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The Influence of Environmental Impacts on Tailings Impoundment Design

Integrating environmental impacts with engineering costs for the design of tailings impoundments

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Submitted in partial fulfilment of the requirements of the degree Philosophiae Doctor in the Faculty of Engineering, Built Environment and Information Technology of the University of Pretoria, Pretoria.

July 2007

I would like to dedicate this thesis to my co-supervisor Professor Geriant (Gary) Alan Jones whom I have had the privilege of studying under. He has mentored me during the past four years and although difficult at times, I do not wish to have it any other way. He truly knows how to inspire a person and has the ability to provide useful input on most subjects.

Prof. Jones's research into soil mechanics led to the development of the piezocone, a powerful tool used worldwide for assessing the strength and compressibility of soft soils, tailings and other materials. Piezocone testing has changed the method of investigation of soft soils around the world and consequently the design of embankments on soft soils.

He was born on 17 October 1933 in Wales. He obtained his BA and MA degrees in engineering from Clare College, Cambridge, in the UK, in 1957 and 1961 respectively. He was awarded a PhD by the University of Natal in 1993. Gary has more than forty year's experience as an engineering consultant and is presently an extraordinary professor of geotechnical engineering at the University of Pretoria.

Gary, I thank you warmly for the tremendous amount of selfless time and energy spent helping me during the lots of good and sometime less good times during my doctoral studies.

“...the key is to find technological ways of disposing debris without ecological upset.”

Robert Pirsig (Pirsig, 1999:128)

“...from a larger point of view it is only tailings deposition not the disposal that ceases and tailings management must continue until such time as the deposited tailings is assured to be permanently stable and environmentally innocuous...”

Steven Vick (Vick, 1983:324)

“Development and technological progress places increasing pressure on the earth’s resources. In this aspect South Africa is no exception and many unfortunate decisions have been taken in the past, often with disastrous consequences, due to ignorance or lack of essential environmental information.”

(van Riet, Claassen, van Rensburg, van Viegen and du Plessis, 1997:63)

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Summary

Mining of South Africa's gold, platinum and base metal resources has given rise to hundreds of mine residue deposits (MRDs) the footprints of which cover large areas of land. Metalliferous mines produce a substantial volume of fine-grained waste and it is estimated that approximately 12 000 ha of land is sterilised by 150 MRDs within the Gauteng province alone (Figure Ex 1).

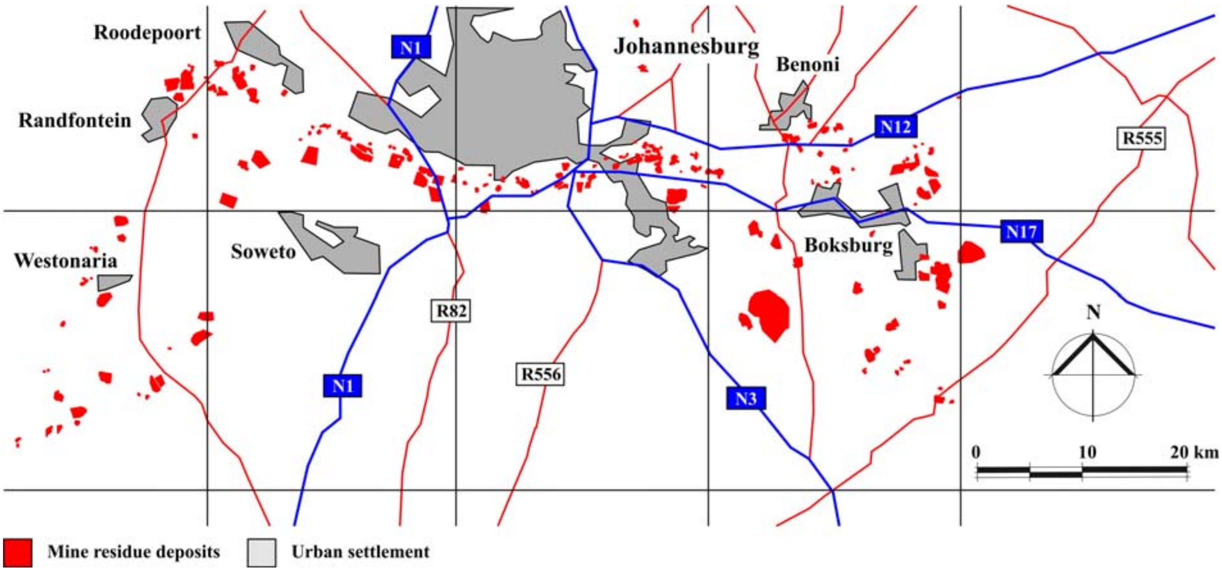

Figure Ex 1: Footprints of mine residue deposits in and around the Gauteng province (Rademeyer and van den Berg, 2005.)

The disposal of mine residue, mainly tailings, can impact on large areas of land through the change in visual landscape, the decrease in air quality, and the degradation of the water resource. MRDs are particularly susceptible to erosion giving rise to long term wind and water borne pollution. Mine residue can contain sulphide minerals which upon weathering give rise to a range of pollutants especially where there is insufficient neutralizing potential. Radionuclides are also found in drainage associated with some MRDs.

The quantitative prediction and integration of these impacts is difficult and the impacts are costly to manage and remedy.

The legacy of the impacts associated with MRDs, particularly in the long term after closure, has given rise to an increasingly complex regulatory regime. Obtaining approvals for upgrading old facilities, for the development of new facilities, and for closure plans are difficult owing to the lack of a suitable framework within which to make decisions. Since efficient development of the South African mining sector is essential, whilst maintaining a balance with an acceptable level of environmental risk, it is necessary to develop systems to facilitate transparent and effective decision making. The current state of the art of prediction and mitigation is not yet developed sufficiently to place South African regulators, in particular, in a position to evaluate and validate tailings impoundment schemes.

The research presented in this study is multidisciplinary. It integrates information from a range of disciplines, many of which have analytical structures and barriers separating them. The results of specialist studies are normally communicated to those within the discipline, and infrequently to specialists in other disciplines and even less so to stakeholders outside the planning and design team. This study describes a system to integrate different environmental impacts and engineering design aspects with the aim to present the results in a rational and understandable manner.

The research applies integrated environmental planning and design principles to the design of upstream deposited ring-dyke tailings impoundments which are widely applicable in South Africa, the result of which is an integrated environmental impact and engineering cost system for the configuration of such impoundments. A theoretical ecological and sustainable philosophical approach was adopted and used to critically evaluate, assess, and analyse environmental impacts and formulate solutions for the post-closure land use of tailings impoundments.

The research is innovative both because it envisages tailings impoundment design from the view of landscape architecture and also because it introduces the concept of visual impacts in a novel way. In essence, there must be a shift in emphasis from designing and operating an impoundment to contain tailings for a 20 year period, to the design of a man-made landform within the landscape with the end of life configuration and land use envisaged prior to construction. Generic models for the environmental impacts and engineering costs throughout the life cycle of a tailings impoundment are described such that the design can be optimised ab initio with respect to the environmental impacts and costs.

The research depends on the use of models and experimental work. The challenge was to develop a system that reflects the real world situation. Uncertainty exists regarding the detailed processes controlling and contributing to the environmental and engineering aspects. Uncertainties are incorporated into the predictions by means of following a systematic and rational approach. A systems approach ensures that the environmental problems associated with tailings impoundments are not considered in isolation but holistically.

The system for the evaluation of the life cycle of tailings impoundments with particular emphasis on post-closure land use can be used to:

- inform the stakeholders in the planning stage to consider alternative configurations;
- assist with decision making;
- provide a platform for constructive discussion with relevant authorities; and
- facilitate transparent liaison with stakeholders.

Regulators, proponents, environmental practitioners, and engineering consultants can use the system to understand better what the implications are of alternative configurations such as flattening tailings impoundment embankment side slopes and changing cover types.

Through a process of elimination the following key environmental issues that influence tailings impoundment design are:

- visual aspects;
- air quality aspects; and
- water aspects.

This study combines and integrates these environmental aspects with engineering costs.

It was recognized early on in the research that a complete model could contain a number of aspects currently not included such as heritage, tourism and the living environment. The exclusion of environmental aspects does not mean that they are in any way less important. Also, the time period for the life cycle considered in the quantification of environmental impacts and engineering costs is for a period from the start of tailings impoundment design up to 20 years after closure. Had a full set of aspects with more indicators been considered over a longer post-closure period some of the conclusions may have been different. However, the view was taken that initially only key aspects will be included and modelled for a 20 year post-closure period with the aim of creating a robust system demonstrating its efficacy.

Some of the input parameters in the system are not definitive and require conservative value judgements to be applied. Future research can refine the predictive models by initiating longer term monitoring programs. Even though there are uncertainties pertaining to some of the parameters used in the study it can be stated that the approach developed and described in this thesis presents a complex problem in such a manner as to make it more useful for rational decision making.

This study demonstrates that real costs can be ascribed to environmental impacts and that these can be added to the direct engineering cost to produce a total cost model. It is from this that rational decisions can be made. For example alternative tailings impoundment configurations and post-closure land uses are compared through the valuation of environmental change which assists to identify critical aspects determining the sustainability of the proposed land use.

Although there are many challenges to the process of estimating values, this study identifies and discusses the requirements to valuate visual, air, and water impacts associated with tailings impoundments. It is recommended that the environmental impact and engineering costing system should be used to inform decision making involving the rehabilitation of existing as well as new tailings impoundments.

Key words in alphabetical order:
Air quality, configuration, decision making, environmental impacts, environmental costs, engineering costs, environmental impact and engineering cost system, integration, land use, post-closure land use, sulphate mass flux, tailings impoundment, upstream deposited ring-dyke tailings impoundments, valuation, visual perception distances, water quality.

Samevatting

Die ontginning van Suid-Afrika se goud-, platinum- en onedele metaalhulpbronne het tot honderde mynoorskotafsetsels (MOA's) aanleiding gegee, waarvan die oppervlaktes groot landsgebiede bedek. Metaalhoudende myne produseer groot hoeveelhede fynkorrelrige afval en daar word geraam dat slegs in Gauteng ongeveer 12 000 ha grond deur 150 MOA's gesteriliseer word (Figuur Ex 1, p. b).

Die wegdoening van mynreste - hoofsaaklik uitskot - kan deur middel van veranderings in die visuele landskap, die afname in luggehalte, en die degradasie van die waterbronne 'n impak op groot landsgebiede hê. MOA's is veral vatbaar vir erosie, wat langtermyn wind- en waterbesoedeling veroorsaak. Mynoorskot kan sulfiedminerale bevat wat tydens verwering tot 'n reeks besoedelende stowwe aanleiding gee, veral waar daar onvoldoende potensiaal vir neutralisering bestaan. Radionukliedes word ook in dreinering wat met sommige MOA's gepaard gaan, aangetref.

Die kwantitatiewe voorspelling en integrasie van hierdie impakte is moeilik, en duur om te bestuur en te remedieer.

