detailed guide to optimise cover design. This cover design guideline focusses on minimising rainwater- and oxygen ingress and mitigating AMD, while still allowing aquifers and underground water resources to regenerate with environmentally acceptable limits of macro- and microelements and inorganic compounds (e.g. SO_{4-}). This cover design guideline, as with the Land Rehabilitation Guideline, also considers long-term viable use of the land and soil cover.

Table 3-4: The Land Rehabilitation Guidelines for Surface Coal Mines

Section Chapter	Topics that are covered in guideline	Relevance to covers
Section A	Planning	
1	Setting the scene	Relevant
2	Legislative requirements	*Important*
3	Planning & Design for land rehabilitation	*Important*
4	Developing the rehabilitation plan	*Important*
Section B	Implementation	
5	Surface landform design and profiling	Relevant
6	Soil stripping	**Key importance**
7	Soil stockpiling	**Key importance**
8	Soil replacement	**Key importance**
9	Soil amelioration	**Key importance**
10	Revegetation	**Key importance**
11	Removal or re-use of surface infrastructure	N/A
Section C	Monitoring	
12	Principles of rehabilitation monitoring	**Key importance**
13	Setting up the monitoring programme	**Key importance**
Section D	Post-mining land management	
14	Why post-mining land management?	Relevant
15	Final closure – managing residual and latent environmental risks	**Key importance**
Appendix	**Topics that are covered in appendix**	**Relevance to covers**
A	Guideline abbreviations and terms	Relevant
B	Relevant land rehabilitation legislative requirements	*Important*
C	Considerations for final landform, modelling, drainage and sustainability	*Important*
D	Determining the soil erodibility factor (K)	*Important*
E	Land capability classification for mined land	Relevant
F	Considerations for surface drainage structure design	*Important*
G	Example of a pre-mining soil survey, and soil stripping and handling plan	**Key importance**
H	Sampling for soil analysis (post-placement assessment)	**Key importance**
I	Soil compaction and its alleviation	**Key importance**
J	Considerations for soil fertilisation and liming	**Key importance**
K	Considerations for vegetation selection	**Key importance**
L	Considerations for demolition of infrastructure	*N/A*

Section B: Implementation

In the implementation phase, the following topics are discussed in detail:

- Surface landform design and profiling;
- Soil stripping;
- Soil stockpiling;
- Soil replacement;
- Soil amelioration;
- Revegetation; and
- Removal or re-use of surface infrastructure.

Soil stripping, stockpiling, replacement, amelioration and revegetation are *key aspects* relating to soil covers and the design thereof. The Land Rehabilitation Guideline provides sufficient detail on these aspects, as well as providing objectives, actions and monitoring guidelines for each aspect. These implementations should be planned properly during the design and permitting phase of the mine's lifecycle. If the implementation is done correctly and according to plan, maintaining physical- chemical- and biological characteristics of the cover material is made easier, thereby assisting in the design of covers and improving the performance thereof.

Section C: Monitoring

Monitoring is of *key importance* in relation to cover design. Concurrent monitoring of implementation and rehabilitation is crucial to:

- Verify that rehabilitation actions are done exactly according to plan, on time and the results are as excepted;
- Ensure that timeous action can be taken to implement corrective action, should the desirable outcome of rehabilitation not be as expected/planned; and
- Verify that relinquishment criteria have been met so that the mine can apply for closure.

The Land Rehabilitation Guidelines' monitoring plan includes some important aspects related to covers, including:

- Erosion;
- Surface water drainage systems and surface water quality;
- Groundwater quality;
- Depth of topsoil stripped and replaced;
- Physical-, chemical- and biological status of replaced soil;
- Vegetation basal cover;
- Reconstructed landform stability;
- Predictive modelling to define monitoring requirements; and
- Surface- and groundwater quality compliance with agreed conditions.

Aspects on water- and oxygen ingress related to cover design over discards are mentioned and deemed as important, but detail, quality requirements and implementation are not discussed. An important topic not discussed in the rehabilitation guide, is cover performance monitoring. This guideline, in Part B, addresses and discusses these aspects in detail.

Section D: Post-mining land management

Post-mining land management, related to cover design, is of *key importance*. The importance of managing residual- and/or latent risks are stressed in the Land Rehabilitation Guideline (Section 15).

The Land Rehabilitation Guideline discusses the risk of decreased groundwater quality and groundwater recharge rates related to post-mining land use, but does not provide recommendations or guidance on how to mitigate these risks. Geosynthetic covers and liners could impair the infiltration of water and recharge of aquifers and other underground water resources, and the cover design guideline, in part B, does not aim at impairing the infiltration of water, but rather limit AMD and CoCs seepage of the receiving (ground)water to acceptable environmental limits.

The guideline series of DWAF (2008), provide ample information for water resource protection, whereas the guideline of LaRSSA *et al.* (2019) provide ample information on rehabilitation of surface mine land. Although ample information is provided, guidance is not specifically provided on soil cover predictive modelling, appropriate cover design and construction and post closure cover performance monitoring at the required detail.

The DWAF (2008) guideline series focusses on water resource protection, whereas the guideline of LaRSSA et al. (2019) focusses on rehabilitation of surface coal mines. The focus of this soil covers guideline involves both of these guidelines. This provides the opportunity to integrate these two guidelines as the focus of this guideline is on the coal mine rehabilitation aspects of soil covers with the aim to protect the water resource by limiting AMD and CoCs seepage from the facility. Consequently, this guideline addresses many of the information gaps between the guideline series on water resource protection and land rehabilitation of coal mines.

3.2 International guidelines

3.2.1 Global acid rock drainage guide

The overall objective of the GARD Guide of the International Network for Acid Prevention (INAP, 2014) Global acid rock drainage (GARD) guide is to collate and facilitate worldwide best practice in prediction, prevention, and mitigation of acid mine drainage (AMD). It is a reference document for stakeholders involved in sulphide mineral oxidation and related mine residue management issues.

According to the GARD guide, a thorough evaluation of AMD potential should be conducted prior to mining and continued through the life of mine. Consistent with sustainability principles, strategies for dealing with AMD should focus on prevention or minimisation rather than control or treatment. These strategies are formulated within an AMD management plan, to be developed in the early phases of the project, together with monitoring requirements to assess their performance. The integration of the AMD management plan with the mine operation plans is critical to the success of AMD prevention. Leading practices for AMD management continue to evolve, but tend to be site-specific and require specialist expertise.

3.2.2 Global cover system design technical guideline

The purpose of INAP (2017) global cover system design technical guideline is to provide guidance on the design, construction, and performance monitoring of cover systems at mine sites globally in supporting the GARD Guide. The guideline includes a design tool that guides users through site-specific elements integral to the design. This document also presents an understanding of how cover designs might affect AMD and CoCs loading.

The technical guidance document also addresses evolving approaches, and provides up-to-date information for designers, regulators, and other stakeholders in the design, construction, operation, and monitoring of cover systems for both reactive and non-reactive mine residue during operations and closure.

3.2.3 Waste Management Association of Australian guideline on phytocaps

The WMAA (2011) has produced the "Guidelines for the Assessment, Design, Construction, and Maintenance of Phytocaps as Final Covers for Landfills" as part of the Australia Alternative Cover Assessment Programme (Aus-ACAP). The objective of the guideline is to provide guidance for landfill stakeholders on the applicability, design, construction and maintenance of phytocaps (water balance) in Australia. Sections of the guideline that are relevant to soil covers are summarised in Table 3-5.

Table 3-5: Waste Management Association of Australian guideline on soil covers

Chapter	Topics that are covered
2	Insight on how water balance covers functions Referenced summary of key finding from Australian and international research on the comparative performance of water balance and compacted clay covers
4	Discusses the roles, responsibilities and needs of the stakeholders Importance of engaging stakeholders throughout cover design and construction
5	Presents recommended design method to meet defined cover design objectives
6	Presents a risk assessment framework, specific to water balance cover design, for use at the screening level assessment and detailed cover design process
7	Discusses specific requirements of water balance cover construction, particularly material specification and quality control of construction
8	Deals with post-rehabilitation care and maintenance, including monitoring of cover performance
Appendix	Provide detail on science, numerical models for soil cover design and case study of soil cover trials

3.2.4 US-ACAP guideline on water balance covers – Principles and practice

The document was created to provide engineers, designers, and regulators with the basic principles behind selection and design of soil covers for waste containment. The guideline includes a review of soil cover types, design principles and procedures, cover monitoring, and long-term performance modelling. Sections of the guideline that are relevant to covers are summarised in Table 3-6.

Table 3-6: US-EPA Alternative Cover Assessment Programme guideline on soil covers

Chapter	Topics that are covered
2	Discusses basic issues affecting selection of covers, where they are appropriate and under what circumstances, and key factors to be considered by engineer, regulator, and owner
3, 4	Provide principles of soil physics, plant ecology, and water balance ecology that are relevant to design and evaluation of soil covers
5	Incorporate fundamental information on preliminary (conceptual) cover design
6	Discusses numerical modelling to validate or refine a cover design, to assess sensitivity, and to evaluate "what if" questions
7	Describes what can be expected in terms of field performance and methods for monitoring performance based on data from US-EPA Alternative Cover Assessment Programme

3.3 Gap analysis

The gap-analysis between international- and South African guidelines are summarised in Table 3-6. The following components of international soil cover guidelines are in place for South Africa and no further development will be required:

- Processes in engaging with the regulator regarding covers to protect groundwater;
- Processes and procedures on stakeholder engagement, which should be used to determine and communicate required cover functionality and design objectives;
- Procedures and tools / models on engineering design, mine water and salt balance modelling, hydrological-, geohydrological-, and geochemical characterisation and modelling;
- Guidelines on rehabilitation of mined land.

These processes, procedures and tools are supported by international soil cover guidelines that is standard practise in South Africa.

Table 3-6: Gap-analysis for soil covers on existing South African guidelines

Phase	Elements	International guidelines				South African guidelines		
		Global acid rock drainage guide	**Global cover system design guideline**	**WMAA guideline on phytocaps**	**US-ACAP guideline on water balance cover design**	**DWA Best practice guideline series**	**DSS on mine residue facilities**	**Guidelines for rehabilitation of mined land**
Planning	Regulator and stakeholder requirements	✓	✓	✓	✓	✓	✓	✗
	Objectives for soil cover design	✓	✓	✓	✓	✗	✗	✗
Design	Soil cover performance criteria	✗	✓	✓	✓	✗	✗	✗
	Screening level risk assessment	✓	✗	✓	✓	✓	✗	✗
	Site-specific climate and characterisation of site cover materials	✓	✓	✓	✓	✗	✗	✗
	Conceptual cover design based on soil cover modelling	✗	✓	✓	✓	✗	✗	✗
	Field trials	✗	✓	✓	✓	✗	✗	✗
	Final designing based on calibrated soil cover modelling	✗	✓	✓	✓	✗	✗	✗
Construction	Cover construction criteria	✗	✗	✓	✗	✗	✗	✗
	Soil cover materials specifications	✗	✗	✓	✓	✗	✗	✗
	Construction methods, soil cover material stripping, handling and placement	✗	✗	✓	✓	✗	✗	✓
	Vegetation establishment and weed control	✗	✗	✓	✓	✗	✗	✓
	Construction quality assurance and quality control	✗	✗	✓	✓	✗	✗	✗
	Record keeping	✗	✗	✓	✗	✗	✗	✓
	Soil cover construction certification	✗	✗	✓	✗	✗	✗	✗
Post-closure care and maintenance	Final post-closure planning	✓	✓	✓	✓	✓	✗	✓
	Monitoring requirements	✓	✓	✓	✓	✗	✗	✓
	Long-term cover performance monitoring and evaluation	✗	✓	✓	✓	✗	✗	✗

The following components of the international soil cover guidelines lacking in South Africa are included in the soil cover guideline discussed in Part B of the report with the specific objective to minimise rainwater ingress- and oxygen ingress and AMD production and seepage:

- A technical guideline that integrates the various processes, procedures, tools and models on soil cover design, construction, and care and maintenance to meet the above-mentioned objective;
- *Cover design*:
  - Setting soil cover performance criteria for design,
  - Baseline (screening level) risk assessment to determine viable soil cover options,
  - Procedure to determine cover materials balance for the site,
  - Procedures to characterise cover materials properties, including material hydraulic properties,
  - Procedures, tools and models to be used for soil cover modelling based on site-specific climate and cover materials properties at site to predict rainwater ingress and moisture content required for oxygen ingress modelling,

Approach and processes of conceptual- and final cover design;

The lessons learned from international experience on the reasons the functionality of a soil cover fails to meet performance expectations can mainly be ascribed to the following:

- *Planning:* No clearly defined and communicated cover objectives and design criteria;
- *Design*:
  - No dedicated soil cover design to optimise the cover specific to protect groundwater, and
  - Lack of incorporating site-specific climate conditions and site-specific cover material properties into the design of soil covers;
- *Construction*:
  - No characterisation of borrow materials,
  - Lack of control on proper placement and management of the materials used for cover construction,
  - No construction quality assurance,
  - Fails to establish vegetation;
- *Post-closure care and maintenance*: Fails to understand the long-term cover performance expectations, as measured against site-specific human health and safety, risk, cost and end land use.

Currently, procedures on soil covers to mitigate groundwater impacts are not in place for South Africa, such as the more recent international guidelines on soil covers. It should also be noted that for compliant covers that detailed procedures on the planning, design, construction quality assurance and performance monitoring do exist for South Africa. Therefore, it is of key importance that similar procedures are developed and implemented for soil covers as alternative cover option to protect groundwater.

4. FIELD INVESTIGATIONS AND LABORATORY TESTING

4.1 Research sites

Suitable research sites on mature, rehabilitated coal discard facilities in the Mpumalanga Highveld were identified to determine in-field material hydraulic properties and vegetation characteristics for covers with a lengthy exposure to climatic conditions. The aim of the site selection process was to select research sites with soil covers that are preferably older than 20 years, and represent paired cover scenarios on:

- Thin and tick (>50 cm) covers;
- Soil covers where root development has been impeded by shallow compacted layer;
- Thick soil covers where root penetration and development are not impeded.

Other aspects that were also considered included are logistical support by the mine, easy access to field investigation sites, and available information on cover design and construction and from previous studies. A limited number of sites were found where mature (old) covers were available to the study and information could also be provided on cover thickness, cover conditions and maintenance.

Three coal discard facilities were selected. Two discard facilities that are about 250 m from each other, namely Dump 1 (D1) and Dump 2 (D2), were selected as paired facilities representing moderately dense and very dense (highly compacted) covers. Three research sites, namely D1-S1, D1-S2 and D1-S3, were established at Dump 1 and two research sites, namely D2-S4 and D2-S5, at Dump 2. Two research sites, namely D3-S6 and D3-S7, were established at a discard Dump 3 (D3), some 7 km from the other dumps. The coal discard dumps are located in Nkangala District Municipality, Mpumalanga, and summarised in Table 4-1.

Table 4-1: Selected research sites

Facility	Research site		Cover type	Cover age[1] (yrs)
	Name	Location		
Dump 1	D1-S1	Top of dump	Dual layered soil covers – Moderately dense	24
	D1-S2	North-western slope of dump		
	D1-S3	South-eastern slope of dump		
Dump 2	D2-S4	Top of dump	Dual layered soil covers – Very dense	21
	D2-S5	North-western slope of dump		
Dump 3	D3-S6	North-western slope of dump	Dual layered soil covers – Moderately dense	16
	D3-S7	Top of dump		

Note: [1] Cover age at 2018.

4.2 Field investigations

4.2.1 Cover characterisation

Profile pits were dug by spade into the discard during fieldwork, and the materials were backfilled and compacted by hand in 10 cm layers according to the sequence of the cover layers. The research sites are shown in Photo 1 to Photo 6, and the cover characteristics and condition are summarised in Table 4-1.

The growth media were constructed with apedal B-horizon, and possibly also the organic rich A-horizon soils, which are suitable growth medium material. Little mixing of growth medium soils with less suitable subsoils, resulting in high quality soil used for the growth media.

Slight to moderate dense cover profiles were observed at D1-S1, D3-S6 and D3-S7 sites. The compaction was, however, not enough to limit root penetration and development. Very dense (highly compact) cover profiles were observed at D2-S4 and D2-S5 sites that limited root penetration and development.

No surface cracks were visible in the apedal soil horizons that were used for the surface layer. Except for D2-S4, slight sheet (inter-rill) erosion occurs between the grass tussocks. Relatively low erosion rates are expected for the apedal soil surface layer which is characterised by good infiltration and low runoff potential from vegetated surfaces. Weak surface crusts observed indicate that surface sealing should not significantly increase runoff and cause erosion damage. Substantial sheet (inter-rill) erosion and rill erosion at localised runoff areas occurs at D2-S4 and D2-S5. This can be ascribed to the severe surface compaction observed in the growth medium resulting in high runoff.

Root depth, distribution and development show a close inverse relationship with extent of compaction. Root development occurs throughout the cover thickness of the moderately dense covers at D1-S1 and D3-S6, with some roots into the discard. Root penetration and development was limited to the upper 100 mm at the severely compacted covers at D2-S4 and D2-S5, even though the covers were constructed with sufficiently thick growth medium and with suitable growth medium material. This is due to the shallow compacted layer at 100 mm limiting root penetration.

4.2.2 Cover layer characterisation

Steenekamp (2018) described the cover layers in terms of material properties, such as thickness, morphological characteristics (colour, structure, field-estimated texture), and the condition of layers that relate to cover performance, such as compaction, root penetration and development and extent of cracks. The cover layers and properties are shown Appendix A for the various covers.

The extent, size and/or spatial distribution of preferential flow paths through desiccation cracks and channels of dead roots and burrow insects were photographed, if present. The distribution, density and patterns of the photographed preferential flow paths were further analysed in office in a similar manner to that described for root development. A lateral plain crack, fine cracks around concretions, and vertical (tension) cracks through severely compacted layers are shown in Photo 7 to Photo 10.

Photo 1: Dump 1 from crest of Dump 2

Photo 2: Dump 3

Photo 3: Site D1-S1 at crest of Dump 1

Photo 4: Site D1-S3 at Dump 1 (at drums)

Photo 5: Site D2-S5 at Dump 2 (at test pit)

Photo 6: Site D3-S6 at Dump 3 (at oxygen tube

Table 4-1: Cover characteristics

Facility	Research site				Soil cover		Vegetation		
	Name	Surface conditions			Thickness (mm)	Compaction	Root		Cover
		Erosion	Crust/ seal	Cracks			Depth (mm)	Occurrence	
Dump 1	D1-S1	Some sheet erosion between grass tussocks	Weak	None	900	Slight to moderate	900	Many to common	Good
	D1-S2				600	Moderate to high	600	Common to few	
	D1-S3				550		550		
Dump 2	D2-S4	Sheet erosion between grass tussocks	Weak	None	1150	High to severe	*100*	Few to none	Good to fair
	D2-S5	Severe sheet erosion with rills at localised runoff areas	Moderate		700			Very few to none	Poor
Dump 3	D3-S6	Some sheet erosion between grass tussocks	Weak	None	900	Slight to moderate	550+	Many to common	Good
	D3-S7				800		450+		

Note: Cover profiles and condition were described by Steenekamp (2018).

Photo 7: Vertical (tension) cracks in compacted layers in the cover at site D2-S4.

Note: Severely compacted layers wont function as low permeability barrier layer due to preferential flows through vertical (tension) cracks. Limited plant transpiration will occur as almost no roots have penetrated or developed in severely compacted layers.

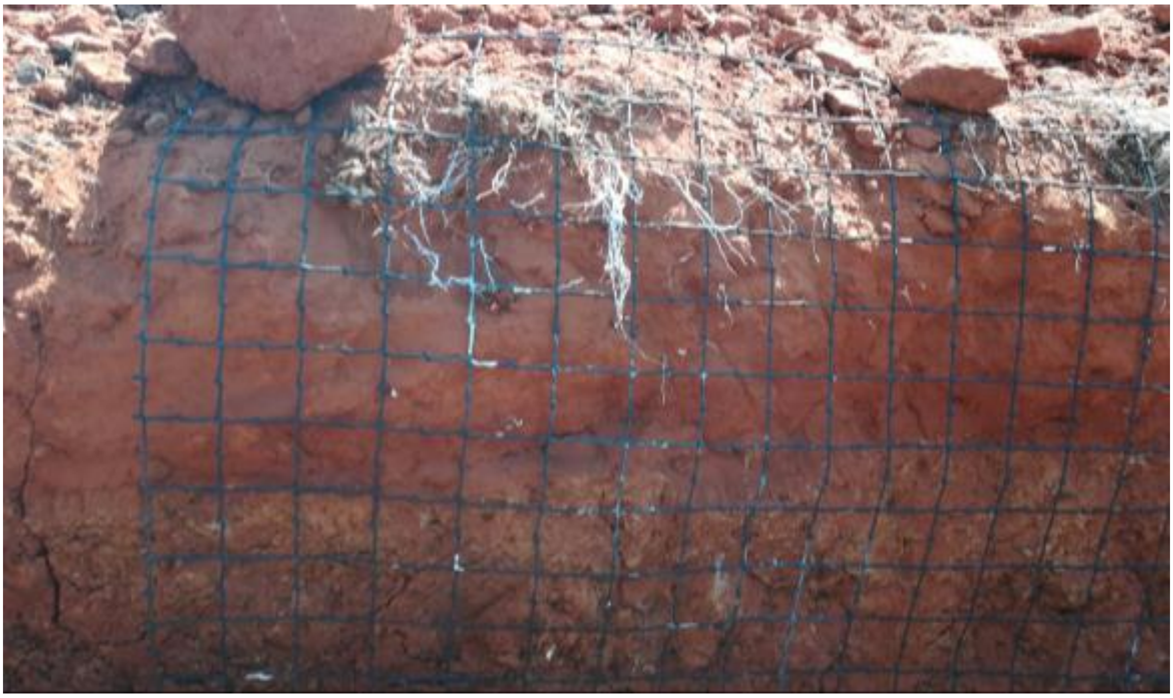


Photo 8: Vertical and lateral cracks in compacted layers in the cover at site D2-S5.

Note: Severely compacted layers won't effectively function as low-permeability barrier layer due to preferential flows through vertical (tension) and lateral cracks. Little moisture loss through plant transpiration will occur as no roots have penetrated compacted layers.

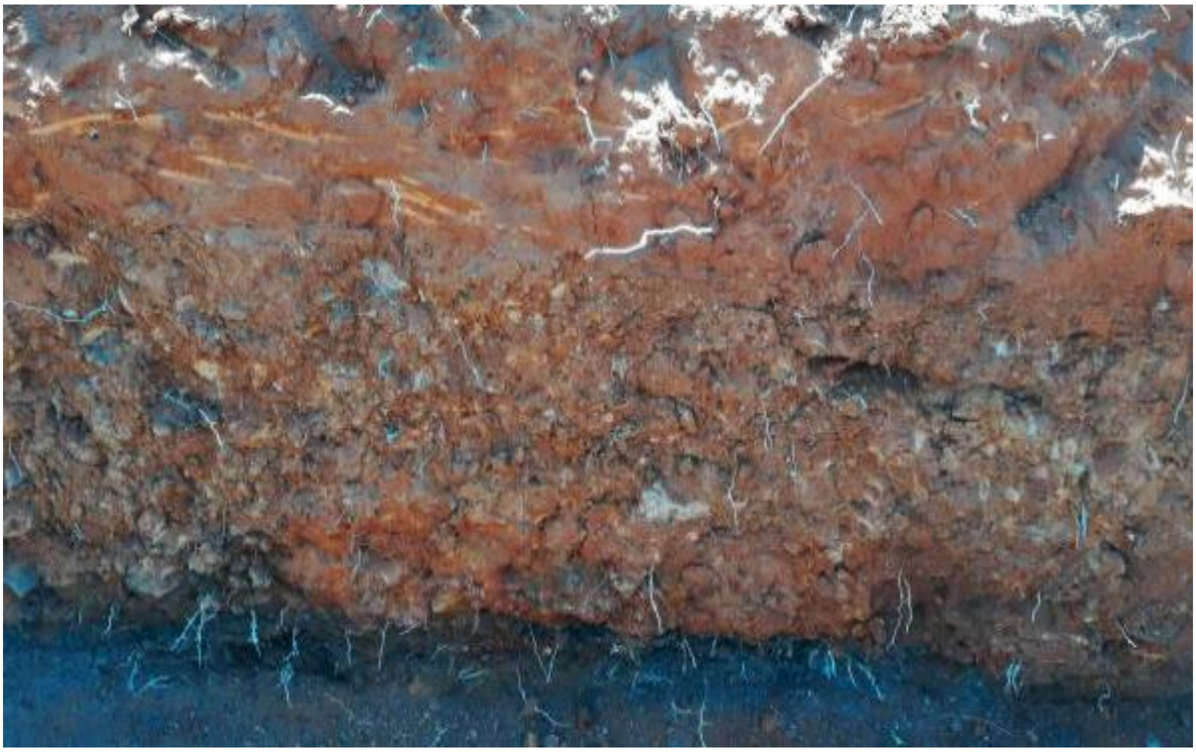


Photo 9: Fine cracks around concretions and weakly structured clayey layer.

Note: Higher saturated flows expected through fine cracks that act as preferential flow paths. 2nd Layer will not effectively function as a low-permeability barrier layer for downward water flow but might have some moisture retention function.

4.2.3 Root development

Visible roots were marked with white PVA and photographed against a grid pattern on the profile of pit walls. The photographed root distribution and densities were further analysed in office. The root development for selected pits is shown in Appendix A.

4.2.4 Sampling

Disturbed samples were collected from each cover layer and sent for laboratory tests on soil physical tests, soil fertility and chemical analyses and tests on selected geotechnical properties.

Core samples were collected from the cover layers and discard to determine bulk density, and water retention curves for intact material. Water retention curves were determined on intact material to account for the effect of bulk density (compaction) and structure since the curves may differ considerably between intact material and disturbed material remoulded in the lab.

4.2.5 In-field permeability tests

In-field infiltrometer data for mature covers, where the effect of cover aging on permeability has been determined *in situ*, is not readily available in South Africa. It was, therefore, imperative to determine saturated hydraulic conductivity (K_{sat}) from in-field infiltrometer tests of intact layers of mature covers to provide key data needed for the research project.

Infiltrometer tests were conducted on the growth medium, cover layers and discard immediately below the cover. The tests include three sets of infiltrometers, namely:

- Standard double ring infiltrometer with an inner ring of 30 cm and outer ring of 60 cm diameter,
- Large diameter ring infiltrometer with an inner ring of 60 cm and outer ring of 90 cm diameter; and
- Single ring infiltrometer with a 60 cm diameter.

The rings were placed and sealed with bentonite clay powder. No vegetation was removed for the infiltrometer tests at the surface. The growth medium and underlying cover layer were removed by hand digging to expose the layer below the growth medium and the discard below the cover respectively to conduct the infiltrometer tests (Photo 10 and Photo 11). Constant head permeameter tests were conducted at selected sites. The K_{sat} values that were calculated from the infiltrometer tests are summarised in Appendix B.

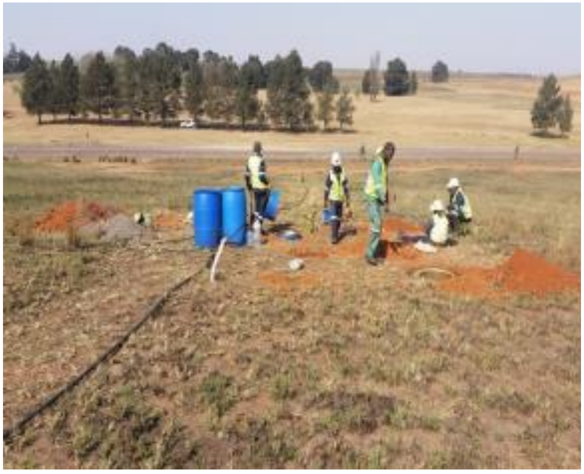


Photo 10: Setting up infiltrometer tests

Photo 11: Conducting infiltrometer tests

4.2.6 Tension infiltrometer tests (unsaturated hydraulic conductivity)

Mini-disc infiltrometer tests were conducted for various cover layers to determine the *in-situ*, near saturated and unsaturated hydraulic conductivities at various low matrix suction ranges. The ceramic disk of the Minidisk infiltrometer was placed at the site of a ring infiltrometer test to conduct the disk infiltrometer test before the ring infiltrometer test was conducted. Typical suction ranges of 0.5, 1, 2, 3 and 5 kPa suction were used. A Mini-disc infiltrometer tests is shown in Photo 12.

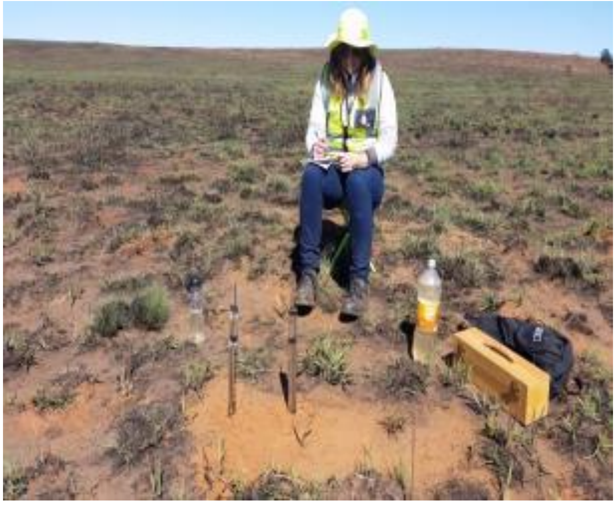


Photo 12: Unsaturated permeability tests using mini-disks

4.2.7 Oxygen concentration monitoring

Monitoring tubes were installed at the research sites to measure the percentage of oxygen concentration on a bi-monthly basis from February 2018 till February 2019 with a portable oxygen probe. The installation of the oxygen monitoring nests and measurements are shown in Photo 13 and Photo 14.

Photo 13: Install oxygen monitoring nest

Photo 14: Measure oxygen concentrations

Noticeable decline in oxygen concentration occurred with depth in the thick soil covers (>50 cm) with progression of the rainy season. The lower oxygen ingress relates to less expected oxidation in the discard and therefore, if seepage occurs, lower AMD seepage can be expected. However, the monitored oxygen concentrations confirm international research that the climate of the Mpumalanga Highveld coalfield is too dry for soil covers to function as oxygen ingress limiting covers and that the focus should be on minimising rainwater ingress to mitigate AMD.

4.2.8 Leaf area index and biomass

Above-ground vegetation is collected on a bi-monthly basis during the growth season from grass clippings from a 1 m^2 plot at each monitoring site. The grass clippings are used to determine the photosynthetic active (required to predict plant transpiration) and dead leaf area and vegetation biomass in the laboratory. Collection and measurement of grass clippings are shown in Photo 15 to Photo 18. Moderate to relatively low photosynthetic active (green) leaf area indices were measured.