Die nalatenskap van impakte wat met MOA's verbind word veroorsaak ná sluiting veral in die lang termyn 'n al hoe meer ingewikkelde regulerende stelsel. Goedkeuring vir die opgradering van ou fasiliteite, vir die ontwikkeling van nuwe fasiliteite, en vir sluitingsplanne is moeilik om te verkry weens die gebrek aan 'n geskikte raamwerk waarbinne besluite geneem kan word. Aangesien die doeltreffende ontwikkeling van die Suid-Afrikaanse mynsektor noodsaaklik is, solank 'n balans met 'n aanvaarbare vlak van omgewingsrisiko gehandhaaf word, is dit noodsaaklik om stelsels te ontwikkel wat deursigtige en doeltreffende besluitneming vergemaklik. Die huidige stand van sake wat voorspelling en versagting van skade betref is nog nie voldoende ontwikkel om veral reguleerders in staat te stel om slikdamskemas te evalueer en te bekragtig nie.

Die navorsing wat deur hierdie studie voorgelê word is multidissiplinêr. Dit integreer inligting uit 'n reeks vakgebiede, waarvan verskeie deur analitiese strukture en versperrings geskei word. Die resultate van spesialisstudies word normaalweg aan dié binne die dissipline oorgedra, en selde aan spesialiste in ander dissiplines, en nog meer selde aan insethouers buite die beplanning- en ontwerpspan. Hierdie studie beskryf 'n stelsel om verskillende omgewingsimpakte en ingenieursontwerpaspekte te integreer, met die doel om die resultate op 'n rasionele en verstaanbare manier voor te lê.

Die navorsing pas beginsels van geintegreerde omgewingsbeplanning en -ontwerp op die ontwerp van slikdamme toe. Die resultaat is 'n geïntegreerde omgewingsimpak- en ingenieursonkostestelsel wat gebruik kan word om tipiese stroomop gedeponeerde ringdyk slikdamme te konfigureer. 'n Teoretiese ekologiese en volhoubare filosofiese benadering is aangeneem en gebruik om omgewingsimpakte krities te evalueer, te takseer en te ontleed, en om oplossings te formuleer vir die nasluitingsgrondgebruik van slikdamme.

Die navorsing is vernuwend omdat dit slikdamme vanuit die oogpunt van landskapargitektuur beskou en ook omdat dit die beginsel van visuele impakte op ‘n nuwe manier bekendstel. In wese moet daar ‘n klemverskuiwing plaasvind vanaf die ontwerp en bedryf van ‘n opdamming om uitskot vir ‘n periode van 20 jaar te bevat, na die ontwerp van ‘n mensgemaakte landvorm in die landskap waar die konfigurasie en grondgebruik aan die einde van die leeftyd daarvan reeds vóór konstruksie oorweeg word. Generiese modelle vir die omgewingsimpakte en ingenieursonkoste dwarsdeur die lewensiklus van ‘n slikdam word beskryf, sodat die ontwerp van die begin af ten opsigte van die omgewingsimpakte en onkoste geoptimaliseer kan word.

Die navorsing steun op die gebruik van modelle en eksperimentele werk. Dit was ‘n uitdaging om ‘n stelsel te ontwikkel wat ‘n werklike situasie sou weerspieël. Daar bestaan onsekerheid ten opsigte van die gedetailleerde prosesse wat die omgewings- en ingenieursaspekte beheer en tot hulle bydra. Onsekerhede word by die voorspellings ingelyf deur ‘n sistematiese en rasionele benadering te volg. ‘n Stelselbenadering verseker dat die omgewingsprobleme wat met slikdamme gepaard gaan nie in afsondering nie, maar eerder holisties oorweeg word.

Die stelsel vir die beoordeling van die lewensiklus van slikdamme met besondere klem op nasluitingsgrondgebruik, kan aangewend word om:

- insethouers reeds in die beplanningstadium aan te moedig om alternatiewe konfigurasies te oorweeg;
- besluitneming te vergemaklik;
- ‘n podium te bied vir opbouende besprekings met die betrokke owerhede; en
- deursigtige skakeling met insethouers te vergemaklik.

Reguleerders, voorstanders en konsultante kan die stelsel gebruik om die implikasies van alternatiewe konfigurasies, soos die afplatting van die kantwalle van slikdamme en die verandering van bedekkingstipes, beter te verstaan.

Deur middel van uitskakeling is die volgende belangrike omgewingskwessies wat die ontwerp van slikdamme beïnvloed, vasgestel:

- visuele aspekte;
- luggehalte-aspekte; en
- wateraspekte.

Hierdie studie kombineer en integreer hierdie omgewingsaspekte met ingenieursonkoste.

Reeds vroeg in die navorsing het dit duidelik geword dat ‘n volledige model verskeie aspekte wat tans nie ingesluit is nie, soos erfenis, toerisme en die lewende omgewing, sou kon bevat. Die uitsluiting van omgewingsaspekte beteken nie dat hulle enigsins minder belangrik is nie. Die uitgangspunt was egter dat slegs sleutelaspekte ingesluit sou word, met die doel om ‘n kragtige, doeltreffende stelsel te skep.

Sommige invoerparameters in die stelsel is nie finaal nie en vereis dat konserwatiewe waardebepalings toegepas word. Toekomstige navorsing kan die voorspellingsmodelle verfyn deur langtermyn moniteringsprogramme in te stel. Hoewel daar onsekerhede bestaan wat sommige van die parameters in die studie betref, kan dit gekonstateer word dat die benadering wat in hierdie tesis ontwikkel en beskryf word ‘n ingewikkelde probleem op só ‘n wyse aanbied dat dit rasionele besluitneming vergemaklik. Hoewel die gebruik van die stelsel nie 'n aanvaarbare uitslag kan waarborg nie, sal dit waarskynlik die konflikte ten opsigte van slikdamkonfigurasie verminder.

Hierdie studie demonstreer dus dat werklike onkoste aan omgewingsimpakte toegeskryf kan word en dat hierdie koste by die direkte ingenieursonkoste gevoeg kan word om 'n totale kostemodel te produseer. En dit is hieruit waar rasionele besluite geneem kan word. Byvoorbeeld, alternatiewe slikdamkonfigurasies en nasluitingsgrondgebruike word vergelyk deur omgewingsveranderings te evalueer, en dít help om kritieke aspekte ten opsigte van die volhoubaarheid van die voorgestelde grondgebuik te bepaal.

Hoewel daar baie uitdagings bestaan wat waardebepaling betref, identifiseer en bespreek hierdie studie die vereistes wanneer visuele, lug- en waterimpakte wat met slikdamme gepaard gaan, geëvalueer moet word.

Sleutelwoorde in alfabetiese volgorde:
Besluitneming, ingenieursonkoste, integrasie, konfigurasie, luggehalte, nasluitingsgrondgebruik, omgewingsimpakte, omgewingsimpak- en ingenieursonkostestelsel, slikdam, sulfaatmassavloeiing, valuasie, visuele waarnemingsafstande.

Acknowledgements

The research presented in this thesis is drawn from a study on the influence of environmental impacts on tailings impoundment design at the Department of Civil and Biosystems Engineering, University of Pretoria (UP), supported financially by Anglo Platinum, Strategic Environmental Focus (SEF), Steffen Robertson and Kirsten (SRK) and the National Research Foundation (NRF). The NRF provided funds through its Technology and Human Resources for Industry Programme (THRIP).

A specific word of mention is firstly due to my study leader and supervisor Prof. Eben Rust, for providing me with the necessary guidance. I also wish to thank my co-supervisor Prof. Gary A. Jones, for mentoring and encouraging me on the many occasions when progress stalled. Both Professors Rust and Jones assisted me in various selfless ways during the preparation of this thesis. I thank them warmly.

I deeply appreciate the selfless input and assistance of the following persons during the past couple of years, listed in alphabetical order:

Brenda Freese	(personal capacity)
Elizabeth Marsden	(Anglo Platinum)
Erich Heymann	(Anglo Platinum)
Heidi van Deventer	(Strategic Environmental Focus)
Jabulile Sibanyoni	(University of Pretoria)
Jaco Viljoen	(University of Pretoria)
Johan van der Waals	(University of Pretoria)
John Wates	(Fraser Alexander)
Ken Lyell	(Anglo American)
Louis Keynhans	(Crown Gold Recoveries)
Lukas Niemand	(personal capacity)
Nicola Liversage (Read)	(personal capacity)
Pierre Rousseau	(personal capacity)
Sanchia Holmes	(personal capacity)
Sean Lindsay	(University of Pretoria)
Steven Bullock	(Anglo Platinum)
Tim Liversage	(personal capacity)
Vee Wolder	(Strategic Environmental Focus)
Wim Mandersloot	(personal capacity)
Yvonne Scorgie	(Airshed Planning Consultants)

The overall system described in this study required specialist input and predictive modelling of various aspects. People who provided input and assistance require acknowledgement and a special word of mention. Hennie Geldenhuys (AngloGold Ashanti) provided background information on the case study site, ERGO Daggafontein tailings impoundment. Permission was also granted to photograph the impoundment as part of the visual perception study.

Mader van den Berg (UP) assisted with the field work and manipulation of the photographs as part of the study to quantify visual perception distances for tailings impoundments. The nominal group technique (NGT) study method was used and required the participation of experts, mentioned in alphabetic order in Appendix A.1, as well as students and academic staff.

The engineering cost model, commissioned as part of this overall study, was developed in collaboration with Caroline Holmes (SRK) (Holmes, 2006). The engineering cost model is based on a system for the costing of environmental mine closure liabilities described by Rademeyer, Jones and Rust (2003). The engineering cost model includes the specific variables required to allow integration with the environmental aspects.

Hanlie Liebenberg-Enslin (Airshed Planning Consultants) provided assistance with the predictive modelling of the air quality impacts (Liebenberg-Enslin, 2006). The roughness height parameter used in the airborne dust dispersion from area sources (ADDAS) model was calibrated as part of this study. This involved field work and required the iterative comparison of predicted results with monitoring data until key parameters were calibrated. The calibrated air quality models used predict the change in dustfall for the various tailings impoundment configurations as part of the overall system requirements. The calibrated models can be used in future to assess the environmental impacts of impoundments with comparable physical tailings properties.

Similarly, the development of the analytical sulphate mass balance model was undertaken in collaboration with Koos Vivier (AGES) as part the input requirement of the overall system (Vivier, 2006).

The following computer software is used:

- ARC/INFO™ geographic information system software is used to spatially represent visual perception influence zones.
- Airborne dust dispersion from area sources (ADDAS) software is used to calculate particulate emission rates. The United States Environmental Protection Agency (US EPA) approved industrial source complex short term (ISCST) Breeze Version 3 dispersion modelling software is used to compute spatial ambient particulate concentrations. Air quality results are mapped as isopleths using Surfer Version 7.
- Both the engineering cost model and analytical sulphate mass balance model uses Microsoft Office™ EXCEL 2003 spreadsheets to analyse information and perform calculations.
- Maps are compiled using ARC/INFO™ geographic information systems software, Corel Draw 12™, Corel Photopaint 12™, and MapSource Version 6,8,0.
- All other text, tables and graphs in the thesis uses the Microsoft Office™ 2003 Suite.