Photo 15: Vegetation cover at Site D1-S2

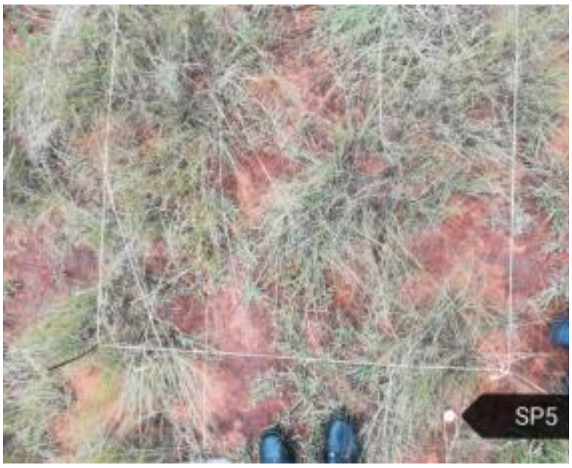


Photo 16: Vegetation cover at Site D2-S5

Photo 17: Vegetation clippings in test grid

Photo 18: Leaf surface area meter

4.3 Laboratory tests

4.3.1 Texture

A detailed particle size analysis was conducted that includes 8 soil particle sizes (very coarse, coarse, medium, fine- and very fine sand, coarse and fine, and clay) and 4 gravel particle sizes (very fine, fine, medium, and coarse gravel). The particle size distributions and soil texture of the various cover layers are summarised in Appendix B.

The rating of the effect of particle size on cover performance is summarised in *Table 20*.

Table 4-2: Effect of particle size distribution on cover performance

<table>
<tr><th rowspan="2"></th><th colspan="5">Effect on cover performance</th></tr>
<tr><th>Plant nutrient retention</th><th>Rain infiltration</th><th>Moisture retention & storage</th><th>Moisture ingress</th><th>Oxygen ingress</th></tr>
<tr><td>Clay</td><td>Increase considerably</td><td>Reduce considerably</td><td rowspan="2">Increase considerably</td><td rowspan="2">Reduce considerably</td><td>Reduce considerably</td></tr>
<tr><td>Silt</td><td>Increase</td><td>Reduce</td><td>Reduce</td></tr>
<tr><td>Fine and very fine sand</td><td>Reduce</td><td>Increase</td><td>Increase</td><td>Reduce</td><td>Increase</td></tr>
<tr><td>Coarse and medium sand</td><td rowspan="2">Reduce considerably</td><td>Increase considerably</td><td>Reduce</td><td>Increase</td><td rowspan="2">Increase considerably</td></tr>
<tr><td>Gravel/rock</td><td>Increase exponential for >30% gravel</td><td>Reduce considerably</td><td>Increase considerably</td></tr>
</table>

The soil texture of the growth media varies between loamy sand and sandy clay loam, but is mostly sandy loam which is the preferred texture for a growth medium. The soil texture of the water retention (2nd) layers at Dump 1 and Dump 2 is sandy clay loam and sandy clay which is suitable for a water retention layer. The soil texture at the Dump 3 is loamy sand for the growth medium and sandy loam for the moisture retention layer, which is marginally suitable texture due to a higher sand fraction.

4.3.2 Volume-mass properties

The dry densities, porosities and void ratios determined from intact core samples collected from the various cover layers are summarised in Appendix B. The Atterberg limits and associated derived limits are also summarised in Appendix B.

Acceptable bulk densities for root development were determined for Dump 1 and Dump 3. This is confirmed by the field investigation study that root development occurs mostly throughout these covers. High bulk densities were determined for Dump 2. The high dry densities indicate that root penetration is limited, which is confirmed by the field investigation study that root penetration is limited to the upper 100 mm.

The plasticity index for the growth medium and moisture retention layers was rated as slightly- to medium plastic, except for the (more clayey) sandy clay layers at the D1-S1 and D2-S5 sites. These sandy clay layers also marginally exceed the plasticity index guideline of 18 specified in the Minimum Requirements (DWAF, 1998) for a compacted clay layer in a landfill cap (soil cover).

The swell/heave potential was rated as low for the growth media, but low to medium for the water retention layers. The clay activity was rated as inactive indicating a low fraction of swelling clays. The swell/heave and clay activity indices indicate that the orthic and apedale soil horizons are suitable materials for covers due to the low probability for desiccation crack development and associated preferential flows through the cracks.

4.3.3 Hydraulic properties

The *water retention curve (WRC)* is central to the application of unsaturated flow models to predict net cover percolation and rainwater ingress into the discard. The characteristics of a WRC that are used for unsaturated flow modelling is summarised in Appendix C.

The water retention characteristics of the sandy cover materials are significantly different to cover materials with higher clay content, such as those with a sandy clay loam and sandy clay texture. This includes higher saturated- and residual water contents and air entry values for the more clayey materials compared to the sandy materials, and a more gradual slope in the desaturation function for clay materials compared to sandy materials. This indicates that the more clayey textured layers are suitable for a water retention layer.

Compaction has a marked effect on the sandier growth mediums. The effect on the more clayey water retention layers is less significant. The effects of compaction include increased air entry values, slope of the desaturation functions that become more gradual, which relates to higher water retention and capillary potential and lower related rainwater ingress rates. However, the saturated water content is noticeably lower resulting in lower water storage capacity of a cover.

The *hydraulic conductivity function* describes the material's ability to conduct water under saturated and unsaturated conditions, and is a measure on how the hydraulic conductivity decreases as more pores become air-filled when an initial saturated material desaturates (dries). Closed-form solution methods were applied to the laboratory determined water retention curve and in-field determined K_{sat} of the respective materials to predict the unsaturated hydraulic conductivity (K_{unsat}) required for model input since measuring K_{unsat} is a time-consuming and expensive procedure that requires specialised laboratory equipment.

The cover layers have a K_{sat} of $>1x10^{-6}$ cm/s specified by DWAF (1998) for a compacted clay layer as a barrier layer in a cap (cover), except for one highly compacted layers in covers at the D2-S5 and D2-S4 sites which marginally meet this criterion.

Reduction in K_{sat} for highly compacted cover layers at Dump 2 is lower than expected. This may be ascribed to preferential flows through vertical (tension) cracks in the compacted cover layers observed during the field investigation. K_{sat} determined from samples remoulded to these compacted densities could be more than an order of magnitude lower as it only accounts for flows through soil matrix and not through cracks.

The determined K_{sat} for water retention layers is favourable for this layer according to Vermaak *et al*. (2004) that should be between 10^{-4} and 10^{-6} cm/s. The K_{unsat} becomes too low for required upward capillary rise of (deep) infiltrated rain for plant transpiration and evaporation when the K_{sat} decreases below 10^{-6} cm/s.

4.4 Laboratory analyses

4.4.1 Soil fertility and chemistry

Optimum soil fertility and chemical conditions are important to promote vigorous vegetation growth and maximise plant transpiration while minimising rainwater ingress rates. The soil analytical results for the various growth media are summarised in Appendix B.

Optimum soil fertility levels were determined at Dump 1 and Dump 3. This indicates that sufficient phosphorus and potassium fertilizers were applied prior to vegetation establishment to increase low levels to near-optimum conditions, and that maintenance doses of fertilizer containing phosphorus, potassium and zinc were applied over a reasonable period after vegetation establishment. The pH is acidic to slightly acid and is within optimum levels for grasses at Dump 2 and Dump 3. Consequently, soil pH is not a limiting factor to plant nutrient availability and uptake. Electrical conductivity (EC), an indicator of salt content of a material, indicates low water-soluble salt concentrations and no salinity effect on plant growth.

Elevated water soluble SO_4 concentration was determined for the highly compacted cover at site D2-S5 research site. This indicates that the highly compacted cover is impacted by upward movement of water soluble SO_4 from the sulphide containing discard through capillary rise. This is also confirmed by the considerably elevated acid saturation at the site, indicating upward movement of acid from the discard through capillary rise.

4.4.2 Geochemistry

Two discard samples each were collected from Dump 1 ad Dump 2 immediately below the soil cover (water retention layers) as mechanical drilling into the facilities was beyond the scope of the project. The samples were prepared and submitted for geochemical testing. The geochemical analytical results are summarised in Appendix D.

From the mineralogy and elemental investigation, it is evident that the discard sampled from Dump 2 has experienced significant weathering and therefore has more secondary minerals than the samples from Dump 1. The weathering depth in the dumps is uncertain as no samples were obtained from deeper depths in the dumps.

The Acid-base test results indicates that discard samples from both Dump 1 and Dump 2 have a high potential to generate acidic drainage as samples from both facilities have high sulphide content and no neutralisation potential to buffer any acid generation. These samples will therefore generate acidic drainage over the long-term if exposed to oxidation.

4.5 Lessons from field investigation and laboratory testing

The following important lessons were learned from the field investigation and laboratory tests:

- No surface cracks were observed for growth media that is constructed from apedal B- and A-soil horizons. This can be ascribed to the massive and weak soil structure of these soil horizons that have a low risk for desiccation crack development. The plasticity index for these soils were rated as slightly to medium plastic, and the swell/heave potential was rated low to medium, except for the (more clayey) sandy clay layers. Consequently, cover layers constructed from apedal B and orthic A soil horizons have a low risk for preferential flows and associated increased cover percolation and rainwater ingress rates into the discard;

- Root depth, distribution and development show a close inverse relationship with extent of compaction. Root development occurs throughout the cover of the moderately dense covers, whereas root penetration was limited to the upper 70-100 mm at highly compacted covers. The 70-100 mm relates mainly to the depth of seedbed preparation that resulted in a lower bulk density that is favourable for root development. The shallow root development and poor vegetation cover (with low leaf area) relates to low plant water uptake and associated moisture losses of infiltrated rain through plant transpiration required for lower cover percolation rates;
- Reduction in K_{sat} for highly compacted cover layers is lower than expected. This may be ascribed to preferential flows through (tension) cracks in the compacted cover layers that were observed during the field investigation. K_{sat} determined from samples remoulded to these compacted densities could be more than an order of magnitude lower as it only accounts for flows through soil matrix and not through cracks. This will result in an over-optimistic predicted cover percolation, rainwater ingress and seepage rates if higher rain infiltration through these cracks are not accounted from;
- The determined K_{sat} of highly compacted layers does not meet the in-field K_{sat} for a barrier layer, except for one layer which only marginally meet this criterion. This further confirms that a lower reduction in K_{sat} for highly compacted layers can be expected for mature covers, as confirmed by international studies;
- Elevated water soluble SO_4 concentration was determined for highly compacted cover, which indicates that this cover is impacted by upward movement of water soluble SO_4 from the sulphide containing discard through capillary rise. This is also confirmed by the considerably elevated acid saturation in the cover. This may be ascribed to an increase in the capillary potential with compaction;
- The monitored oxygen concentrations confirm international research that the climate of the Mpumalanga Highveld coalfield is too dry for soil covers to function as oxygen ingress limiting covers, even though noticeable decline in oxygen concentration occurred with depth in the thick soil covers (>50 cm) with progression of the rainy season. Consequently, the focus should be on minimising rainwater ingress with soil covers to mitigate AMD.

5. MODELLING OF INVESTIGATED COVERS

5.1 Unsaturated flow modelling

5.1.1 Modelling approach

An unsaturated flow, also referred to as cover water balance, numerical model was applied to predict net cover percolation rates for the investigated covers as a function of:

- *Climatic conditions* of research sites such as precipitation, rain distribution and climate;
- *Cover configuration* (cover type, layer thickness) of the investigated covers;
- *Material hydraulic properties* determined for the growth media, underlying water retention layer and discard;
- *Vegetation characteristics* such as the seasonal distribution in photosynthetic active leaf areas for plant transpiration, inter-annual variability in vegetative vigour to account for moisture availability during dry, average rainfall and wet years and standard of rehabilitation on vegetative vigour.

The predicted cover percolation rates represent the net infiltration or rainwater ingress rates into the discard after rain interception of vegetation, runoff and rain infiltration, evaporation, plant transpiration and changes in the water storage of the cover and upper metre of coal discard have been accounted for. The modelling capabilities required from an unsaturated flow model to simulate key processes on cover percolation are discussed in Part B of report.

5.1.2 Model input data

A climate dataset of daily recorded meteorological data was prepared for model input. The climate dataset was prepared from daily recorded data to conserve the relation between daily rain and the other climatic variables, and to account for the effect of rainfall distribution such as consecutive days of rainfall.

Potential evaporation was calculated from the Penman-Monteith equation. The Penman-Monteith calculated reference evapotranspiration (Et0) represents the atmospheric demand for evapotranspiration from vegetated surfaces and is more applicable to soil covers than potential evaporation measured from water surfaces such as S-pan or A-pan.

The annual distribution in precipitation was determined for a 90-year rainfall record from raingauges near the study area with long-term rainfall records. The daily rain of the prepared climate dataset was adjusted so that the annual precipitation distribution matched the annual precipitation distribution of the 90-year rainfall record to accounts for the effect of extreme rain events and periods when daily rainfall exceeds evaporation for consecutive days.

The cover profiles that were simulated are shown in Photo 20 to Photo 24.

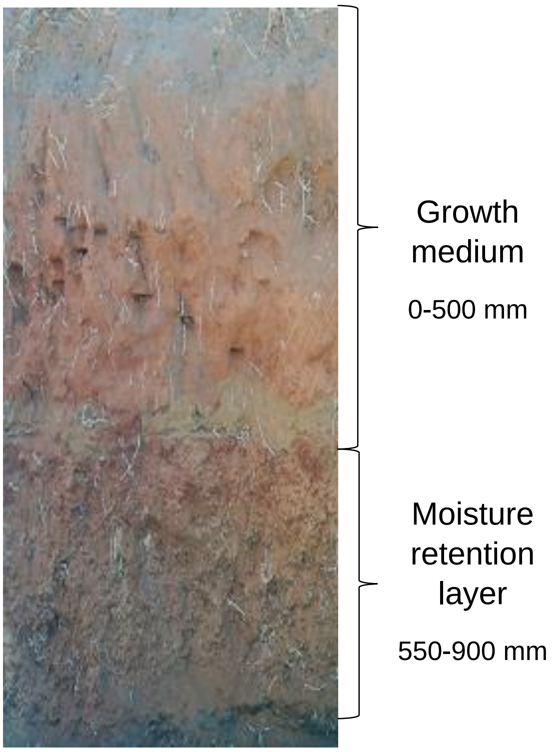


Photo 20: Cover profile of site D1-S1

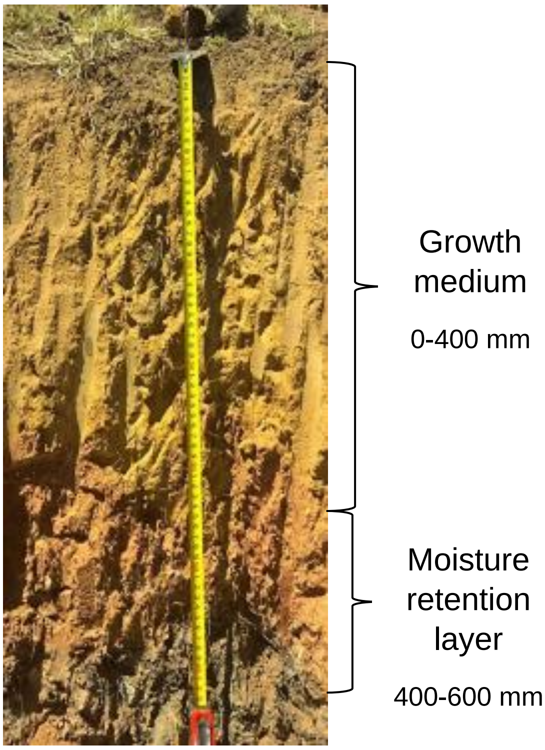


Photo 21: Soil cover profile of D1-S2

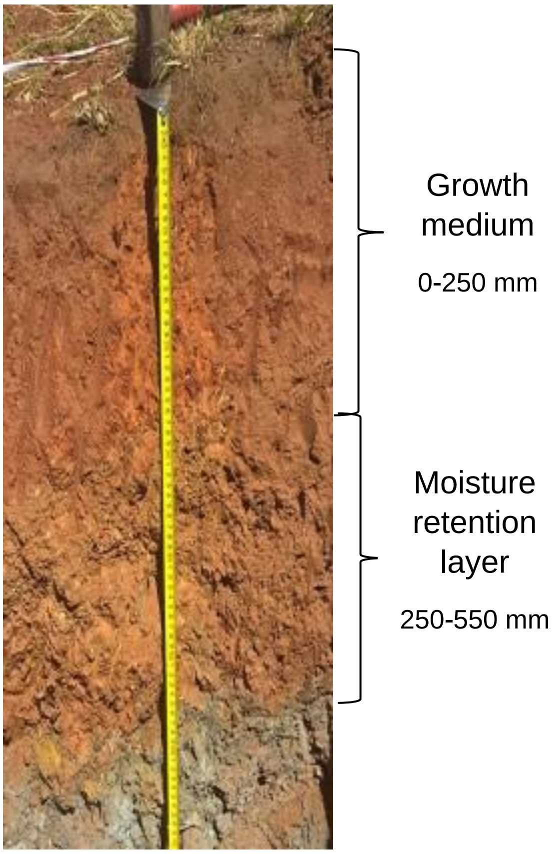


Photo 22: Soil cover profile of D1-S3

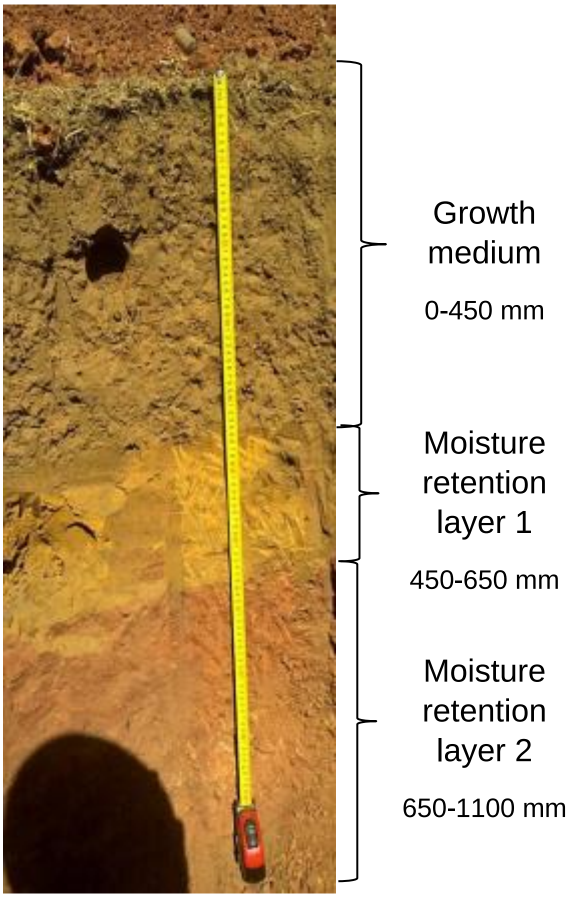


Photo 23: Soil cover profile of D2-S4

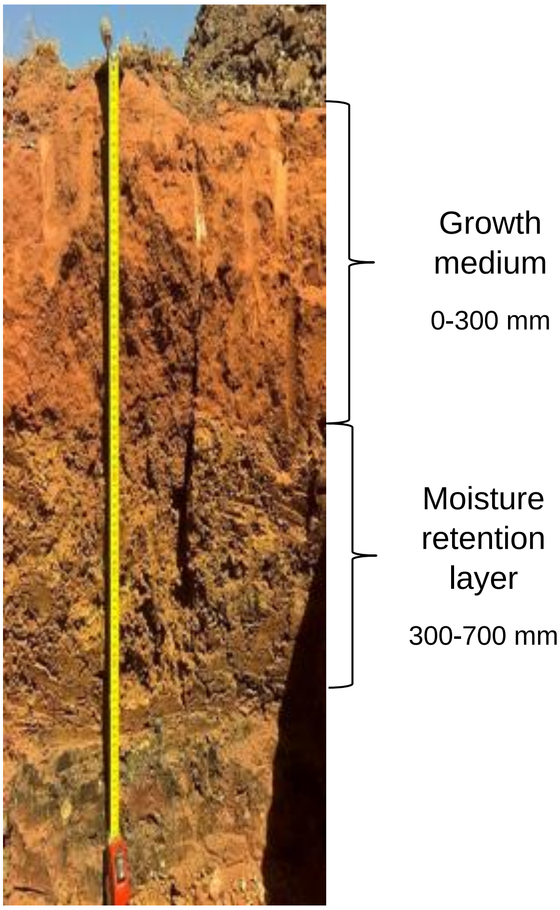


Photo 24: Soil cover profile of D2-S5

An unsaturated flow model requires the following material property functions:

- *Water retention curve* which describes a material's ability to water balance moisture as the material desaturates and the capillary potential of the material; and
- *Hydraulic conductivity function* which describes a material's ability to conduct water under saturated and unsaturated conditions.

Material hydraulic properties were determined for each soil cover layer and for the upper layer (0.3-0.5 m) of underlying discard. Water retention curves were determined from laboratory determined water retentivities of intact core samples collected from each cover layer and discard. The water retention curves were determined by applying the Fredlund and Zing (1994) closed-form solution method to the laboratory determined water retentivities. The hydraulic conductivity function (K_{unsat}) for the cover materials and underlying discard were defined by applying the Fredlund and Zing (1994) closed-form solution method to the water retention curve and K_{sat} values of the respective materials.

The leaf area indices (LAI) used for model input are based on the seasonal leaf area and biomass data collected at the research sites for the 2017/2018 and 2018/2019 growing seasons. Three sets of LAIs were used to represent the grasses with low, fair and high LAI. The root depths applied as model input are based on the root development observations made in tests pits.

5.1.3 Model assumptions and limitations

The assumptions on which the unsaturated flow modelling was based are:

- Water retention and permeability of intact cover materials are governed by the particle size distribution and not by clods or cracks. The effect of preferential flows through the development of soil structure and desiccation cracks were accounted for in the modelling through measured in-field saturated hydraulic conductivities and associated hydraulic conductivity function. Although fine isolated cracks were observed in the highly compacted covers, moderately dense cover materials are not prone to the development of (moderate to strong) soil structure and have a low risk for increased percolation rates associated with preferential flows through desiccation cracks;
- The effect of a decreasing cover thickness due to erosion on cover percolation rates is not accounted for;
- The effect of pedogenesis on covers was accounted for as material hydraulic properties that were determined from in-field tests and laboratory tests conducted on intact core samples from the mature covers. Covers can be viewed as mature and have been exposed to climatic conditions on site for long enough that the process of pedogenesis can be considered complete;
- Impact of burrow animals were not accounted for.

5.1.4 Predicted net cover percolation

The predicted net percolation rates through the covers investigated are summarised in Table 5-1. The predicted cover percolation rates represent the net infiltration into the discard after runoff, evaporation, plant transpiration and changes in the cover soil-moisture storage have been considered. According to Vermaak *et al.* (2004), the design of rainwater ingress limiting covers should aim to reduce percolation rates to typically 5% of MAP for semi-arid climates.

Table 5-1: Predicted net cover percolation

Research site	Cover thickness	Soil texture of cover layers	Vegetation condition	Predicted cover percolation (% of MAP)	
				Mean annual	90th Percentile
D1-S1	90 cm	SaCL-SaC	Poor	4.9	8.1
			Fair	2.7	4.1
			Good	1.4	2.0
D1-S2	70 cm	SaL-SaCL	Poor	9.2	13.4
			Fair	7.3	9.5
			Good	5.7	7.1
D1-S3	60 cm	SaCL-SaC	Poor	11.8	18.8
			Fair	8.6	13.4
			Good	6.0	8.2
D2-S2	60 cm	Compacted SaCL-SaC	Poor	6.3	10.6
			Fair	4.3	6.6
			Good	3.3	5.4

Predicted percolation rates at the 90th percentile is significantly higher than the mean annual values. Significantly higher percolations rates are predicted for wet years that include a series of consecutive rainy days, cloudy conditions and low potential evaporation rates. The skewed distribution of cover percolation rates indicates that total percolation is mainly determined by the wettest years.

The target acceptable value of 5% of MAP for semi-arid climates can be achieved for 90 cm and thicker covers with sandy clay loam or sandy clay water retention layer (2nd layer) and root development throughout the cover. The target value can also be achieved for the highly compacted cover if good vegetation conditions can be achieved.

Mean annual net percolation rates with poor vegetation conditions exceed target rates, except for the 90 cm thick covers. This emphasises the importance of vegetative vigour and high leaf area indices to maximise plant transpiration with the aim of minimising moisture ingress rates and groundwater impacts.

It should be noted that seepage rates at the base of discard facilities is attenuated by water retention within the discard material. Seepage reporting to drains, or seeping from the base of the discard facility, will display significant less variability about long-term average percolation rates predicted for the cover percolation rates.

5.2 Geochemical modelling

5.2.1 General mine drainage classification

In general, drainage from disturbed geological material at mines is classified into three types, namely: Acid Mine Drainage (AMD), Saline Mine Drainage (SMD) or Neutral Mine Drainage (NMD). AMD occurs when a significant degree of pyrite oxidation is present with inadequate neutralising effect from other (especially carbonate) minerals in the rock. With AMD, the pH typically remains below 5.5-6.0, often with a high to very high saline drainage. SMD also results from significant sulphide oxidation, although a significant carbonate content is present in the rock to maintain circumneutral conditions. Drainage typically has a pH above 5.5-6.0 with a medium to high saline and metal load. Some metals with amphoteric behaviour may however still be elevated in mine drainage.

With NMD, low or no sulphide oxidation occurs, and adequate carbonate minerals are present in the rock to maintain circumneutral drainage. Drainage typically has a pH above 5.5-6 with a low saline and no/low metal load. Some metals with amphoteric actions may however still be present.

In Figure 5-1 the different fields for mine drainage are plotted on a TDS vs. pH diagram. AMD is present below pH 5.5-6 and saline and neutral mine drainage above that. The boundary between fresh and saline water is arbitrary and the US Geological Survey reports the boundary at a TDS concentration of 1 000 mg/l.

The impact on drainage at a mine depends on the interaction between the solid, water and air phases. The drainage quality is a function of the dissolution and reactivity of the minerals, the relative degree of acidification and neutralisation, and the interaction of minerals with oxygen and water.

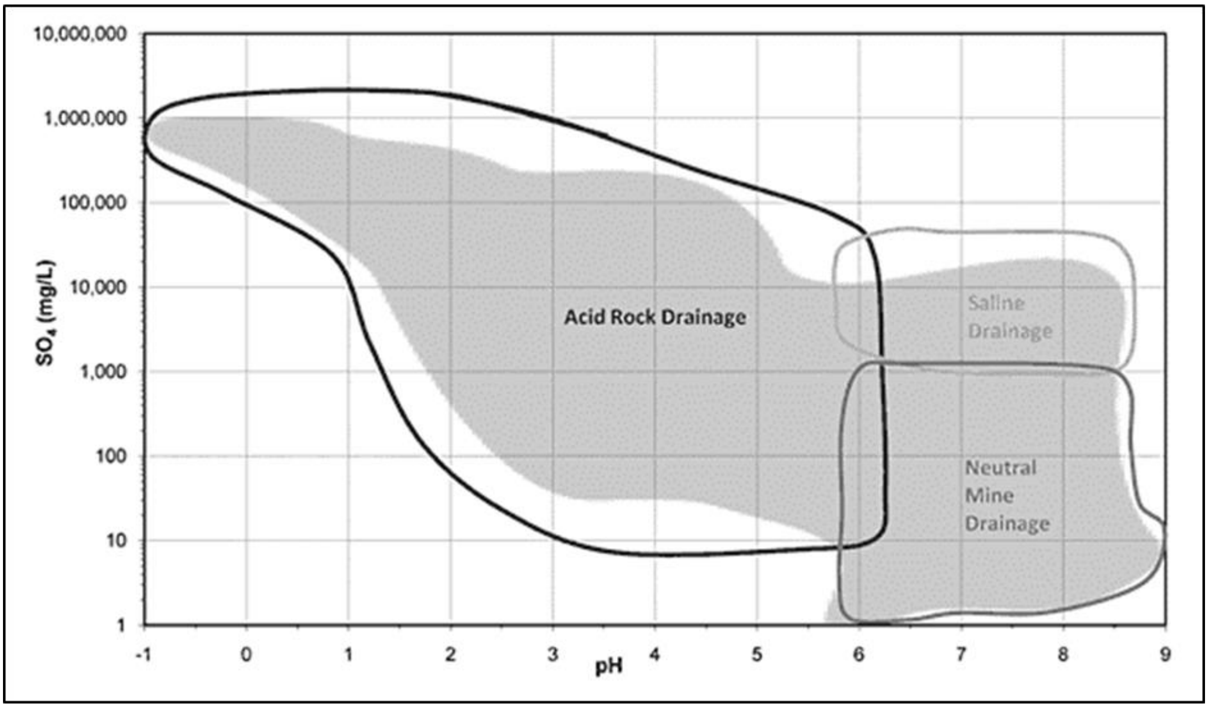


Figure 5-1: Diagram showing mine drainage as a function of pH and TDS[1]

[1.] *INAP, 2009 – adapted from Plumlee, 1999.*

Disturbed geological material with a high pyrite content (that is also in contact with oxygen) will typically generate a high sulphate load. Whether the drainage will be acidic or saline depends on the presence of neutralisation minerals. However, if the mining area is sealed off from the atmosphere (e.g. through flooding) before acidification occurs, then no oxygen ingress is possible with no resultant oxidation of sulphides and the mine will then produce saline or neutral mine drainage. Disturbed geological material with no pyrite content usually generates neutral drainage. However, amphoteric metals may form soluble complexes which can potentially leach from geological materials under neutral conditions, for example Al, Cd, Cr and U.

5.2.2 Impact mechanism

Consumption of oxygen in a mine residue dump will result in a gradient in the oxygen fugacity (Figure5-2) that initiates oxygen diffusion (flow from high concentration to low concentration). The oxygen concentration will be at its highest in material directly in contact with the atmosphere and due to its consumption, the oxygen concentration will gradually become depleted within only a few meters. Initially, only the upper part of the material will be situated in the oxygenated zone and the oxidation front will shift deeper into the material as sulphide minerals are depleted.

According to the shrinking core model of Ritchie and Davis (1986), oxygen diffusion takes place through the pore spaces of the mine residues followed by diffusion into a moving reaction front within the particles. In other words, the front of the oxidation zone is at the reaction front within the pyrite grains and no sharp oxidation front is present in mine residue itself (which will result in the presence of a transitional zone). Fully oxidized pyrite remnants will be present at the top of the oxic zone, partially oxidized pyrite deeper down, with unoxidized pyrite grains present only in the anoxic zone.