The following organisations are acknowledged for information used to reproduce maps:

- Chief Director: Geological Survey, Council for Geoscience, Pretoria.
- Chief Director: Surveys and Land Information, Mowbray, Cape Town.
- Water Research Commission, Pretoria.

Lastly, I would like to thank Wendy Jones for much needed professional editing pointers over the past couple of years.

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CHAPTER ONE: INTRODUCTION

> "In the past, selecting a preferred alternative disposal method or tailings impoundment site was a relatively simple procedure. Cost estimates could be generated for each option, and the lowest cost option would ordinarily be the hands-down winner. More recently, however, environmental considerations have gained increasing importance, and perhaps nowhere else in mining operations are these environmental issues of more significance than in tailings disposal. Environmental factors are often of equal or greater importance than economic issues in tailings disposal planning, at least in the eyes of regulatory agencies with overall authority for approval of the mining operation and citizens' groups having considerable influence in the political process."
>
> Vick (1983:129)

1.1 The need for a more sustainable legacy for mine residue deposits

Mine residue is the generic term for all types of mining waste and is contained in a mine residue deposit (MRD). Tailings is fine-grained waste material derived from metallurgical processing and tailings impoundment, in the context of this thesis, specifically refers to the structure which contains hydraulically placed fine-grained metallurgical waste.

Mine residue is commonly identified as the single most important source of environmental impact for many mining projects and if its disposal is not designed and managed properly can give rise to environmental contamination. Mine residue deposits are often susceptible to wind and water erosion. Seepage to groundwater and discharge to surface water can give rise to water pollution over large tracts of land. Furthermore, failure to incorporate rehabilitation considerations into the planning stage may result in a mine residue deposit that is difficult and expensive to rehabilitate during the closure stage.

Mining of South Africa's gold and platinum resources has given rise to hundreds of mine residue deposits of which the footprints cover large areas of land. It is estimated that 12 000 ha of land is sterilised by approximately 150 gold MRDs within the Gauteng province alone (Figure 1). The MRDs on this map include sand dumps, slimes dams, tailings impoundments and rock dumps.

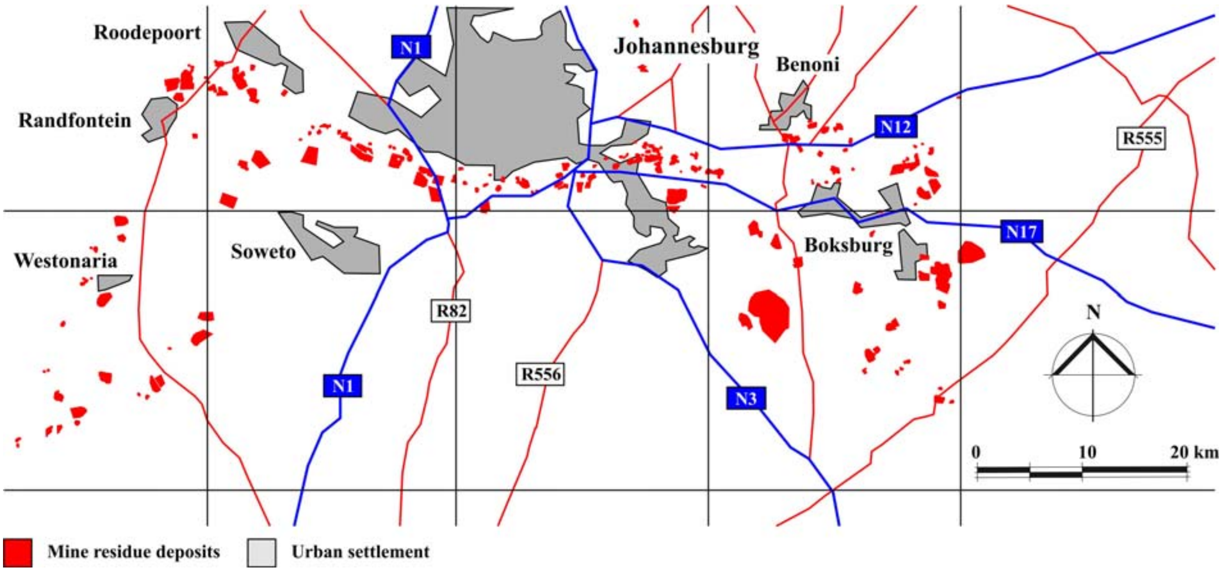


Figure 1: Footprints of mine residue deposits in and around the Gauteng province, South Africa (Rademeyer and van den Berg, 2005).

The legacy of the impacts associated with MRDs, particularly in the long term and after closure, has given rise to an increasingly complex regulatory regime. Approvals for upgrading old facilities, for development of new facilities, and for closure plans are difficult to obtain owing to the lack of a suitable framework within which to make decisions. Since efficient development of the South African mining sector is essential, whilst maintaining a balance with an acceptable level of environmental risk, it is necessary to develop approaches to facilitate transparent and effective regulatory decision making.

Increasingly stringent legislation coupled with more responsible attitudes have in recent years radically changed the situation so that current practice results in tailings impoundments being left in a relatively safe state with minimum immediate physical influence. Whilst this would have been considered acceptable a few years ago, a growing understanding of sustainable development means that the post-closure state of a scheme requires a more positive approach. Aspects such as the post-closure land use and residual impacts of a tailings impoundment have become increasingly important.

Figure 2 (p. 3) illustrates the general perception that the cost of environmental protection works has, over the years, become a much larger proportion of the total tailings impoundment development costs and suggests that this is ever increasing as:

- there is a growing expectation for sustainable development;
- environmental legislation becomes more stringent, and
- stakeholders become more aware of the potential long as well as short term environmental hazards.

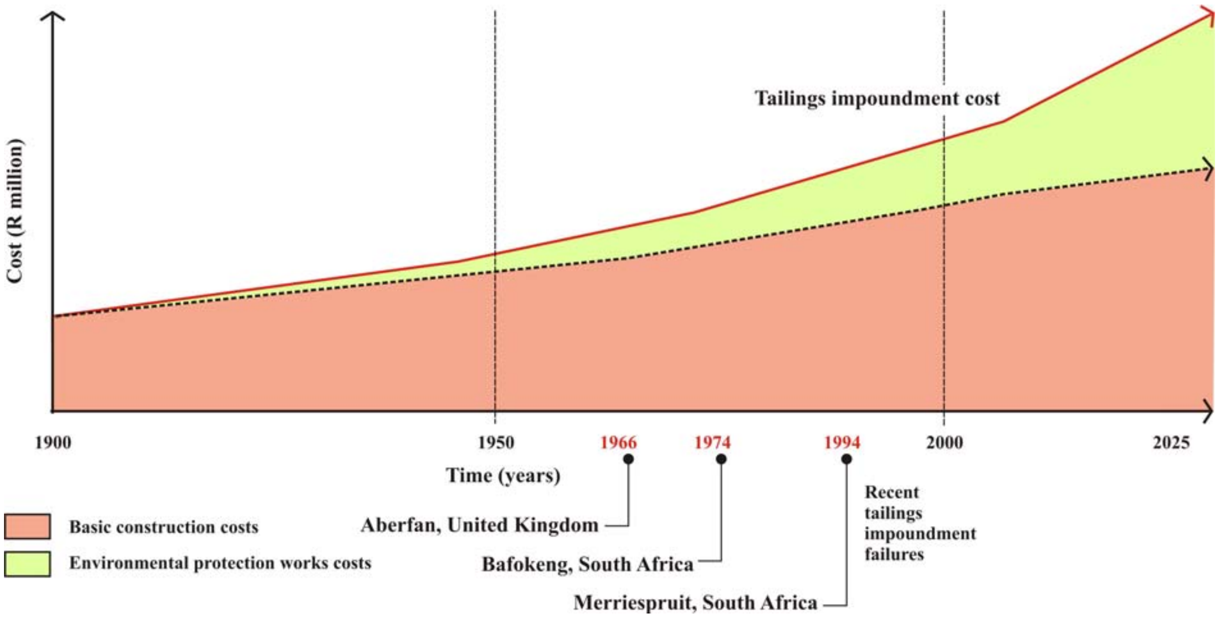


Figure 2: Schematic illustration of perceived increase in tailings impoundment cost over time.

This shows that environmental impacts and costs need to be managed to attain reasonable objectives. What is needed is an approach whereby these objectives can be agreed by all the stakeholders and the impacts and costs evaluated rationally for the especially the post-closure stage of the impoundment. This research presents a comprehensive approach for this purpose. Sustainable development concepts, when applied to tailings impoundments, include rehabilitation with plans for acceptable land use and eliminating or reducing adverse environmental impacts to a long-term acceptable condition. Land development pressures necessitate a paradigm shift when dealing with the problem and what may have been standard practice some years ago is no longer acceptable. This can probably be best illustrated with examples. New residential developments are constructed on vacant land in-between and in some instances adjacent to old mine residue deposits (Figure 3, photograph 1).

1 New residential development in Krugersdorp, Gauteng, South Africa, adjacent to existing un-rehabilitated mine residue deposits.

2 The Top Star drive-in is located on an old mine residue deposit South of the Johannesburg CBD, Gauteng, South Africa.

Figure 3: Land development pressures often lead to the reclamation of old mine residue deposits to make space available. Rehabilitation of existing tailings impoundments also takes place to create some sort of appropriate landform while also addressing significant environmental impacts.

The Top Star drive-in, South of the Johannesburg CBD, is located on a mine residue deposit and demonstrates how something which would otherwise have laid barren after closure is used for something quite novel (Figure 3, photograph 2).

The Geraldton tailings impoundment rehabilitation project is a prime example of how mine residue can be used to create a sculptural landform within a landscape (Figure 4). This impoundment is located at the main entrance to Geraldton, Ontario, Canada. Approximately 14 Mt gold tailings was deposited over 70 ha at an average height of 16 m. It was decided, as part of an economic redevelopment initiative, to reshape the abandoned impoundment and improve its appearance. The landform is not only sculptural but provides for activities such as walking, mountain biking, bird watching and snow boarding. The impoundment could have been designed like this in the first place with sufficient forethought allowing for the same advantages.

1 and 2 The McLeod High tailings impoundment was reshaped to create an environmentally stable sculptural landscape (photographs courtesy of Martha Swartz Partners).

Figure 4: Reshaping an abandoned tailings impoundment into a sculptural landscape.

The planning process is driven by legislation which ensures that the mine owner must comply with the intention of achieving those end conditions, which are defined in broad terms by guidelines. The Mineral and Petroleum Resources Development Act No. 28 of 2002 (MPRDA, 2002) and associated regulations (MPRDA, 2004) set out the process whereby a mine requires a closure certificate, the application for which must be accompanied by an environmental risk report and agreed to by the Chief Inspector and the Department of Water Affairs and Forestry (DWAF). The Minister is given certain rights with regard to the financial provision for closure. The closure objectives which form part of the required environmental management plan must inter alia identify key objectives, define future land use objectives and provide proposed closure costs. It is the latter which transforms laudable aims into reality and with the increasing stringency of regulations and standards, the necessity for reliable closure cost estimates has become paramount.

1.2 Problem statement

> "At first try and understand a new fact not so much in terms of the big problem as for its own sake. That problem may not be as big as you think it is. And that fact may not be as small as you think it is. It may not be the fact that you want but at least you should be very sure that before you send the fact away. Often before you send that fact away you will discover it has friends who are right next to it and are watching to see what your response is. Among the friends may be the exact fact you are looking for. After a while you may find that the nibbles you get are more interesting than your original purpose of *completing what you initially set out to do* (italics indicate own words and emphasis). When that happens, you have reached a kind of point of arrival. Then you are no longer a motorcycle mechanic, you are also a motorcycle scientist, and you have completely conquered the common sense trap of value rigidity."
>
> Robert Pirsig (Pirsig, 1999:312)

The research presented here is an attempt to develop a rational approach to solve problems that relate to the configuration of tailings impoundments and the integration of environmental impacts with engineering design.

Uncertainty exists regarding the detailed processes controlling and contributing to the environmental impacts and engineering aspects. These uncertainties are incorporated into the predictions of the system's behaviour by following a systematic and rational approach. This will ensure that the problems associated with tailings impoundment configuration will not be considered in isolation but holistically.

1.2.1 Typical issues

The typical issues include the:

- lack of rational and systematic approach to facilitate decision making at planning level;
- the need to balance South Africa's economic development and environmental quality;
- geotechnical stability and engineering design aspects.

Rational tailings impoundment planning decisions with regard to engineering and environmental costs and impacts are constrained by the fragmented nature of specialist knowledge and the difficulty in understanding the relative importance of the different impacts in context within an overall design philosophy. Related to this is the problem of not knowing whether to address certain impacts through mitigation during the initial construction stage, or much later as a function of impoundment closure. It is also problematic that in most cases the end use and landform of impoundments are not clearly defined before the onset of the design and assessment of the potential adverse impacts of such a facility. It would therefore appear that impoundment closure plans and post-closure land uses are not informed by following a rational systematic approach.

The Environmental Conservation Act No. 73 of 1989 (ECA, 1989) defines the environment as the sum of the surrounding elements, influences and situations which affect the life and habitat of individual organisms, and the collection of organisms. It also states that the environment can be described as the surroundings in which a scheme is proposed and includes natural resources such as:

- air;
- water;
- soil and landform; and
- people, animals, plants and their interaction.

It is therefore important to understand how a tailings impoundment can impact on these resources in order to determine the nature and level of present and future environmental pollution. The overall objective of understanding and the subsequent management of environmental resources is to maintain a pre-determined environmental quality. Integrated waste management aims to achieve just this through reducing both the generation and the environmental impact of waste. Although economic development of South Africa is necessary, it is important that the health of its people and the quality of its environmental resources are no longer adversely affected by uncontrolled and uncoordinated disposal of waste.

The geotechnical stability of an impoundment is and will remain a very important part of considering the acceptability of either a proposed or existing tailings impoundment and the main engineering emphasis is on the detailed aspects influencing such or the different mechanisms and modes of failure. The flow of large volumes of materials can result in physical impacts to downstream land, property and ecosystems. Biochemical and eco-toxicological effects of pollutants in the slurry can also result in impacts and may even extend beyond the zone physically affected by such materials (Peck, 2005:10). Two recent examples demonstrate this where certain management and operational factors contributed to the tailings impoundment failures at Bafokeng, near Rustenburg, in 1974 and Merriespruit, near Virginia, in 1994.

At Bafokeng, from the breach in the impoundment, the liquefied slurry spread at a distance of 4 km to a width of 800 m and a depth of 10 m. The flow of slurry continued down the Kwa-Leragane River into the Elands River. It is estimated that approximately 2 million m^3 of slurry eventually flowed into the Vaalkop dam 45 km downstream of the impoundment.

The Merriespruit failure occurred on the evening of 22 February 1994. The failure of the North wall occurred following a heavy rainstorm. More than 600 000 m^3 tailings and 90 000 m^3 water were released. The slurry travelled about 2 km covering nearly 50 ha. It is fortunate, given the downstream population, that only 17 people lost their lives in this tragedy.

1.2.2 Planning constraints

Planning constraints can present a problem to the designer and planner of a tailings impoundment in terms of time, cost, space and environmental protection. Similarly the regulatory authorities are mostly concerned with socio-environmental issues. They all have internal constraints such as resources to do the work.

The present planning process is unsatisfactory since it is insufficiently defined. Essentially it comprises analysing an application at the design, construction, operation or closure stages in the life of a mine residue deposit (MRD) to ascertain whether it does or will comply with various regulatory criteria intended to prevent adverse environmental impacts (Rademeyer, Wates, Bezuidenhout, Jones, Rust, Lorentz, van Deventer, Pulles and Hattingh, 2007).

This planning process, as with many decision processes, has three distinct elements. These are:
- an acceptable set of environmental standards and criteria;
- an acceptable measurement or prediction of environmental impacts; and
- a complete set of questions linking the criteria and impacts.

For example, the question may be "Will the local groundwater regime be unacceptably polluted by the proposed MRD?" To answer this it is necessary to have defined an acceptable level of pollution – which may or may not be zero – and also to have appropriate measurement or prediction of possible pollution together with an appreciation of the reliability of the measurement or predictions.

Despite the present process containing these elements in some manner, the lack of definition (as said before) means that it cannot be described as a complete, formal, consistent system. The overall result is that neither the regulatory authorities, nor the proponents of a scheme and its designers are satisfied.

There are many constraints which exist or could exist to dictate the final post-closure land use of tailings impoundments. Lyell (1989) stated, more than a decade ago, that:

> '…modern tailings disposal is influenced by economic and environmental factors…' and that '…environmental aspects are being influenced by outside legislative forces, whereas economic aspects are within the control of the mining companies and therefore require careful deliberation.'

It is apparent that regulators are moving into an era where it is expected of mines to gear their operations towards achieving sustainable post-closure environments. There is a tendency for authorities to favour or demand reclamation in the pre-mining conditions. With this expectation comes the requirement to reshape the original topography, or re-establish indigenous vegetation, which in most cases is unattainable and could severely limit the potential for development of sustainable post mining land uses with the potential for financial gain (Robertson, Devenny and Shaw, 1998b).

An expectation to achieve such a post-closure land use for present tailings impoundments has certain constraints – steepness of slopes, length of slopes, shape of slope, characteristics of tailings, suitability and availability of material on site for rehabilitation, establishment of vegetative covers, surface run-off and groundwater pollution to name but a few. Therefore, it could be argued that there is no reasonable expectation for such facilities ever returning to the original pre-mining environment.

It therefore seems reasonable to broaden the legislative view in order to consider other sustainable land uses, which may or may not include returning the land to its original use. The land use selection process after Roberson and Shaw (1998a) is illustrated in Figure 5.

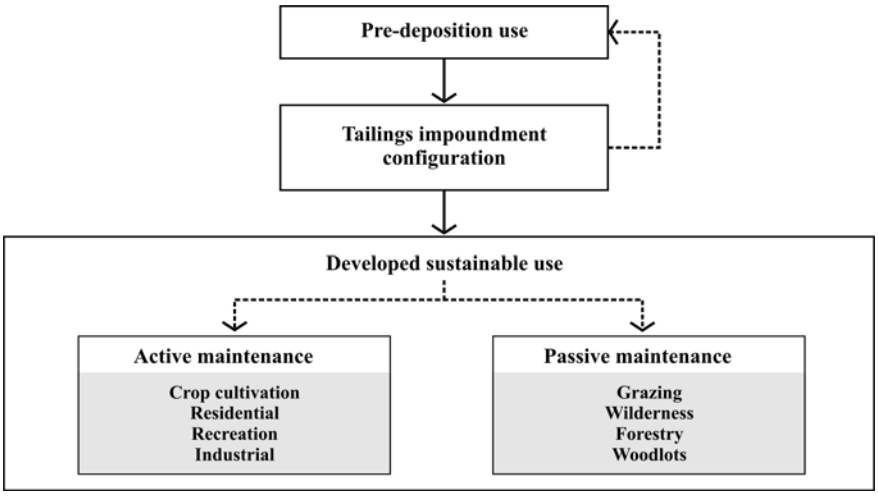


Figure 5: The land use selection process for developed sustainable land use (Roberson et al., 1998a).

Thus a need exists to develop a system and models so that various strategies for alternative land uses can be compared. Any of the proposed end land uses may in itself be the subject for further research. A number of land uses have been and are currently being investigated. It is anticipated that these investigations will develop their own criteria for assessing their viability in the short to medium term and their sustainability in the long term, i.e. they will have developed their cost benefit and value criteria. One of the intentions of the proposed system is to integrate these individual projects and their sustainability assessments by using a common basis for the evaluation of very different land uses.

1.2.3 Modelling liability and cost

Tailings impoundment environmental liability over time is modelled and illustrated in Figure 6 (p. 9). This simplistic model demonstrates the change in environmental liability and the shaded envelope indicates what can be best described as the hypothetical environmental liability at any stage. The dashed red line is only representative of a typical situation at present before closure and will fluctuate within the envelope depending on design and construction (development), operation and closure considerations. The solid plum coloured line represents a tailings impoundment with a slight increase in environmental liability over time after closure and is typical of an impoundment that although shaped to provide rain storm holding capacity the post-closure land use is not clearly defined, the impoundment is aesthetically unacceptable, and it will require ongoing maintenance after closure.

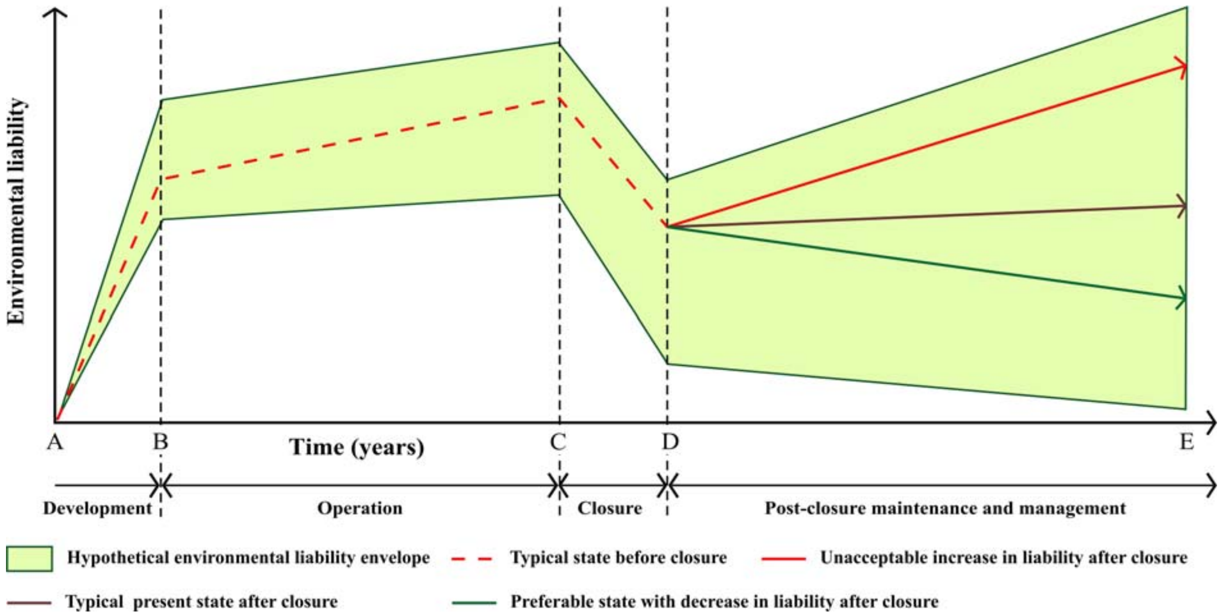


Figure 6: Conceptual environmental liability over the life of an impoundment.