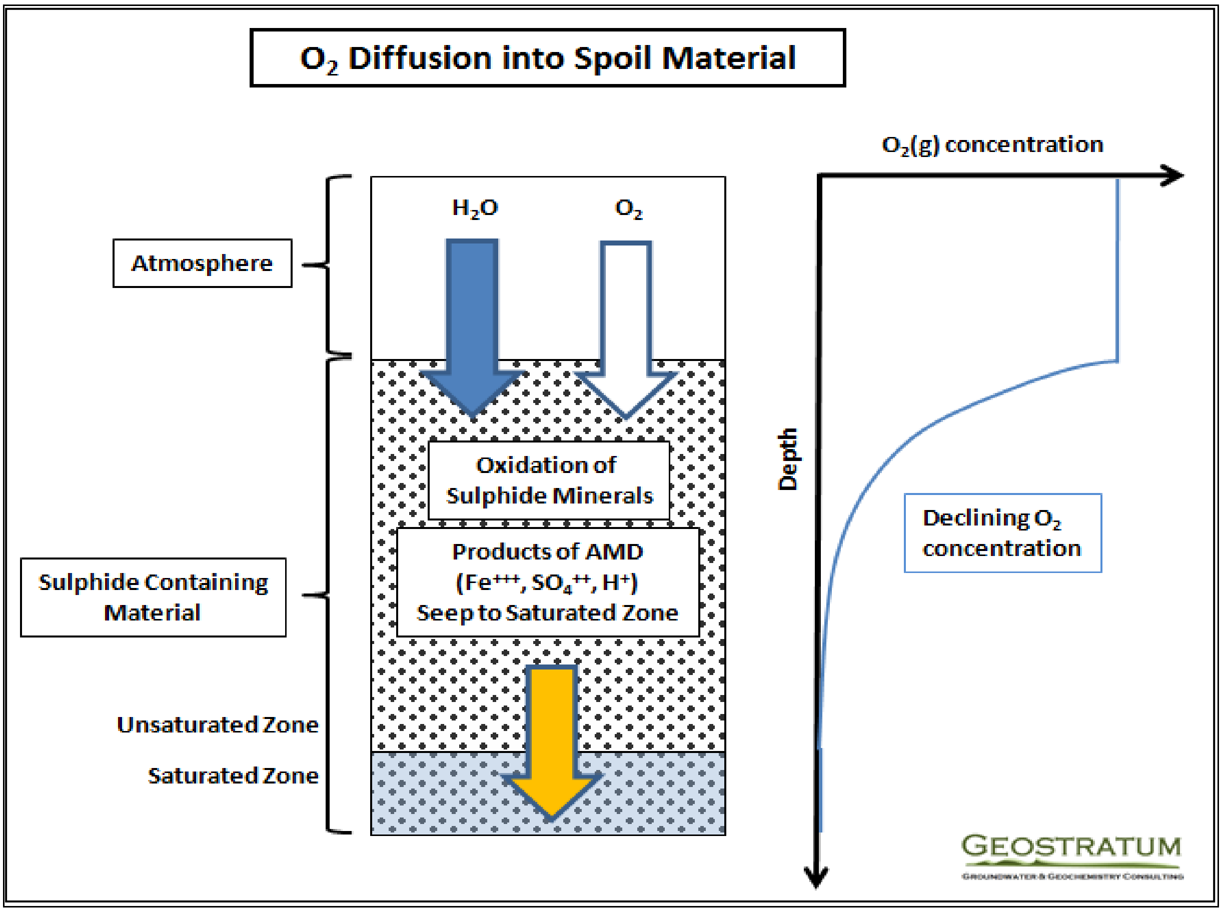


Figure 5-2: Oxygen infiltration and subsequent sulphide oxidation in mine residue

The mine residue is comprised of a solid, water and gas phase. Without one of these phases present, no AMD production is possible. The rock material (solid phase) is the reactive part of the three phases and contains sulphide minerals that react spontaneously with oxygen and water.

Upon oxidation, pyrite will react with ingressed oxygen and water to produce Fe^3, SO_4 and acidity:

$$\text{Pyrite} + 3.5H_2O + 3.75O_{2(aq)} = Fe(OH)_{3(ppd)} + 2SO_4 + 4H$$

Water serves as the transport medium for the products of AMD as it percolates through the rock material. The water phase also serves as the medium in which dissolution of neutralizing minerals can take place. The acid produced by the pyrite will be consumed by calcite (and/or dolomite) if present in the rock:

$$\text{Calcite} + 2H = Ca^2 + CO_{2(g)} + H_2O$$

The Ca^{2+} and SO_4^{2-} produced will form gypsum and the above equations could be rewritten as follows:

$$\text{Pyrite} + 2\text{calcite} + 5.5H_2O + 3.75O_{2(aq)} = Fe(OH)_{3(ppd)} + 2\text{gypsum} + 2CO_{2(g)}$$

If all the carbonate minerals (generally, calcite and dolomite in the Vryheid Formation) are depleted, the seepage from the material becomes acidic. Silicate minerals can also consume some of the acidity. However, silicate minerals react too slowly to prevent acidification in a material with significant acid generation potential. Metals will also leach in acidic seepage at elevated concentrations and the final stage of AMD would have been reached.

An important aspect in the environmental geochemical modelling of mine residue is, therefore, to determine whether enough neutralization minerals are present, and if so, when they will become depleted. It is not possible to determine the timescale for these mineral reactions from laboratory tests. Even with leach tests neutralization minerals are often not depleted and the tests also do not have the same rock/water/gas ratio as actual conditions at the mine. Numerical kinetic modelling provides the only possible means to model the rock, water and gas phases and to add a time scale to the problem.

5.2.3 Numerical geochemical modelling

The objective of the geochemical modelling was to predict oxygen ingress into the coal discard dumps as well as the subsequent pyrite oxidation and interstitial water quality. Oxygen ingress was predicted using the modelled soil cover properties calibrated with the field observations.

Analytical results cannot be used directly to establish the changes in the leachate quality from a mine over time. Due to the complexity in the interaction between the solid, water and gas phases, numerical modelling was used to predict the most important parameters of expected Acid Mine Drainage (AMD).

The oxygen diffusion into the backfill was modelled using a customized code developed in Python 3. The code models 1) the diffusion of oxygen through the unsaturated zone, 2) the oxygen consumed by mineral oxidation, and 3) the subsequent sulphate, iron and acidity production.

The interaction between the mineral-, water- and the gas phases was modelled using the Geochemist's Workbench Professional. The Geochemist's Workbench is a set of interactive software tools for solving problems in aqueous geochemistry. This model solves the hydro-chemical and mineral reactions with the equilibrium model as well as the kinetic rate law for mineral dissolution.

Seven models were compiled as summarized in Table 5-2. Oxygen ingress was modelled for each site using the modelled soil cover properties. In order to compare the effectiveness of the soil cover to minimise pyrite oxidation, a reactive geochemical model was performed using the oxygen diffusion results as input.

In order to compare the effect of the soil covers on the pyrite oxidation and interstitial water quality in the underlying coal discard, the same physical and geochemical properties of the discard were defined in all the models.

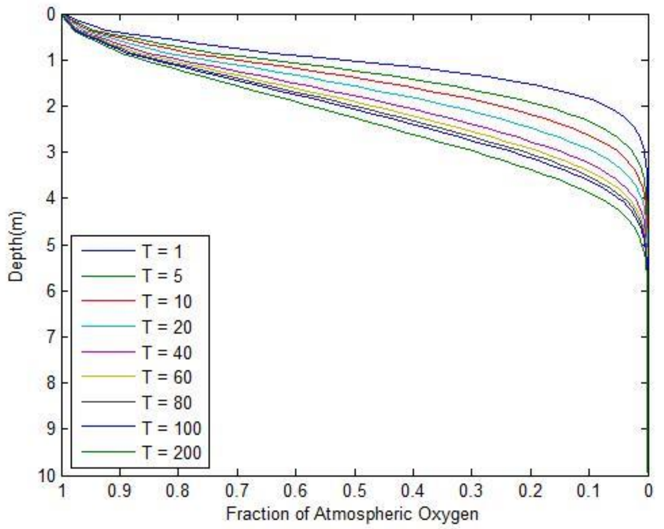
The vertical extent of the models was 30 m. The mineralogical content comprised of quartz and kaolinite with traces of muscovite, pyrite, calcite and dolomite.

Table5-2: Geochemical modelling scenarios

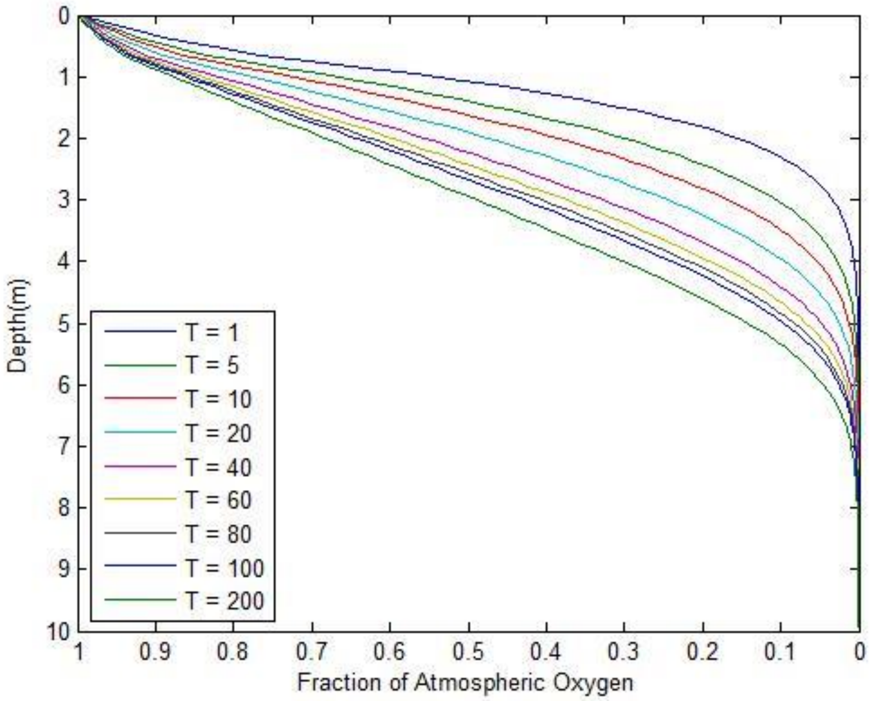
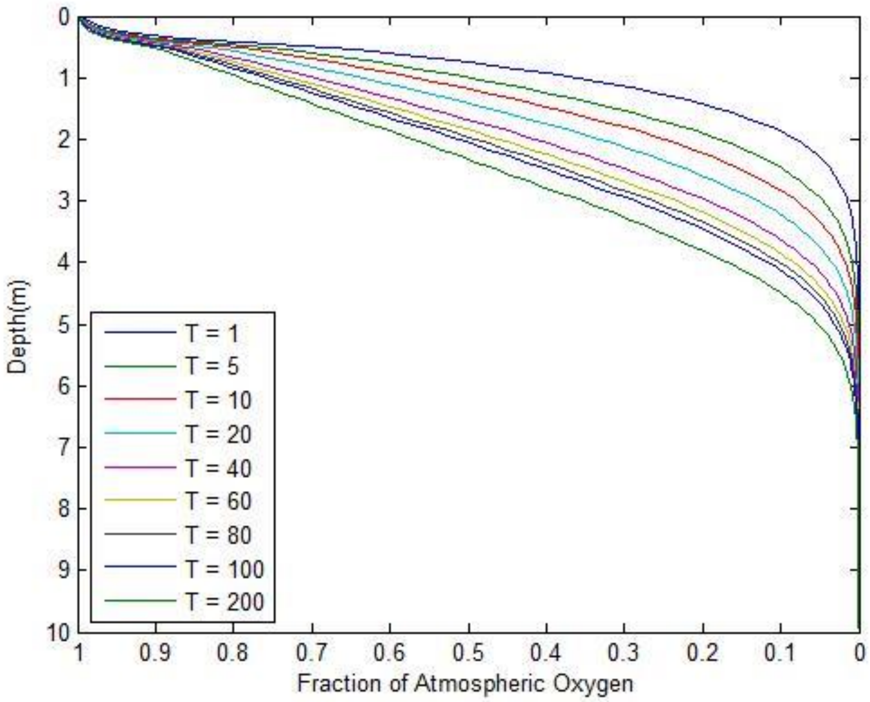
Model Scenario	Location	Material	Selected properties
Model A	Dump 1 Site D1-S1	Coal discard with a 90 cm soil cover	S% = 1 NP = 5 kg $CaCO_3$/t
Model B	Dump 1 Site D1-S2	Coal discard with a 70 cm soil cover	S% = 1 NP = 5 kg $CaCO_3$/t
Model C	Dump 1 Site D1-S3	Coal discard with a 60 m soil cover	S% = 1 NP = 5 kg $CaCO_3$/t
Model D	Dump 2 Site D2-S4	Coal discard with 120 m soil cover	S% = 1 NP = 5 kg $CaCO_3$/t
Model E	Dump 2 Site D2-S5	Coal discard with 60 m soil cover	S% = 1 NP = 5 kg $CaCO_3$/t
Model F	Dump 3 Site D3-S6	Coal discard with 90 m soil cover	S% = 1 NP = 5 kg $CaCO_3$/t
Model G	Dump 3 Site D3-S7	Coal discard with 80 m soil cover	S% = 1 NP = 5 kg $CaCO_3$/t

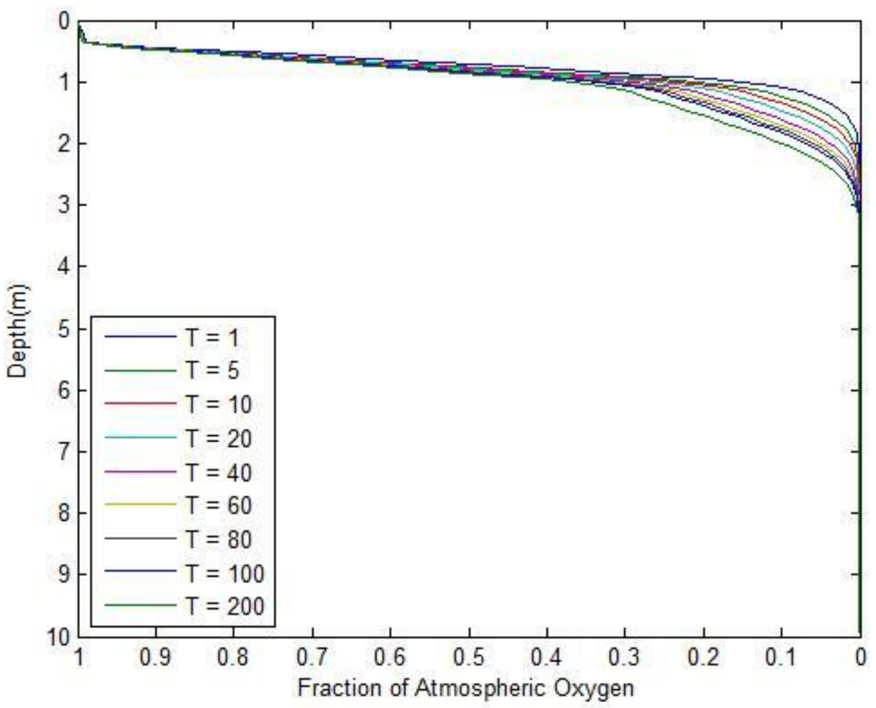
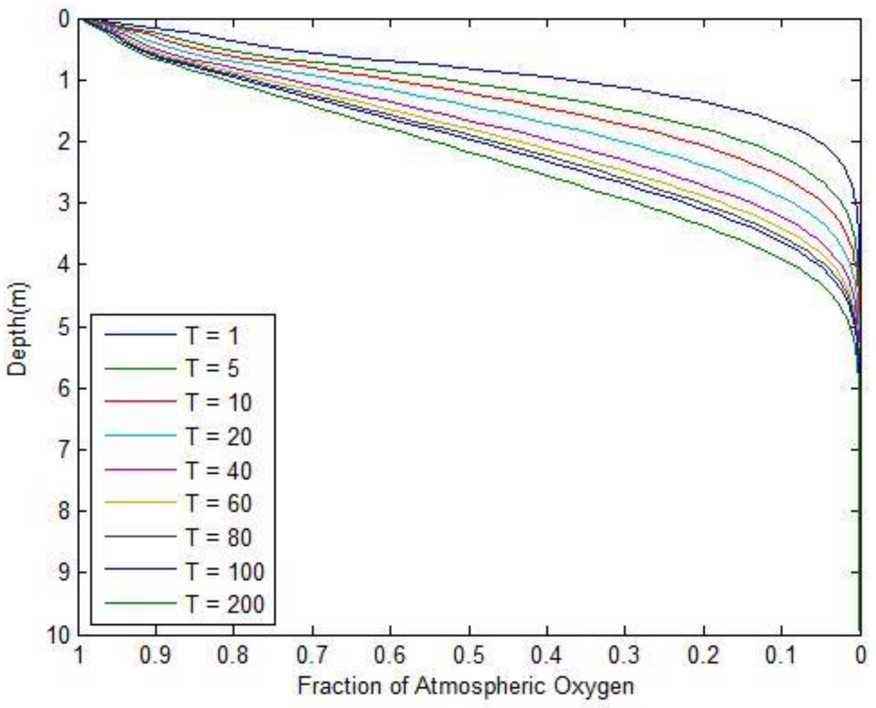
5.2.4 Predicted geochemistry

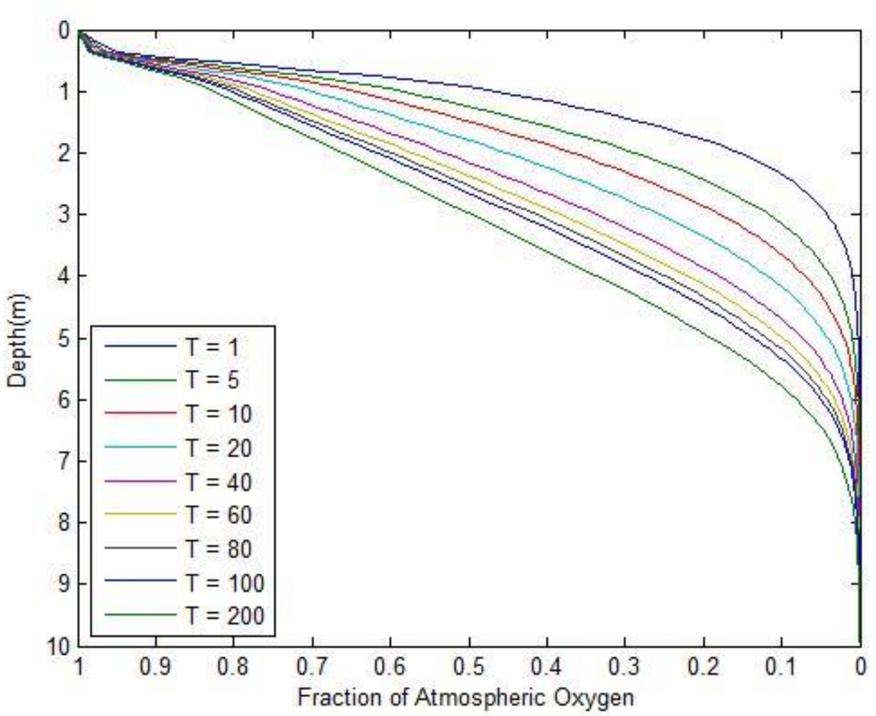
The oxygen diffusion and the reaction path model results are shown in Figure 5-3 and Figure 5-4.