An increase in environmental liability is not desirable and the worst case is the significant increase of liability after closure as represented by the solid red line. An acceptable state may be described as any line within the envelope where the liability decreases after closure. In an ideal situation the line would show zero at the end of closure with no future liability. Although this may not always be possible, it should be aimed at. Almost anything before closure could be acceptable even if not necessarily desirable and most economical.

This figure illustrates the liability at any stage during the construction and operation of a tailings impoundment. For example, for the dashed line from A to B, whilst the impoundment is being developed – starter walls and drainage systems constructed – the liability increases more or less linearly as the earthworks and drainage systems are being built.

From B to C as deposition begins and continues it may be assumed that the environmental liability increases as a function of the height or the volume of the material impounded and reaches a maximum at the end of life.

From C to D during closure, some form of rehabilitation takes place with the intention to drastically reduce the environmental liability. As mentioned before, this liability will ideally be reduced to zero, but at present it must be accepted that a some sort of environmental liability is likely to remain and indeed that this will probably increase in time as shown from D to E even if ongoing maintenance measures are put in place.

Conceptually similar models could be drawn up showing total costs, i.e. normal operation costs plus environmental protection costs, throughout the life cycle of a tailings impoundment (Figure 7).

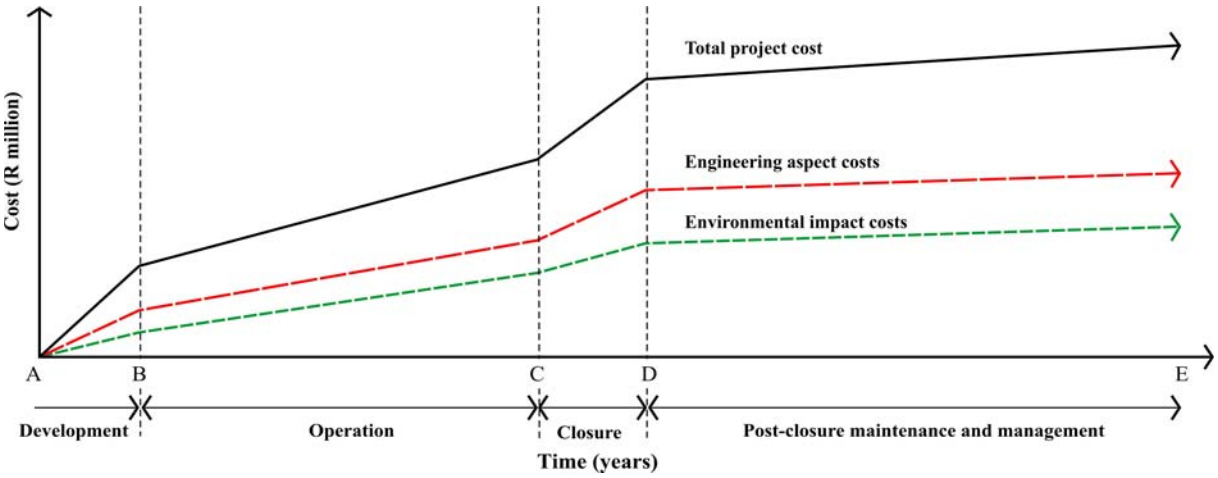


Figure 7: Total tailings impoundment life-cycle costs combining environmental impact costs and engineering aspect costs.

These models could be integrated to show cumulative costs at any point in the cycle. All these models use the common measuring unit of costs and can simplistically be shown as equations of the form:

	Impoundment development stage			
	Development[1]	**Deposition**	**Closure**	**Post-closure**
Total Cost AE =	Cost AB +	Cost BC +	Cost CD +	Cost DE

[1] Development is the term used to describe the design and initial construction stages.

The system if it is to be optimised is not linear but has iterative loops so that, for example, cost AB cannot be determined without first knowing what the end land use is for period DE. This indeed is the essence of the research, which is that the current approach is operated as a simple linear system in which the sustainable end use does not inform the planning and design decisions and that this approach needs to change.

It has been deliberately stated that the proposed cost model is in some sense simplistic and by this it is implied that such models will not satisfactorily represent reality. This is because human values cannot be seen only in terms of economics (Figure 8, p. 11). Three examples, which could readily be applied to tailings impoundments, are the aesthetic evaluation, long term environmental impacts and the social benefits of the end land use. The aesthetics could be an evaluation of the appearance of the rehabilitated impoundment. Does it look natural or is it too geometrically precise? The social benefits could be that one particular end use provides some benefit to a community albeit at a cost. These benefits, or disadvantages, must also be added to the cost models to produce a more complete picture and they apply not only to the end land use but also throughout the process, supporting the concept of sustainable development.

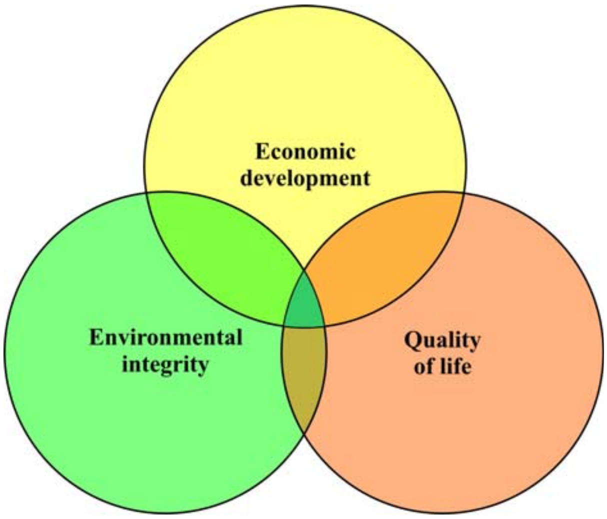


Figure 8: Three components of sustainable development.

The methodology for establishing the criteria and evaluating any situation against these criteria is now well defined through conventional environmental impact assessments. Some careful consideration, however, has to be given to balance costs and other values in any situation. Again, methodologies are available from the social sciences for this purpose.

Although some methodologies are available the problem is that the second line in the table below is not readily expressed as a cost in money terms preventing the addition of lines 1 and 2. In other words at as long as line 1 is apples and line 2 pears they cannot be added, but if line 2 can be converted to apples they can be added. This will result in a total cost model where the parallel equation which evaluates impacts, both negative and positive, will be supplemented by an impact cost:

	Construction	Deposition	Closure	Post-closure
Engineering Cost =	Cost AB +	Cost BC +	Cost CD +	Cost DE
Impact Cost =	Impact AB +	Impact BC +	Impact CD +	Impact DE
Total Cost =	Cost + Impact AB +	Cost+ Impact BC +	Cost + Impact CD +	Cost + Impact DE

With a realistic total cost model, different options can be evaluated. At the planning stage ideally, but if necessary at any later stage, different end land uses can be tested so that rational selections of the most appropriate use can be made.

In addition the influence of different strategies during construction and operation can be tested in the model to optimise the cost/impact of those strategies. The simplest example of this is evaluating the cost/impacts of the construction of the end use preferred slopes from the start of the impoundment, or at any intervening phase and hence deciding the most beneficial approach.

Clearly for construction and operation periods of typically two or more decades the cost calculation aspects of the model must be financially correct. Similar financial models already exist, for example in the road construction and maintenance field, which have comparable life spans. It is proposed that these or other appropriate methods should be modified where necessary and agreed after discussion with the mining industry.

1.3 Hypothesis

> "A hypothesis is a supposition or proposed explanation made on the basis of limited evidence as a starting point for further investigation."
>
> (Oxford, 2002:570)

> "What you are up against is the great unknown...you need some ideas, some hypotheses. Traditional scientific method, unfortunately, has never quite gotten around to say exactly where to pick up more of these hypotheses."
>
> Robert Pirsig (Pirsig, 1999:280)

It is postulated that tailings impoundment can be designed and constructed taking account of both the environmental costs and benefits and engineering costs to produce an optimal sustainable end land use. In order for this integration to succeed a systematic approach and rational system is required that can model the environmental and engineering costs for a range of design options such as slope change or different covers. The system must also allow that one item can be examined either individually or in total to test the sensitivity of the overall system to each item's input. The system must also be robust enough to be modified if necessary to deal with changed environmental and engineering criteria.

Models which can realistically evaluate costs in monetary terms are required of the following aspects (Figure 9):

- visual aspects;
- air quality aspects;
- water aspects;
- soil and landform aspects; and
- engineering aspects.

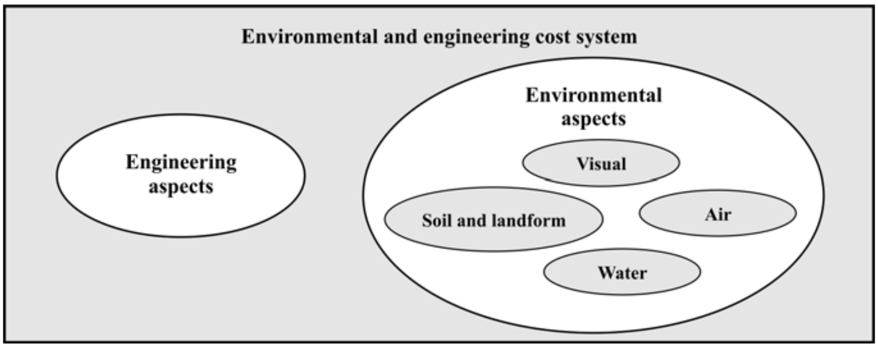


Figure 9: Components of the overall costing system.

The hypothesis therefore states that if the tailings impoundment is designed with the short- and long-term land use of storing tailings and functioning as an acceptable natural landform in its context, it will potentially increase the rehabilitation success, decrease the total construction cost, and support a future land use acceptable to all stakeholders. Integrating environmental planning aspects with engineering design will result in environmental, social and economic benefits in the long-term.

1.4 Problem solution

> "We are at the very beginning of time for the human race. It is not unreasonable that we grapple with problems. But there are tens of thousands of years in the future. Our responsibility is to do what we can, learn what we can, improve the solutions, and pass them on."
>
> Richard Feynman, US educator & physicist (1918 - 1988)

This thesis focuses on the landform configuration of tailings impoundments and the management of environmental impacts associated with such configurations. The emphasis is on post-closure land use alternatives and examines how end uses and resulting environmental impacts will influence the initial conceptualisation, design, construction and operation of tailings impoundments.