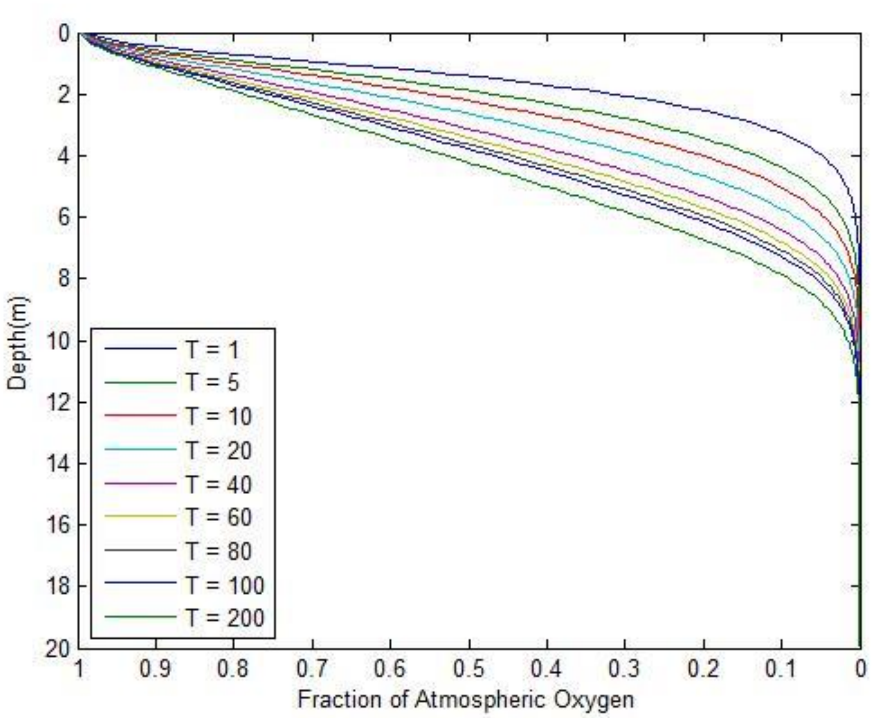
Model A
Dump 1
Site D1-S1

	Model B Dump 1 Site D1-S2
	Model C Dump 1 Site D1-S3

	Model D Dump 2 Site D2-S4
	Model E Dump 2 Site D2-S5

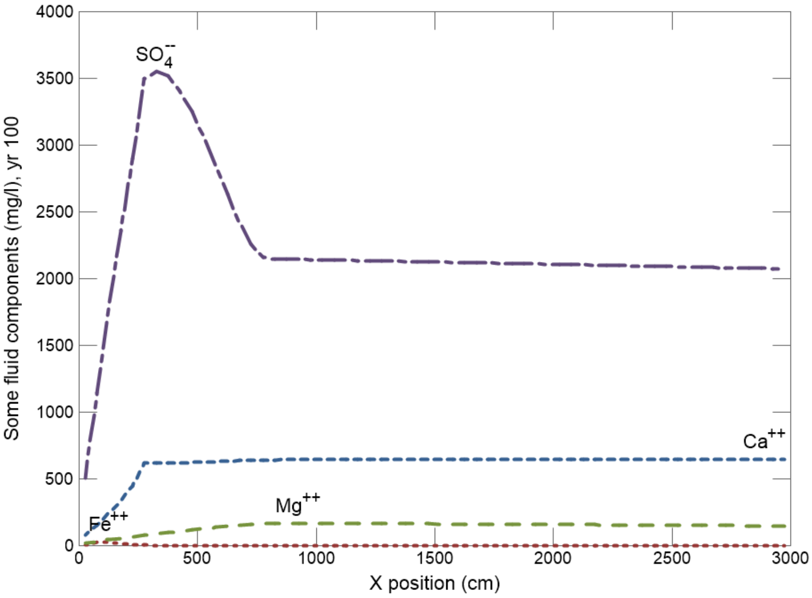
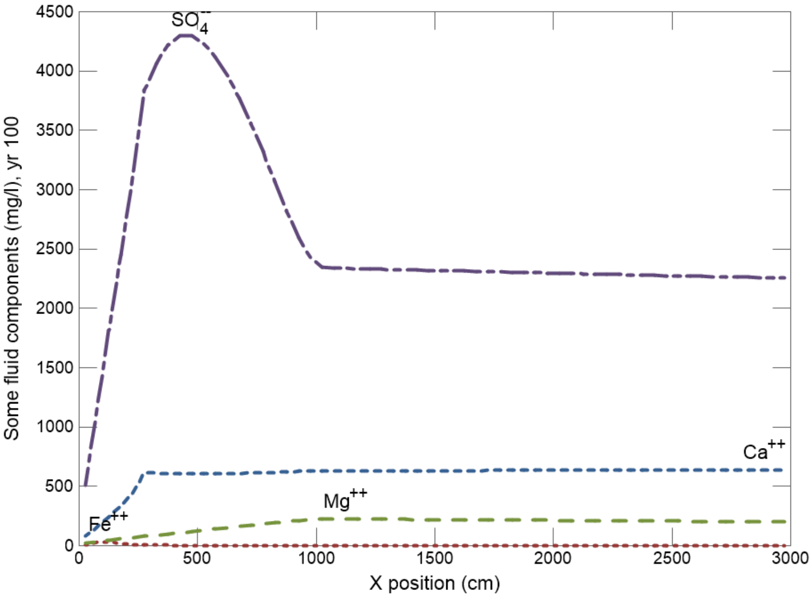


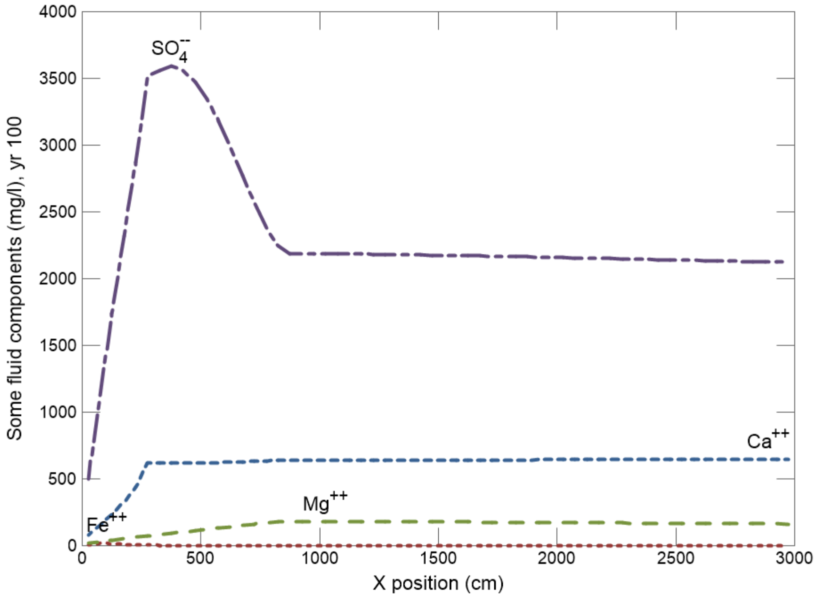
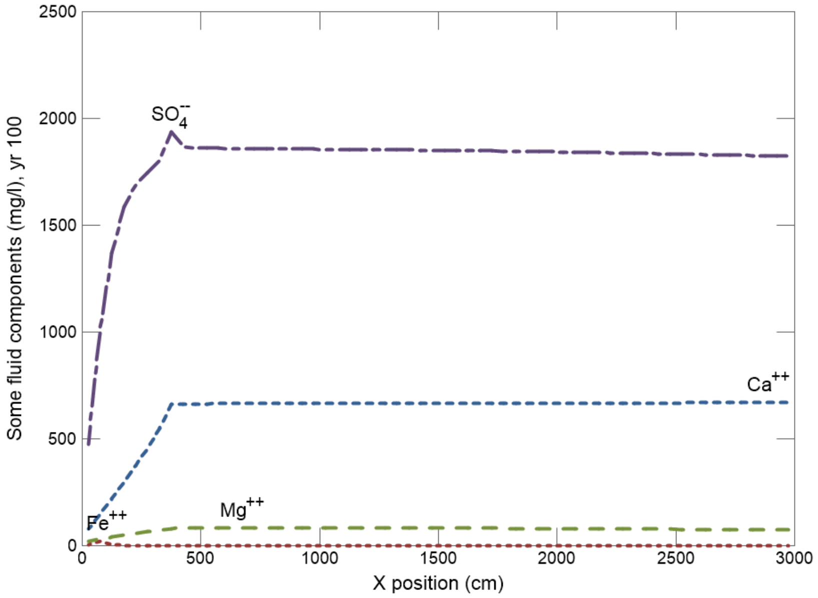
Model F
Dump 3
Site D3-S6

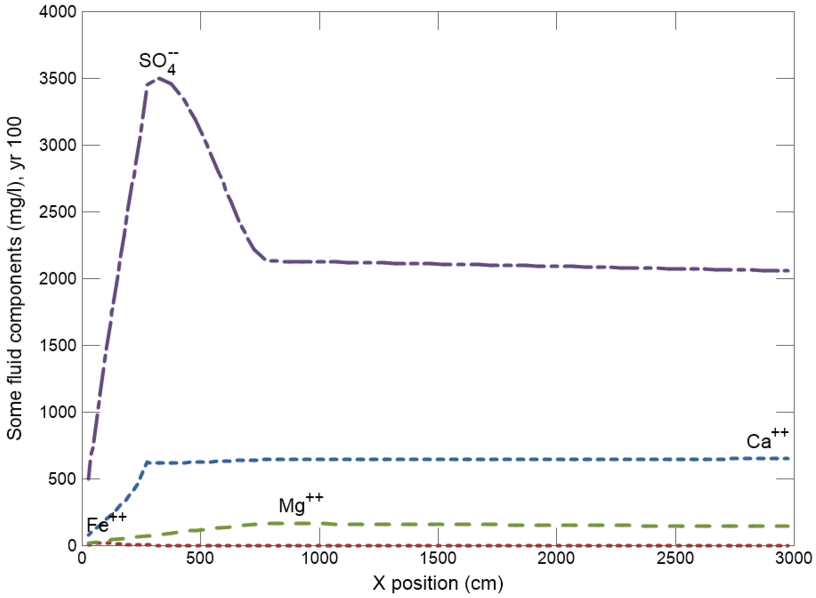


Model G
Dump 3
Site D3-S7

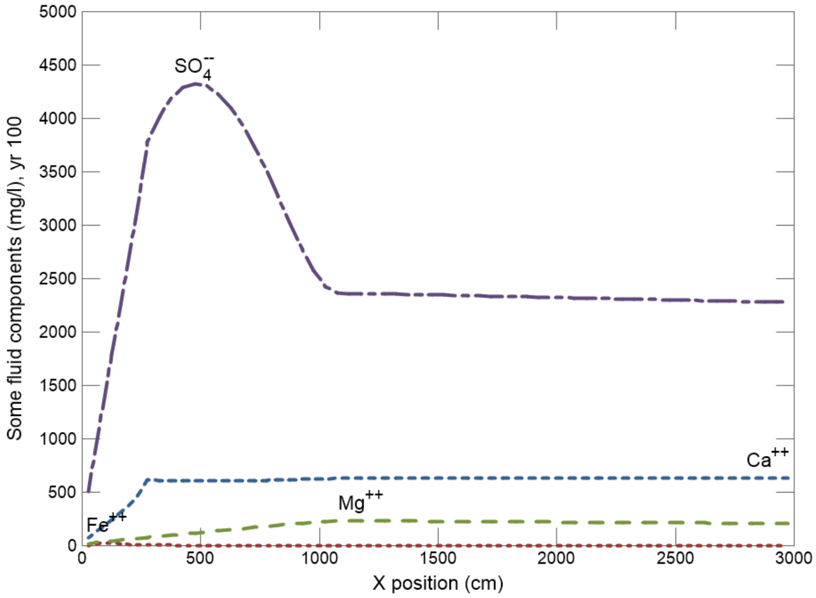
Figure 5-3: Predicted oxygen diffusion over time into the discard facilities

	Model A Dump 1 Site D1-S1
	Model B Dump 1 Site D1-S2

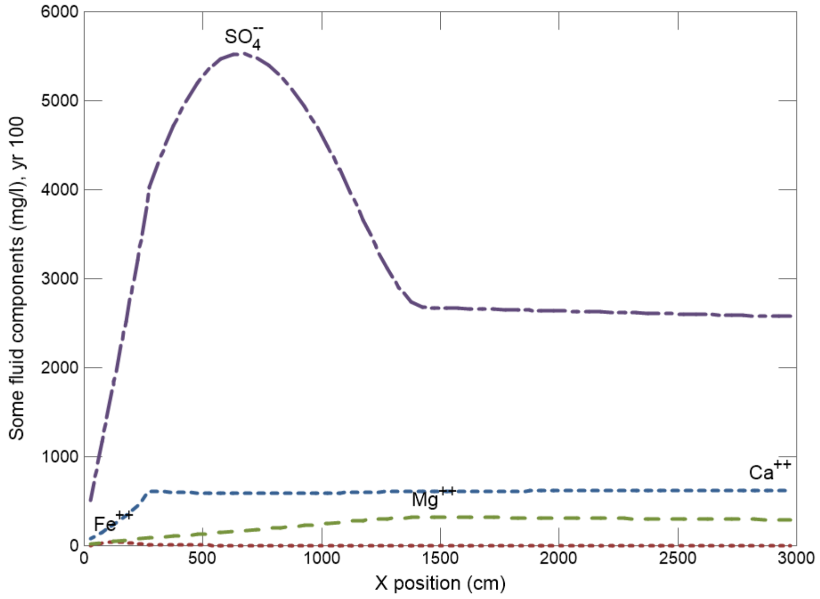
	Model C Dump 1 Site D1-S3
	Model D Dump 2 Site D2-S4



Model E
Dump 2
Site D2-S5



Model F
Dump 3
Site D3-S6



	Model G Dump 3 Site D3-S7

Figure 5-4: Predicted major components in interstitial water over time of discard facilities

6. CONCLUSIONS FROM COVER ASSESSMENT AND MODELLING STUDY

The following key findings can be made from this cover assessment and modelling study.