Although there are many environmental and engineering aspects in the tailings impoundment planning continuum which influence decision making (Figure 10), the following issues define the basis and scope of the problem statement:

- visual intrusion;
- decrease in air quality; and
- impact on water.

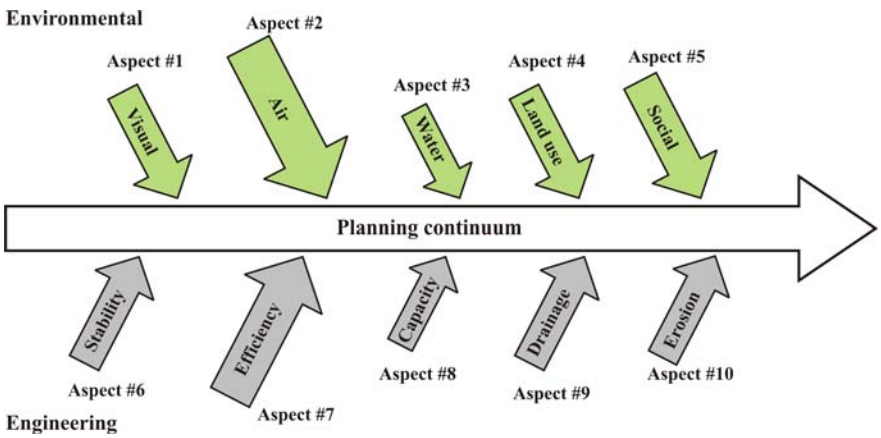


Figure 10: Representation of environmental and engineering aspects in the planning continuum.

This requires the development of an approach whereby environmental and engineering cost are modelled and used as the basic measuring method. To achieve this it is necessary that environmental change must be quantified and valuated. A further requirement will be to develop procedures where methods to quantify such impacts are lacking. It may even be required that the total costs will have to be supplemented by value scales to assess intangibles such as aesthetics and perceived social benefits.

The system aims to provide a rational framework to:

- inform the planning process during the conceptualisation of feasible alternatives;
- assist with decision making;
- facilitate constructive discussion with relevant authorities; and
- enable transparent liaison during public participation with interested and affected parties.

1.5 Thesis organisation and structure

The thesis describes a system for the sustainable configuration of tailings impoundments and consists of the following chapters:

CHAPTER ONE: INTRODUCTION

Chapter 1 serves as an introduction to the thesis providing enough information to set the context for the thesis, and discusses and states the problem.

CHAPTER TWO: LITERATURE REVIEW

The literature on several key components relating to the art, philosophy, science and technical aspects of the influence of tailings impoundments on the environment are presented and discussed in Chapter 2.

CHAPTER THREE: EXPERIMETAL WORK AND MODELLING

Chapter 3 describes the experimental method and case study site, models the key environmental aspect influences on the environment, and costs the engineering aspects for various impoundment configurations.

CHAPTER FOUR: RESULTS

This chapter presents the results of the key environmental aspects and engineering cost for the various tailings impoundment configurations modelled.

CHAPTER FIVE: COMBINING ENVIRONMENTAL IMPACTS WITH ENGINEERING COSTS

This chapter combines the environmental impacts with engineering costs to determine and describe the influence of slope and cover change on engineering costs.

CHAPTER SIX: INTEGRATING ENVIRONMENTAL IMPACTS COSTS WITH ENGINEERING COSTS

Chapter 6 demonstrates that by valuating environmental impacts they can be added to engineering costs to provide a total cost which can be used to evaluate the change in slope and cover.

CHAPTER SEVEN: INFLUENCE OF ENVIRONMENTAL IMPACTS ON TAILINGS IMPOUNDMENT DESIGN - DISCUSSION

This chapter discusses the influence of environmental impacts on tailings impoundment design.

CHAPTER EIGHT: CONCLUSIONS

Chapter 8 draws conclusions from the system developed and provides recommendations.

CHAPTER TWO: LITERATURE REVIEW

"...we have been chosen to look after life in our lonely cosmos, by fate or providence or whatever you wish to call it. As far as we can tell, we are the best there is. We may be all there is. It's an unnerving thought that we may be the living universe's supreme achievement and its worst nightmare simultaneously."

Bill Bryson (Bryson,2004:572)

"If a scientist had at his disposal infinite time it would only be necessary to say to him, "Look and notice well"; but as there isn't time to see everything, and it is better not to see than to see wrongly, it is necessary for the scientist to make a choice in terms of the scope of the research."

Jules Henri Poincaré (Poincaré, 1946)

"...tailings disposal methods have progressed from early days, when tailings – without knowledge of or concern for their ultimate fate – were allowed to flow into streams, up to present day disposal methods, which ideally match the tailings characteristics, and disposal methods in a somewhat rational manner..."

Vick (1983:301)

2.1 Manmade landforms within the natural landscape

Landscape design may well be recognized as one of the most comprehensive of arts for the following reasons:

- the activities of man disturb the existing balanced order of nature within the biosphere and it would therefore seem that man can through intervention restore the balance;
- man's intervention calls for efficient and sustained existence; and
- man creates around him an environment that is a projection into nature of his abstract ideas.

The mind of intellectual man has always responded to the tranquillity and assurance of certain geometrical forms such as the square and circle, although the manifestations of these in the landscape vary according to:

- geography;
- society;
- economics;
- morals; and
- philosophy.

Similarly, the response of man to an artificial landform made today out of mine residue is probably identical with the response to such a hill made in ancient Pre-Columbian America or Egypt, no matter how different the environment. The mechanism of the five senses, i.e. sight, smell, taste, touch, and hearing, through which all perceptions pass to stimulate emotions have scarcely changed since pre-history. Ancient civilisations, such as the Mayas and Egyptians, set their mark on the landscape by raising artificial hills or re-arranging stones. The Mayas built huge ceremonial centres which were designed to impress externally – an ordered and geometric microcosm of surrounding mountains and valleys. The Mayan pyramids (Figure 11, photograph 1) were typically stepped, faced with cut stone, and furnished with one or more ceremonial stairways leading to the temple or sacrificial altar at the summit. Buildings, mounds and pyramids were part of a comprehensive space design. Inca constructive energy was directed towards food terraces and fortifications rather than the building of monuments and temples. The engineering splendour lies more in creating something that is in harmony with the environment than in aesthetic and architectural skill (Figure 11, photograph 2).

[1] A typical Mayan pyramid used for ceremonies (photograph from www.bigstockphoto.com).

[2] Machu Picchu, an Inca citadel of the Andes, is placed sensitively within the landscape (photograph from www.bigstockphoto.com).

Figure 11: Ancient man's expression within the landscape.

Egyptian expression of the aesthetic was visual rather than literary. Monuments were inspired by mountains and whether temple, monument or tomb the scale was superhuman to express an idea greater than life. The pyramid (Figure 12 photographs 1 and 2) was the eternal mountain formed from a profound knowledge of geometry with the golden mean underlying all proportions and is still the grandest symbol on earth of human aspiration as seen through abstract geometry. The geometry of elements within the landscape reflects a view of the world in which every object and being has its allotted place.

The Egyptian pyramids at Giza (c. 2500 B.C.) are perhaps the simplest and most fundamental man-made landforms in all landscape architecture. The largest of the three pyramids, the funerary great pyramid of Cheops, is the largest in the world and built by 20 000 men with 2,3 million limestone blocks weighing on average 2,75 t each (Jellico, 1987).

Photographs [1] and [2] from www.bigstockphoto.com.

Figure 12: The Egyptian pyramids are perhaps the simplest and most fundamental man-made landforms in all of landscape architecture.

2.2 Minerals and mining

2.2.1 Introduction

The need for energy, minerals and metals results in the alteration of the earth's surface. The environmentally-conscious society of today demands that the disturbed areas must be returned to a predetermined acceptable and sustainable land use. In principle, it is no longer acceptable to leave disturbed land to heal by itself. However, the current consideration of mine residue deposit closure liabilities leaves much to be desired – general environmental law is unambiguous and yet the perceived implementation and enforcement thereof pertaining to tailings impoundments is far from satisfactory. So does the configuration of tailings impoundments in South Africa require new laws? Probably not! There must instead be a continuation of environmental protection through the existing environmental impact assessment laws, regulations and tools and in particular there is a need to acquire more skills in the art of integrated environmental planning that will result in sustainable landscapes.

South Africa's mining industry has developed from the mid to late nineteenth century to a well-established global industry responsible for approximately 7,5 % of South Africa's annual gross income (MMSD, 2001) and produces almost 15 % of the world's gold and 60 % platinum group metals (PGMs). It is more than a hundred and fifty years ago that Pieter Jacob Marais panned for and found gold in the Jukskei and Crocodile rivers to the North of Johannesburg (Mendelsohn and Potgieter, 1986:1). It was not long after this first discovery that initial prospecting gave way to mining with the subsequent establishment of a great industry along the line of the Witwatersrand. PGM resources of the Bushveld Complex were discovered in 1924 by Hans Merensky and Andries Lombaard (Matthey, 2005). While gold production has been on the decline over the past decade PGM production has increased steadily resulting in numerous new and expansion PGM projects not only on the western but also on the eastern limb of the Bushveld Complex.

2.2.2 Mineral wealth of South Africa

The geology of South Africa is a diverse and unique. Despite occupying only 1 % of earth's land surface, the country was or still is the world's largest producer of chromium, gold, manganese, platinum group metals (PGMs) and vanadium. South Africa possess large resources and reserves and is a world-class producer of iron, titanium, zinc, coal, fluorspar, refractory minerals, phosphorus as well as copper and lead. Hectare for hectare, the northern half of South Africa is the richest piece of real estate on earth. In addition, South Africa has a very long and complex geological history with its oldest rocks dating back 3 600 million years and contain a very special and long record of life preserved as fossils in the rocks (Wilson, 1998:1; McCarthy and Rubige, 2005:14).

Significant exploitation of South Africa's mineral resources started with copper mining in the Namaqualand area in the middle of the nineteenth century. The mining industry experienced rapid growth after the discovery of diamonds near Kimberly and gold on the Witwatersrand in 1867 and 1886 respectively, followed by the opening up of coal fields and the discovery of platinum in the Transvaal Supergroup and Bushveld Complex respectively. The development led to the mineral industry becoming the economic backbone of the country and a major force in world mineral supply. The mineral industry has been instrumental in developing much of the country's secondary industries as well as infrastructure.

2.2.3 Witwatersrand Supergroup

Geologists classify and group together rocks that are related both in time and space, the largest grouping of such rocks is known as a Supergroup (Mendelsohn and Potgieter, 1986:21). The Witwatersrand Supergroup (Figure 13), underlying the northern Free State, southern Gauteng and North West provinces in an elongated basin, consists mainly of sedimentary rocks that accumulated 2 800 and 2 400 million years ago in layers 6 000 m thick. Rock types include, predominantly shales (former mud and silt) and quartzites (former sand) as well as conglomerates (Mendelsohn and Potgieter, 1986:21).