- *In-field determined hydraulic conductivities.* In-field conductivity tests conducted on mature covers (older than 20 years) indicate that cover materials are more permeable than would be expected. Observations made during this study suggest that intact soils are one to two orders of magnitude more permeable than expected. This tends to confirm observations made in international studies. Increased conductivity tends to indicate some structural change in soil properties of cover materials. When designing soil covers, it should become recognised practice to allow for increased soil permeability over time after construction of the cover.
- *Determined seasonal photosynthetic active (green) leaf area indices.* Measured leaf area indices and other vegetation characteristics suggest a lower quality of vegetative cover than would otherwise be expected. More emphasis needs to be placed on establishing a good quality vegetative cover to maximise plant transpiration rates with an aim to minimise rainwater ingress and associated seepage rates. Leaf area indices (LAIs) measured on the mature discard facilities are noticeably lower than values expected in natural areas in the region that have similar soils. While compaction clearly plays a role and severely restricts plant growth, it is also clear that a limited range of fine-bladed grasses do not provide the best vegetation cover. A greater leaf area will obviously lead to increased transpiration and improved function of the store-and-release cover.
- *Unsaturated flow modelling to optimise cover designs.* International research studies have demonstrated the importance of water retention curves and unsaturated flow modelling to optimise cover designs in semi-arid climate conditions. In South Africa these elements traditionally receive less attention. The complex interactions between rainfall, runoff and infiltration, or between seepage, soil water storage and plant water demand, that take place within a soil cover are best analysed within a numerical model. Unsaturated flow models allow iterative testing of design options to refine the design to meet specific performance objectives.
- *Predicted cover percolation and rainwater ingress.* Predicted percolation rates at the 90^{th} percentile is significantly higher than the mean annual values due to significantly higher percolations rates for wet years that include a series of consecutive rainy days, cloudy conditions and low potential evaporation rates. Target acceptable value of 5% of MAP for semi-arid climates can be achieved for 90 cm and thicker covers with sandy clay loam or sandy clay water retention layer (2^{nd} layer) and root development throughout the cover. The target value can also be achieved for the highly compacted cover if good vegetation conditions can be achieved. Mean annual net percolation rates with poor vegetation conditions exceed target rates, except for the 90 cm thick covers. This emphasises the importance of vegetative vigour and high leaf area indices to maximise plant transpiration with the aim of minimising moisture ingress rates and groundwater impacts.

- *Geochemical modelling.* Geochemical numerical modelling at trial sites indicates that soil covers should be thicker than 1 m to be effective in reducing oxygen ingress to an extent that Acid Mine Drainage development is restricted to manageable level. The focus of soil covers to mitigate AMD and related seepage impacts should, therefore, be on minimising net cover percolation and rainwater ingress into the discard.

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Appendix A

Cover layer descriptions of investigated covers

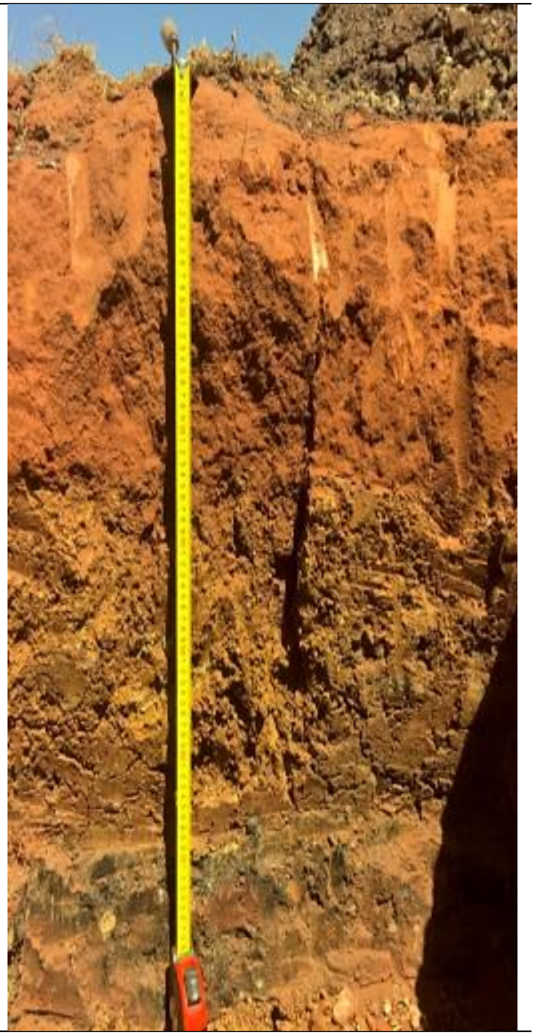
Cover layer properties of cover at research site D1-S1

Depth (mm)	Cover layer properties			Cover layer condition		Roots	Comments	Cover profile
	Soil material	Structure	Texture	Soil quality	Compacted			
500	Red apedal	Massive	Sandy clay LOAM	High	Highly to moderately	Moderate amount of roots Fairly good root development and distribution	Good growth medium Suitable for surface layer	
550	Yellow-brown apedal	Massive	Sandy LOAM	High	Slightly	Moderate number of roots	Good growth medium	
900	Plinthic	Massive Small concretions (10% of matrix)	Sandy CLAY	Medium	Moderately	Many roots Fairly good root development and distribution	Low suitability for surface layer Highly suitable for low permeable / moisture retention layer	
900+	Discard					Few roots		

Cover layer properties of cover at research site D1-S2

Depth (mm)	Cover layer properties			Cover layer condition		Roots	Comments	Cover profile
	Soil material	Structure	Texture	Soil quality	Compacted			
400	Yellow-brown apedal	Massive	Loamy SAND to Sandy LOAM	High	Moderately to highly	Many roots in upper 100 mm Few roots in remainder of layer	Good growth medium Suitable for surface layer	
600	Plinthic	Massive Concretions (5-10% of matrix)	Sandy clay LOAM to Sandy CLAY	Medium	Moderately	Moderate amount of roots Fairly good root distribution	Low suitability for surface layer Highly suitable for low permeable / moisture retention layer	
600+	Discard					Few roots		

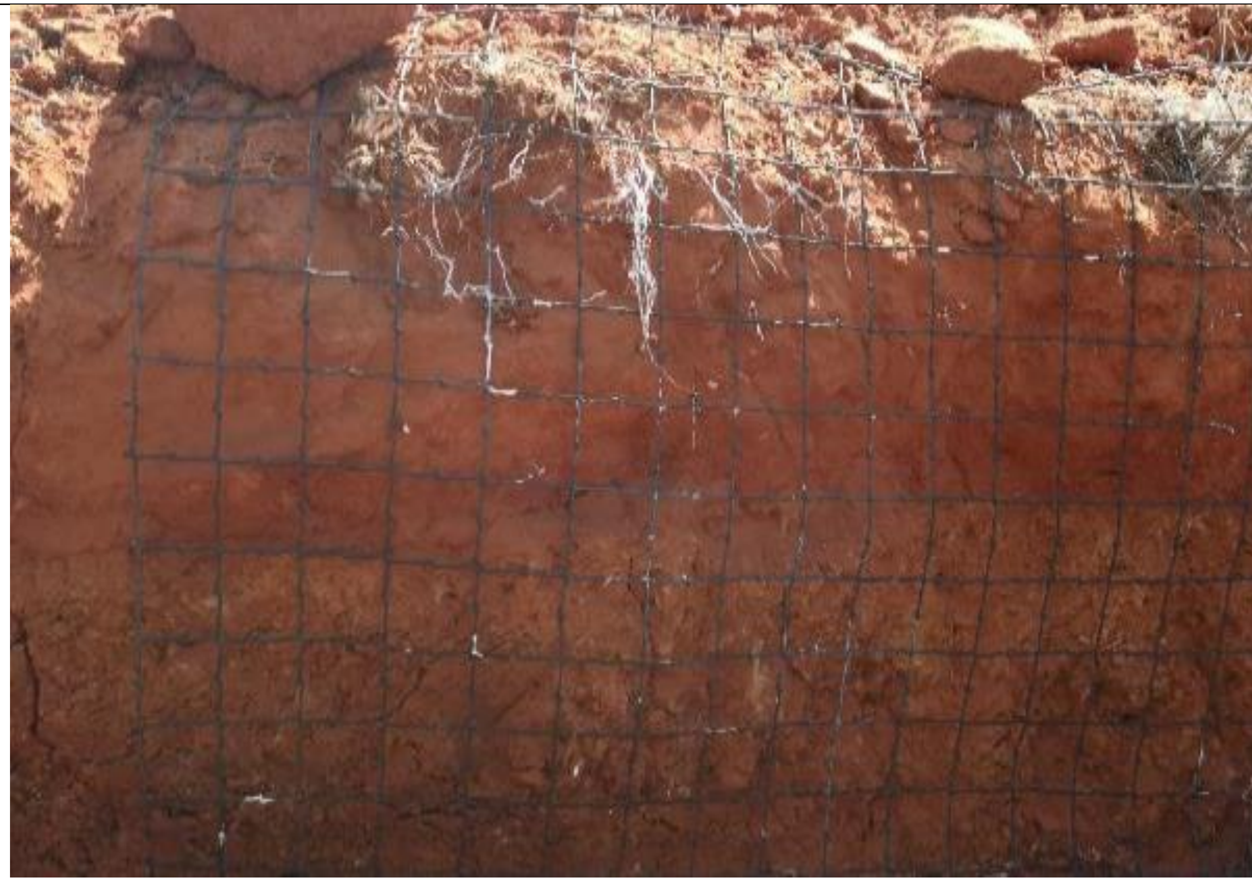
Cover layer properties of cover at research site D2-S5

Depth (mm)	Cover layer properties			Cover layer condition		Roots	Comments	Cover profile
	Soil material	Structure	Texture	Soil quality	Compacted			
300	Red apedal	Massive	Sandy clay LOAM	High	Severely	Some roots in upper 100 mm Almost no roots in remainder of layer	Good growth medium Suitable for surface layer	
700	Plinthic	Massive Concretions (15-20% of matrix)	Sandy CLAY	Medium	Highly	No roots	Low suitability for surface layer Highly suitable for low permeable / moisture retention layer	
700+	Discard							

Root profile of moderately dense cover at research site D1-S1

Depth (mm)	Description	Root profile
500	Moderate amount of roots Fairly good root development and distribution	
550	Few roots that growths through fine cracks Poor root distribution	
900	Moderate amount of roots Fairly good root distribution	

Root profile of very dense (highly compact) cover at research site D2-S5

Depth (mm)	Description	Root profile
	Some roots	
50	Root development occurs laterally	
300	About no roots	
700	No roots	

Appendix B

Summary of laboratory results for the cover layers

Table A1: Summary of volume-mass properties

Facility	Research site	Cover layer	Texture[1,2]	Dry density (kg/m^3)	Porosity[3]	Void ratio[3]	Comment[4]
Dump 1	S1	Growth medium	SaCL	1452 (1431-1472)	0.45	0.83	Root penetration *not* restricted
		Moisture retention layer	SaC	1242 (1238-1245)	0.53	1.1	
		Discard	SaL	1317 (1293-1345)			
	S2	Growth medium	LSa / SaL	1449 (1349-1566)	0.45	0.83	Root penetration *not* restricted
		Moisture retention layer	SaCL / SaC	1573 (1478-1668)	0.41	0.68	
		Discard	SaL	1723 (1613-1832)			Root penetration restricted but not limiting
	S3	Growth medium	SaCL	1622 (1593-1650)	0.39	0.63	Root penetration restricted but not limiting
		Moisture retention layer	SaC	1645 (1643-1647)	0.38	0.61	Compacted, root penetration limiting
		Discard	SaL	1339 (1291-1386)			Root penetration *not* restricted

Note: *1. Texture abbreviations: LSa: Loamy sand, SaL: Sandy loam, SaCL: Sandy clay loam, SaC: Sandy clay*

2. Field-estimated texture

3. Based on particle density (SG) of 2.65 g/cm^3

Table A1: Summary of volume-mass properties (cont.)

Facility		Research site	Cover layer	Texture[1,2]	Dry density (kg/m^3)	Porosity[3] (fraction)	Void ratio[3] (fraction)	Comment[4]
Dump 2		S4	Growth medium	LSa	1775 (1751-1800)	0.33	0.49	Root penetration restricted but not limiting
			2nd Layer	SaL	1827 (1814-1841)	0.31	0.45	Highly compacted, root penetration limiting
			1st Moisture retention layer	SaCL	1683 (1643-1724)	0.36	0.57	
			2nd Moisture retention layer	SaC	1713 (1652-1774)			
		S5	Growth medium	SaCL	1762 (1747-1776)	0.34	0.50	Highly compacted, root penetration limiting
			Moisture retention layer	SaC	1674 (1663-1686)	0.37	0.58	
			Discard	SaL	1486 (1361-1611)			Root penetration *not* restricted
Dump 3		S6	Growth medium	LSa / SaL	1514 (1422-1602)	0.43	0.75	Root penetration *not* restricted
			Moisture retention layer	SaL	1385 (1307-1442)	0.48	0.91	
		S7	1st Growth medium	SaL	1641 (1620-1661)	0.38	0.61	Root penetration *not* restricted
			2nd Growth medium	SaL	1565 (1537-1593)	0.41	0.69	
			Moisture retention layer	SaCL	1707 (1695-1720)			Root penetration restricted but not limiting

Note: *1. Texture abbreviations: LSa: Loamy sand, SaL: Sandy loam, SaCL: Sandy clay loam, SaC: Sandy clay*

2. Field-estimated texture

3. Based on particle density (SG) of 2.65 g/cm^3

Table A3: Summary of Atterberg properties

<table>
<tr><th>Facility</th><th>Research site</th><th>Cover layer</th><th>Texture[1,2]</th><th>Liquid limit</th><th>Plastic limit</th><th>Shrinkage limit</th><th>Plasticity index[4] (PI)</th><th>Clay activity[3,4]</th><th>Swell potential[3,4]</th></tr>
<tr><td rowspan="9">Dump 1</td><td rowspan="3">S1</td><td>Growth medium</td><td>SaCL</td><td>50.4</td><td>36.0</td><td>16.9</td><td>14.4
(Medium plastic)</td><td rowspan="5"><0.75
(Inactive)</td><td rowspan="2">Medium</td></tr>
<tr><td>Moisture retention layer</td><td>SaC</td><td>51.9</td><td>31.9</td><td>17.8</td><td>19.9
(High plastic)</td></tr>
<tr><td>Discard</td><td>SaL</td><td>41.7</td><td>34.0</td><td>16.7</td><td>7.7
(Medium plastic)</td><td rowspan="3">Low</td></tr>
<tr><td rowspan="3">S2</td><td>Growth medium</td><td>LSa / SaL</td><td>40.9</td><td>35.1</td><td>16.0</td><td>5.9
(Slightly plastic)</td></tr>
<tr><td>Moisture retention layer</td><td>SaCL / SaC</td><td>41.6</td><td>31.2</td><td>19.3</td><td>10.4
(Medium plastic)</td></tr>
<tr><td>Discard</td><td>SaL</td><td>41.2</td><td>17.9</td><td>19.0</td><td>23.3
(High plastic)</td><td rowspan="2">0.75-1.25
(Normal)</td><td>Medium</td></tr>
<tr><td rowspan="3">S3</td><td>Growth medium</td><td>SaCL</td><td>45.8</td><td>32.0</td><td>19.6</td><td>13.8
(Medium plastic)</td><td rowspan="3">Low</td></tr>
<tr><td>Moisture retention layer</td><td>SaC</td><td>41.0</td><td>27.8</td><td>16.3</td><td>13.2
(Medium plastic)</td><td rowspan="2"><0.75
(Inactive)</td></tr>
<tr><td>Discard</td><td>SaL</td><td>46.3</td><td>42.7</td><td>20.6</td><td>3.6
(Slightly plastic)</td></tr>
</table>

Note: *1. Texture abbreviations: LSa: Loamy sand, SaL: Sandy loam, SaCL: Sandy clay loam, SaC: Sandy clay*
2. Field-estimated texture
3. Calculated from field-estimated clay content

Table A3: Summary of Atterberg properties (cont.)