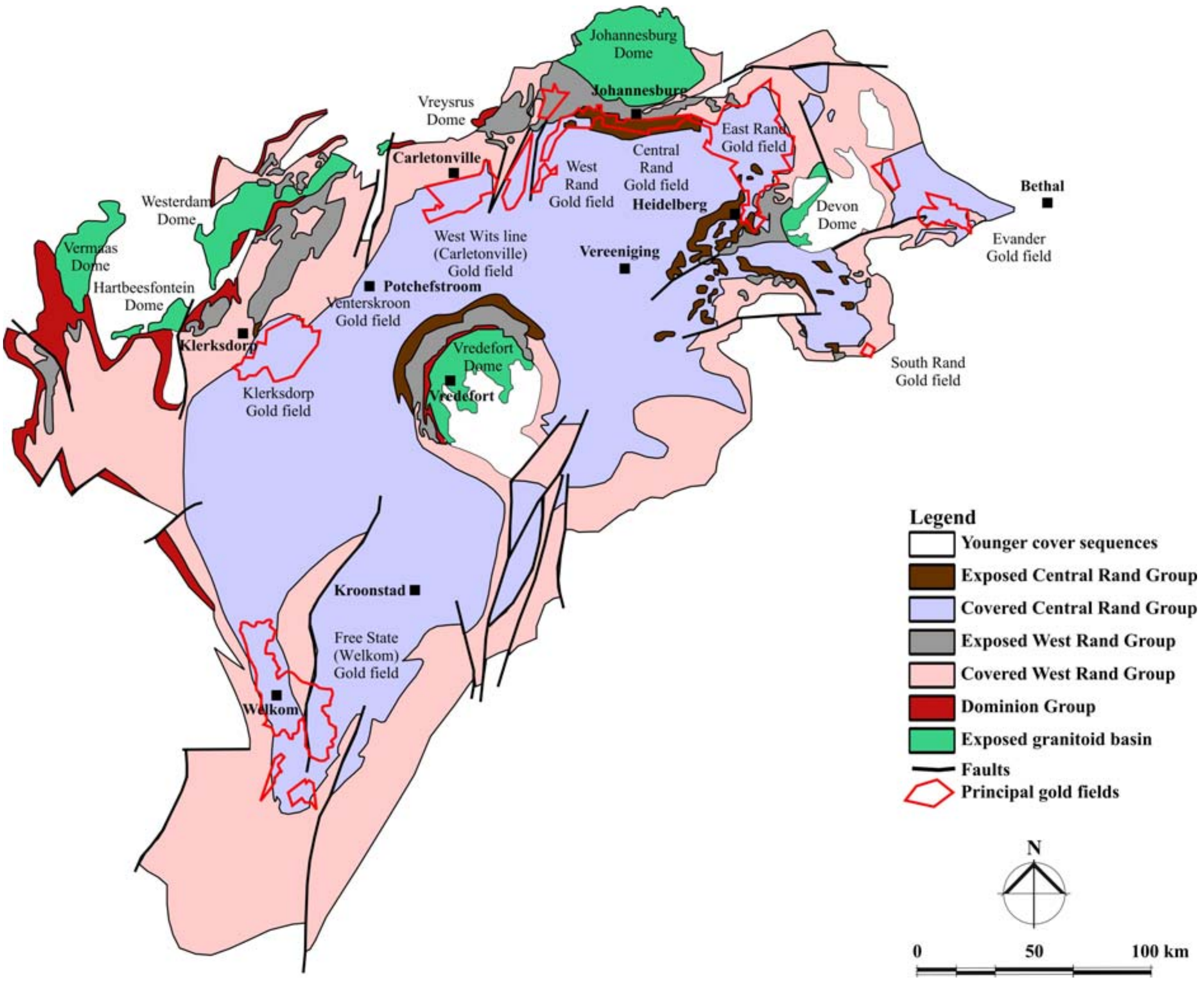


Figure 13: Simplified geological map of the Witwatersrand Basin with the principal gold fields delineated (Robb and Robb, 1998:296).

Parts of the Witwatersrand Supergroup were capped by lava more than 1 600 m thick known as the Ventersdorp lava. As a result of the outpouring of lava the rocks of the Witwatersrand basin experienced severe faulting and folding having a profound effect on the geology of Johannesburg. When the rocks were formed conditions on earth were vastly different from today. Perhaps the most significant difference was the absence of plants, which resulted in rapid erosion (Mendelsohn and Potgieter, 1986:21, 34). Today, most of the Witwatersrand Supergroup rocks are still buried beneath younger rocks and soil, and outcrops in the northern half of the basin.

The Witwatersrand Supergroup has been subdivided into two main groups, namely the lower West Rand Group, which consists of equal proportions of shale and quartzite, and the upper Central Rand Group, which consists mainly of quartzite with abundant conglomerates. These groups are further subdivided into subgroups. The West Rand Group is subdivided into three subgroups, namely the Hospital Hill, Government and Jeppestown subgroups, while the Central Rand Group is subdivided into two subgroups – the Johannesburg and Turffontein subgroups. The Witwatersrand Supergroup, in particular the Johannesburg subgroup of the Central Rand Group, is the world's largest repository of gold containing an estimated 82 000 t of the metal (Wilson, 1998:1; Mendelsohn and Potgieter, 1986:23).

Gold industry

The origin of gold mineralization in the Witwatersrand basin has been controversial for decades, with the argument favouring detritus (placer), modified placer and hydrothermal origins. The placerists noted a strong sedimentological and lithhological control on gold distribution, whereas the hydrothermalists emphasized the secondary characteristics of the ore mineral suite. The modified placer model attributes the present position of gold composition and shape to small scale movement in solution of the detrital gold.

Despite the controversy around the origin of the gold morphological evidence for two distinct varieties of gold show that gold occurred both as grains and nugget-like shapes, produced by the disintegration, weathering and movement of rocks, as well as secondary grains with obvious recrystallised textures ranging in size between 0,005 and 0,5 mm in diameter. The gold-bearing conglomerates also contain several other minerals, all characterised by above average density. Such minerals contain predominately uranium and iron sulphide as well as carbon-rich minerals known as bitumen (McCarthy and Rubige, 2005:106). By-products include silver, uraninite-brannerite, pyrite and platinum group elements (Robb and Robb, 1998:339).

Gold was South Africa's largest export for a number of years, but has now been replaced by platinum (Table 1). Despite this gold mining still contributes approximately 4 % directly to the GDP.

Table 1: South Africa's precious metals production, 1994 – 2003.

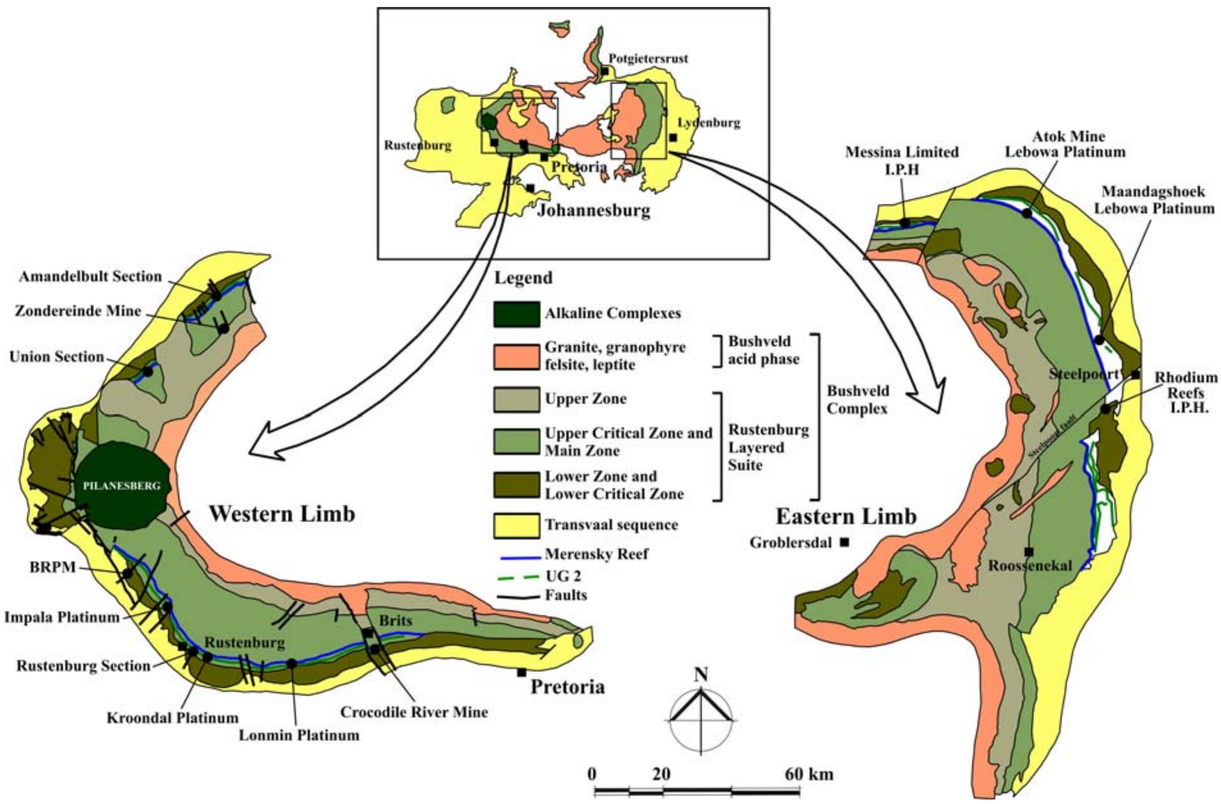
		Production (kg)	
		Gold	**PGM**
Time (years)	**1994**	580 200	183 900
	1995	523 800	183 000
	1996	498 300	188 600
	1997	490 600	196 000
	1998	465 100	199 900
	1999	451 200	216 400
	2000	430 800	206 770
	2001	394 800	228 700
	2002	389 300	236 600
	2003	372 800	266 200
	Total	**4 596 900**	**1 929 300**

South African precious metals production statistics from DME (2004:43, 49).

Much of the materials used in gold mining are sourced from the domestic economy. Taking into consideration these indirect contributions, gold mining's total contribution to GDP is closer to 10 % (DME, 2004). The gold mining industry will, therefore, continue to play a substantial role in the export earnings of South Africa. In 1995, the gold reserve base was ranked number 1 in the world with 37 885 t (40,4 %). South Africa also produced 523,8 t of gold in 1995, down 10 % from the previous year. Gold production continued to decline with only 372,8 t of gold being produced in 2003 (Table 1, p. 20).

2.2.4 Bushveld Complex

The Bushveld Complex (Figure 14) is the world’s largest known layered intrusion, centred in the Limpopo province it extends 65 000 km^2 into the Mpumalanga, North West and Gauteng provinces.



Map of the limbs of the Bushveld Complex after Eales (2001:8).

Figure 14: A geological map of the exposed limbs of the Bushveld Complex indicates the extent of inferred PGM and other mineral resource.