Facility	Research site	Cover layer	Texture[1,2]	Liquid limit	Plastic limit	Shrinkage limit	Plasticity index (PI)	Swell potential[3,4]	Clay activity[3,4]
Dump 2	S4	Growth medium	LSa	27.2	16.5	10.8	10.7 (Medium plastic)	<0.75 (Inactive)	Low
		2nd Layer	SaL	27.4	23.4	12.0	4.0 (Slightly plastic)		
		1st Moisture retention layer	SaCL	34.9	27.8	18.9	7.1 (Slightly plastic)		
		2nd Moisture retention layer	SaC	56.9	41.9	24.9	15.1 (Medium plastic)		Medium
	S5	Growth medium	SaCL	37.8	25.6	16.5	12.2 (Medium plastic)		Low
		Moisture retention layer	SaC	43.8	27.5	17.7	16.3 (High plastic)		Medium
		Discard	SaL	42.8	24.2	18.3	18.6 (High plastic)	0.75-1.25 (Normal)	
Dump 3	S6	Growth medium	LSa / SaL	23.5	22.9	10.4	0.6 (Nonplastic)	<0.75 (Inactive)	Low
		Moisture retention layer	SaL	41.8	27.6	16.4	14.3 (Medium plastic)		Medium
	S7	1st Growth medium	SaL	27.9	25.5	11.6	2.4 (Slightly plastic)		Low
		2nd Growth medium	SaL	30.3	27.2	12.4	3.1 (Slightly plastic)		
		Moisture retention layer	SaCL	43.1	29.2	18.2	13.9 (Medium plastic)		Medium

Note: *1. Texture abbreviations: LSa: Loamy sand, SaL: Sandy loam, SaCL: Sandy clay loam, SaC: Sandy clay*

2. Field-estimated texture

3. Calculated from field-estimated clay content

Table A4: Summary of saturated hydraulic conductivity determined from in-field infiltration tests

Facility	Research site	Saturated hydraulic conductivity (m/d)			
		Surface	**Growth medium**	**Moisture retention layer**	**Discard**
Dump 1	S1	0.95 (0.76-1.24)	0.42 (0.29-0.73)	0.25 (0.10-0.58)	0.27 (0.11-0.58)
	S2	0.65 (0.12-1.01)	0.32 (0.13-0.56)	0.18	0.30 (0.09-0.71)
	S3	0.47 (0.13-0.63)	0.30 (0.11-0.48)	0.20 (0.09-0.47)	0.11
Dump 2	S4	1.26	0.20 (0.04-0.78)	0.14 (0.03-0.37)	
	S5	0.08	0.21 (0.05-0.39)	0.16 (0.08-0.24)	
Dump 3	S6		1.07	0.85	
	S7		0.67	0.45	

Table A5: Summary of soil fertility for the growth medium layers

Facility			Dump 1			Dump 2		Dump 3	
Research site			**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**
Texture			SaCL	LSa / SaL	SaCL	LSa	SaCL	LSa / SaL	SaL
Available plant nutrients (reserve)	P (Bray 1)	mg/l	34	20	6	2	2	69	13
	K	mg/l	97	174	220	87	91	131	144
	Ca	mg/l	200	194	782	267	263	370	347
	Mg	mg/l	50	56	147	66	162	111	104
	Base saturation	%	81	80	100	100	82	100	100
	Ca:Mg	ratio	2	2	3	2	1	2	2
	Mg:K	ratio	2	1	2	2	6	3	2
	Ca+Mg:K	ratio	6	3	9	8	11	8	7
	Sulphur	mg/l	75	12	10	72	16	17	7.3
	Zinc	mg/l	2.5	3.1	2.3	1.9	0.47	2.2	3.6
	Boron	mg/l	0.15	0.14	0.21	0.1	0.14	0.08	0.08
	Copper	mg/l	0.63		8.4	0.87	1.2	0.58	1.1
	Iron	mg/l	49	172	244	132	21	212	243
	Manganese	mg/l	35	25	79	54	31	18	44
Factors determining nutrient availability	pH (H_2O)		5.0	4.7	6.9	6.1	5.7	5.5	6
	pH (KCl)		4.1	3.9	6.2	4.8	4.8	4.3	5
	Acid saturation	%	20	21	0	0	18	0	2
Factors determining nutrient retention	CEC	cmol/kg	2.0	2.3	5.5	2.0	2.4	2.9	2.9
	Carbon	%	0.9	1.6	0.6	0.8	0.5	0.9	0.7
Restricting factors to plant growth	EC	mS/m	35	49	68	18	223	45	27
	SAR		0	0.2	0	0	0.1	0	0
	SO_4-S	mg/l	71	17	84	20	447	67	41

Note: *1. Texture abbreviations: LSa: Loamy sand, SaL: Sandy loam, SaCL: Sandy clay loam, SaC: Sandy clay*
2. Field-estimated texture

Table A6: Summary of soil fertility for the moisture retention layers

Facility			Dump 1			Dump 2		Dump 3	
Research site			**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**
Texture			SaCL	LSa / SaL	SaCL	LSa	SaCL	LSa / SaL	SaL
Available plant nutrients (reserve)	P (Bray 1)	mg/l	2	2	2	2	3	1	2
	K		51	47	42	49	73	94	42
	Ca		569	414	734	228	1101	556	827
	Mg		307	175	195	76	358	255	357
	Base saturation	%	100	100	100	94		100	100
	Ca:Mg	ratio	2.1	1.4	2.3	1.8	1.9	1.3	1.4
	Mg:K		19	12	15	5	16	9	28
	Ca+Mg:K		41	29	49	14	45	20	67
	Sulphur	mg/l	75	28	20	33	73	63	75
	Zinc		0.39	0.41	0.55	0.35	0.96	0.34	0.31
	Boron		0.02	0.01	0.07	0.1	0.06	0.11	0.03
	Copper		0.89	0.95	1.5	1.3	1.0	2.3	2.
	Iron		18	26	22	33	43	3	40
	Manganese		55	45	51	83	66	108	139
Factors determining nutrient availability	pH (H_2O)		5.6	6.1	5.6	5.1	3.5	6.2	6.8
	pH (KCl)		4.8	5.4	4.9	4.4	3.4	5.2	6.1
	Acid saturation	%	0	0	0	6	38	0	0
Factors determining nutrient retention	CEC	cmol/kg	5.4	3.4	4.7	1.9	7.2	5.1	6.8
	Carbon	%	0.13	0.25	0.27	0.27	0.13	0.33	0.2
Restricting factors to plant growth	EC	mS/m	47	70	156	29	832	22	107
	SAR		0.3	0.1	0.1	0.1	0.1	0	0.1
	SO_4-S	mg/l	67	107	310	33	3354	50	149

Note: *1. Texture abbreviations: LSa: Loamy sand, SaL: Sandy loam, SaCL: Sandy clay loam, SaC: Sandy clay*

2. Field-estimated texture

Appendix C

Characteristics and application of water retention curves

The water retention curve (WRC), also referred to as soil water characteristic curve, is the relationship between the amount of water retained in a material at a given (soil) matric potential (suction). The WRC is mainly influenced by the particle size distribution, soil structure, compaction and soil organic matter.

WRCs are central to the application of unsaturated flow (cover water balance, unsaturated geohydrological) models to predict net cover percolation (rainwater ingress or rain recharge) rates and cover moisture contents. The characteristics of a WRC that are used for unsaturated flow modelling includes:

- *Water retention* to retain infiltrated rain in the cover for evapotranspiration. Water retention increases with increasing clay, silt, very fine sand and soil organic carbon contents, and with compaction. Gravel and sand have low moisture retention.
- *Water storage capacity* to store infiltrated rain in the cover during wet periods for evapotranspiration during subsequent drier periods. Water storage capacity increases with increasing water retention, but can decrease with compaction.
- *Capillary potential* required for (deep) infiltrated rain to move upwards to the surface for evapotranpiration. Capillary potential increases with increasing water retention and compaction.
- *Plant available water capacity*, which increases with increasing water storage capacity.

In general, cover percolation rates decrease with increasing water retention, water storage capacity, capillary potential and plant available water capacity. A number of parameters can be determined from a water retention curve, which is shown in Figure 1.

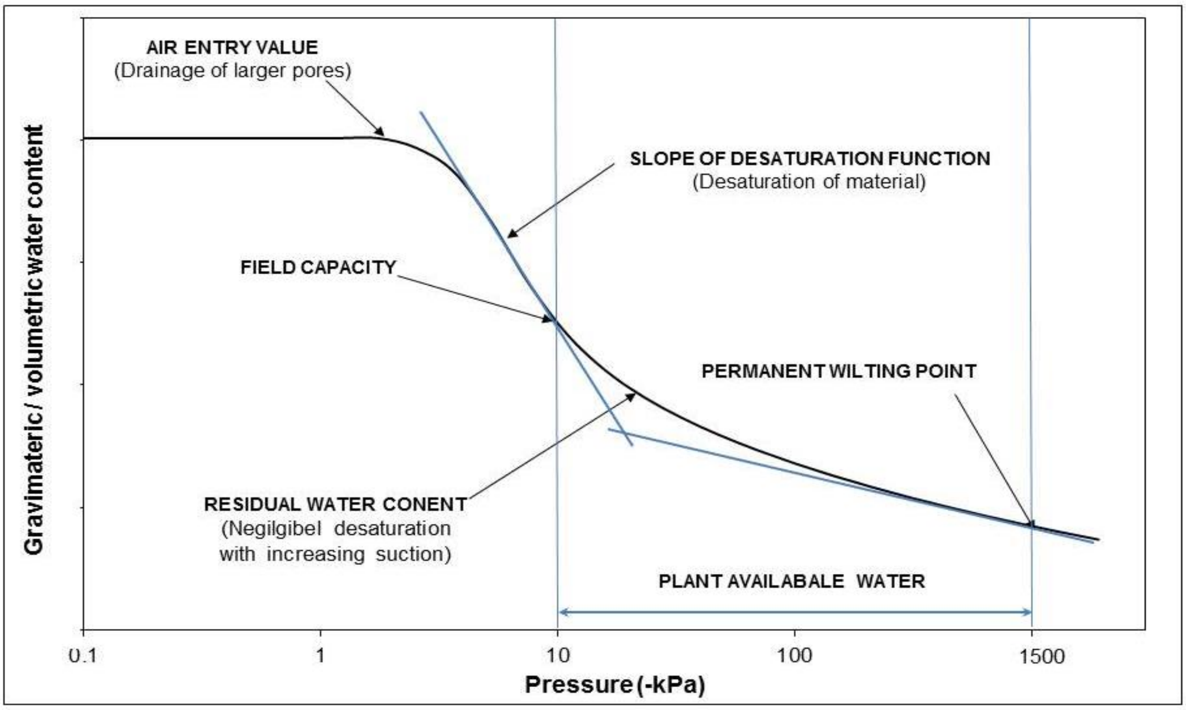


Figure 1: Water retention curve characteristics.

The water retention curve is defined by the following parameters:

- *Saturated water content* is the water content of a saturated material when all the voids are filled with water;
- *Air entry value* is the matric suction where the larger pores of a saturated material begins to drain freely. Low air entry values indicate that a saturated material drains easily/quickly;
- *Slope of the desaturation function* that represents the rate at which a material dry out. A steep slope indicates that the material will lose moisture easily and dry out quickly;
- *Residual water content* where negligible moisture is lost with desaturation.

The saturated water content, air entry value and residual water content increases with increasing clay, silt, very fine sand and organic carbon content, and with compaction. The values of these parameters are low for gravel, medium- and coarse sand and for loose material.

The following parameters related to plant water uptake can also be determined from the WRC:

- *Field capacity* that is the fraction of water remaining in a soil after free draining water has drained and the rate of downward movement has decreased. This usually takes place within 2-3 days after the soil was saturated. The field capacity is also referred to as the upper limit of plant available water;
- *Wilting point* where the soil has dried to a matric potential that plants cannot take up water anymore and the wilted plant can no longer recover turgidity. The wilting point is also referred to as the lower limit of plant available water; and
- *Plant available water* that is the fraction of water that can be absorbed by plant roots. Plant available water is determined from the difference in water content at field capacity and wilting point.

A good representation of the (usually highly) non-linear WRC can be accomplished by applying mathematical fitting methods to (laboratory) determined water retentivity data to interpolate the measured water retentivities. WRCs can be determined by applying for example the van Genuchten, van Genuchten and Mualem or Fredlund and Zing closed-form solution methods to the laboratory determined water retentivities of material.

Appendix D

Geochemical analytical results

Table A-7: X-ray Diffraction results (weight %)

Mineral ID	Dump 1	Dump 2
Quartz	76.1	37.4
Kaolinite	11.9	18.6
Anatase	0.190	0.190
Rutile	2.69	0.300
Muscovite	2.51	1.13
Dolomite	0.720	15.1
Gypsum	5.02	27.3
Clinochlore	0.920	-

Table A-8: X-ray Fluorescence, major and minor oxides test results (weight %)

Sample ID	Dump 1	Dump 2	AUC[1]		
			Above AUC	3-5 times above AUC	> 5 times higher than AUC
LOI	16.6	23.3			
Al_2O_3	9.33	10.9	15.4	46.2	77
CaO	0.434	7.00	3.6	10.8	18
FeO	7.30	6.81	5.04	15.1	25.2
Cr_2O_3	0.021	0.023	0.027	0.081	0.134
K_2O	1.19	0.727	2.8	8.4	14
MgO	0.178	1.84	2.5	7.44	12.4
MnO	0.124	0.061	0.1	0.3	0.5
Na_2O	<0.010	<0.010	3.3	9.81	16.4
P_2O_5	0.131	0.185	0.2	0.45	0.75
SiO_2	63.1	44.9	66.6	-	-
TiO_2	0.553	0.517	0.6	1.92	3.2
V_2O_5	0.025	0.019	0.035	0.104	0.173
BaO	0.089	0.049	0.07	0.21	0.351
SrO	0.011	0.044	0.037	0.11	0.184
ZrO_2	0.066	0.04	0.026	0.078	0.13
SO_3	0.169	2.648	0.154	0.462	0.77

Table A-9: Acid-Base Accounting (ABA) test results

Sample Nr	Paste pH	Sulphide %S	Total %S	AP $CaCO_3$ kg/t	NP $CaCO_3$ kg/t	NNP $CaCO_3$ kg/t	NP/AP	Rock Type NNP	Rock Type %S	Rock Type NP/AP
S1	4.64	0.513	0.564	16.0	0.000	-16.0	0.000	Uncertain	Rock Type I	Rock Type I
S2	3.73	1.38	1.66	43.1	0.000	-43.1	0.000	Rock Type I	Rock Type I	Rock Type I

Table A-10: Potential for the discard to generate acid drainage

Sample ID	%S > 0.3 2 < NP/AP < 2	%S 0.1-0.3 NP/AP < 2	%S 0.1-0.3 NP/AP > 2	%S <0.1 NP/AP < 2	%S <0.1 NP/AP > 2
Potential for acid mine drainage	Likely/possibly acid generating High salt load.	Low potential for acid generation Low to medium salt load.	Very low potential for acid generation Very low to low salt load.	No potential for acidic drainage Very low/no salt load.	No potential for acidic drainage Very low/no salt load.