Broadly, the Complex is compiled of several successive layers of crystallized magma (igneous rock) grouped into five different suites based on the chronological progression of magmatic events. These suites include the Rooiberg Group, the Marico Diabase Suite, the Rustenburg Layered Suite, the Rashoop Granophyre Suite and the Lebowa Granite Suite.

The Rooiberg Group, the oldest group of igneous rocks, is a series of volcanic rocks formed by basaltic magma that did not reach the surface and is, therefore, considered part of the underlying Transvaal sequence. The intrusive basalt (mafic rocks), comprising the Rustenburg Layered Suite, formed the largest known underground chamber in the world. The Lebowa Granite Suite intruded above the older basalitic body and crystallized as granite (McCarthy and Rubige, 2005:121). The Rustenburg Layered Suite is further subdivided into five zones, namely the Marginal, Lower, Critical, Main and Upper zones from the base upwards. The Marginal zone contains no known economic mineralisation, while the Lower and Critical zones contain the 25 chromitite layers as well as the Merensky layer (known for its PGM deposits) and the Bastard layer. The Main zone is particularly resistant material commonly known as black granite (also know as the dimension stone) and the Upper zone contains Iron-rich deposits as well as magnetite, anorthosite and vanadium (Viljoen and Schürmann, 1998:534, 535, 537). The Bushveld Complex is also often referred to in terms of its geographic compartments, namely the Far Western Limb, the Western Limb, the Eastern Limb, the Northern Limb (also known as the Potgietersrust lobe) and the Bethal Limb, differing in area, thickness and degree of exposure (Eales, 2001: 7, 36).

What makes the Bushveld Complex unique from other igneous rock formations is its extraordinary size, thickness and continuity of the layers, the magnificent exposures of structural details and the importance of the economic minerals (Eales, 2001:7). Most of the minerals and rock types found in the Bushveld Complex are quite common and have no commercial value, but some layers are composed of more unusual minerals and are economically important. Three layers are particularly well known for the mining of PGMs, namely the Merensky Reef, the Platreef and the UG2 (McCarthy and Rubige, 2005:124). Currently, the Merensky Reef has been the source of most of South Africa's PGMs, with an estimated reserve of 17 000 t. It is characterised by its high PGM grades and a higher ratio of platinum to the other PGMs.

The UG2 Reef, which is more consistent throughout the Bushveld Complex, is richer in chromite, but lacks the Merensky's gold, copper and nickel by-products. Its PGM reserves are estimated to be almost twice as large as those of the Merensky Reef. In the northern extension of the Bushveld Complex, the Platreef platinum to palladium ratio is found in equal measure, as opposed to three to one in the Merensky and UG2 deposits (DME, 2004). In addition, the Bushveld Complex has significant deposits of magnetite, vanadium, titanium and tin making it one of earth’s treasure chests (Eales, 2001:8; McCarthy and Rubige, 2005:124).

Platinum industry

Platinum mining has a relatively short history as a result of the fact that, even within prime sources of platinum, the particle size of the ore minerals is measurable in microns or less, rendering it difficult to recover the metal. Furthermore, the metal is highly refractory, with a melting point of 1 769 °C, well above that obtainable in laboratories in the early twentieth century. The presence of platinum had been more of a nuisance in the gold mining activities in Colombia. Gold deposits were abandoned where the platinum content was found to be too high, as platinum needed to be hand picked or extracted by mercury amalgamation (Eales, 2001:70).

There are six PGMs, namely palladium (Pd), rhodium (Rh), ruthenium, (Ru), iridium (Ir), platinum (Pt) and osmium (Os), all with exceptional properties of resistance to corrosion, high melting points, high lustre and performance as catalysts for chemical reactions. These properties are beneficial, amongst others, in the chemical, electrical and petroleum refining industries as well as the jewellery trade (Viljoen and Schürmann, 1998:532; Eales, 2001:73).

South Africa is firmly established as the premier source of these metals as its proportion of platinum is at 40 – 60 % of the total PGMs recovered. In general, the ore mined contains only some 5 – 10 parts by weight of precious metals in every million parts of host rocks (Eales, 2001:77). In 2000, South Africa accounted for 56 % (63 000 t) of the world's known PGM reserves (112 820 t) and produced 46 % (206,7 t) of the world supply (Table 1, p. 20 and Table 2).

Table 2: World PGM reserves and supply, 2003.

	Reserve Base*				Supply		
Country	**t**	**%**	**Rank**		**kg**	**%**	**Rank**
South Africa	70 000	87,7	1		266 150°	59,3	1
Russia	6 600	8,3	2		128 768@	28,7	2
Canada	3909	0,5	4		20 335@	4,5	3
USA	2 000	2,5	3		18 700*	4,2	4
Other	850	1,1	-		15 241@	3,4	-
Total	79 840	100,0			449 194	100,0	

Sources: * USGS (2004, pp 124 – 125)
@ Kendall (2004, pp 52 – 56)
Notes: ° Production
@ Platinum, palladium and rhodium only
* Platinum and palladium production only

World PGM reserves and supply statistics from DME (2004)

The export value of this was close to R25 billion (Table 3). At the current rate of extraction, South Africa has reserves that could maintain production for the next 600 years (Eales, 2001:73, McCarthy and Rubige, 2005:12). The demand for platinum is set to continue, certainly in the auto industry where sales of gasoline-powered vehicles are increasing and as platinum replaces palladium as an auto-catalyst (DME, 2001). The outlook for Western supplies of platinum should increase by up to 10 % as expansions in South African and North American mining capacity come on stream.

Table 3: The role of South Africa in world mineral supply reserve base.

Commodity	**Unit**	**Reserve Base**	**World**	
			%	**Rank**
Chromium	Mt	3 100	68,3	1
Copper	Mt	13	2,1	12
Diamonds	-	NA	NA	4
Gold	t	37 885	40,4	1
Iron	Mt	5 900	5,7	8
Lead	Mt	3	2,4	6
Manganese	Mt	4 000	81,4	1
PGMs	t	62 816	55,7	1
Silver	kt	10	2,4	7
Titanium minerals	kt	72 000	17	2
Uranium	kt	179,1	5,6	7
Vanadium	kt	12 500	44,8	1
Zinc	Mt	15	4,5	4
Zirconium	kt	14 300	26	2

The role of South Africa in world mineral supply reserve base from Wilson and Anhaeusser (1998:7)

2.2.5 Other economically significant minerals in South Africa

In 1995, some 57 different minerals, produced from 816 mines and quarries were sold domestically and exported to 81 countries amounting to R44 billion earnings. Coal, diamonds, iron ore, copper, nickel, chrome, manganese, zirconium minerals and granite are of the more popular after gold and platinum (Wilson and Anhaeusser, 1998:5, 6).

2.2.6 Summary

Since humans first started to use simple stone tools, they have become increasingly dependent on mineral-derived products and artefacts. The earth's growing population and their improving standards of living perpetuate an increasing dependence on minerals. As a result, large quantities of minerals are crushed, milled and processed to recover the metals and minerals required for industrial and consumer products. With a product to residue ratio varying between 1:60 000 and 1:200 000, the mining industry has a substantial amount of fine-grained waste (tailings) to dispose. Tailings disposal is, therefore, a significant part of most precious metals mining operations.

In South Africa, the areas around Johannesburg, Carletonville, Klerksdorp, Welkom, Evander, Mokopane (Potgietersrus), Polokwane (Pietersburg), Rustenburg and more recently, Lydenburg, hosts some of the most striking man-made landforms within the natural landscape demonstrating mankind's ability to modify natural landscapes in a most intrusive manner.

It is estimated that about 12 000 ha land is sterilised by approximately 150 impoundments within the Gauteng Province. Wilson and Anhaeusser (1998:15) provide a figure of 4 000 ha for the Witwatersrand basin alone. To sustain the present rate of precious metals recovery which is in excess of 640 000 kg per annum, between 3 000 and 9 000 ha land is required during the life of mine for the purpose of disposing mine residue. And it is further estimated that of this, between 1000 ha and 3500 ha, will be required to sustain PGM production within the Bushveld Complex. Figure 15 provides a 'figure-ground' snapshot of gold mine residue deposit footprints within the Gauteng province after 150 years.

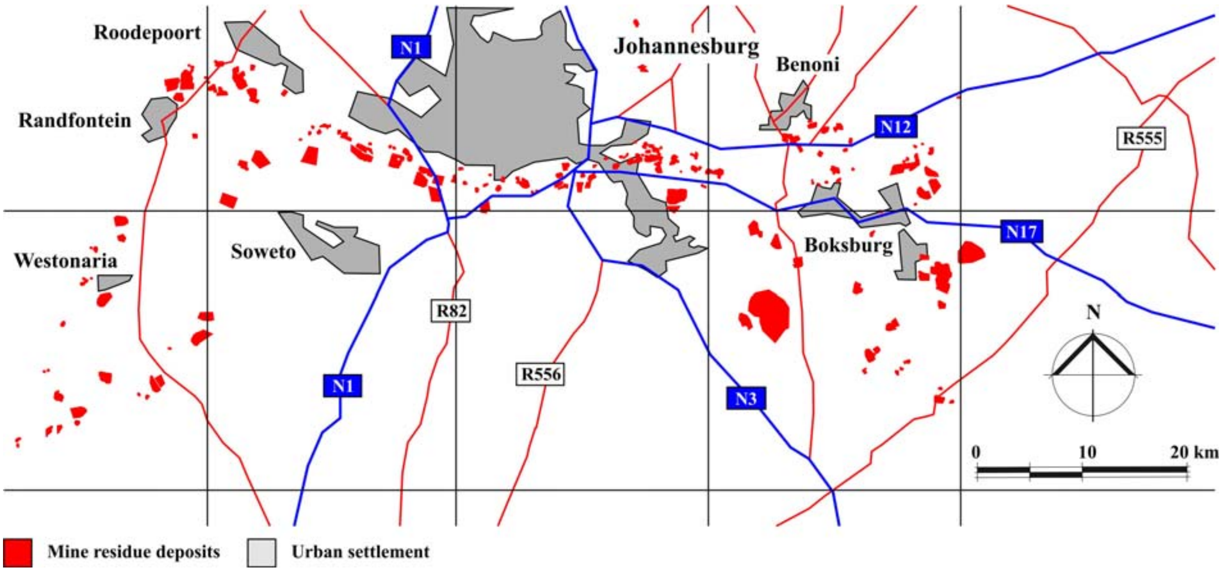


Figure 15: Surface area covered by mining residue deposits within and around Gauteng Province (Rademeyer and van den Berg, 2005).

Figure 14 (p.21) provides a geological map of the exposed limbs of the Bushveld Complex which indicates the extent of the inferred platinum group metals (PGMs). Similar to Figure 15 (p.24) which indicates the land covered by mine residue deposits in and around Gauteng, Figure 16 provides a snapshot of the extent, at present, of mine residue disposal in the Rustenburg Region. With thousands of tonnes still in PGM reserves for the Western and Eastern Limb it is asked whether the Bushveld Complex's Eastern Limb follow suit?

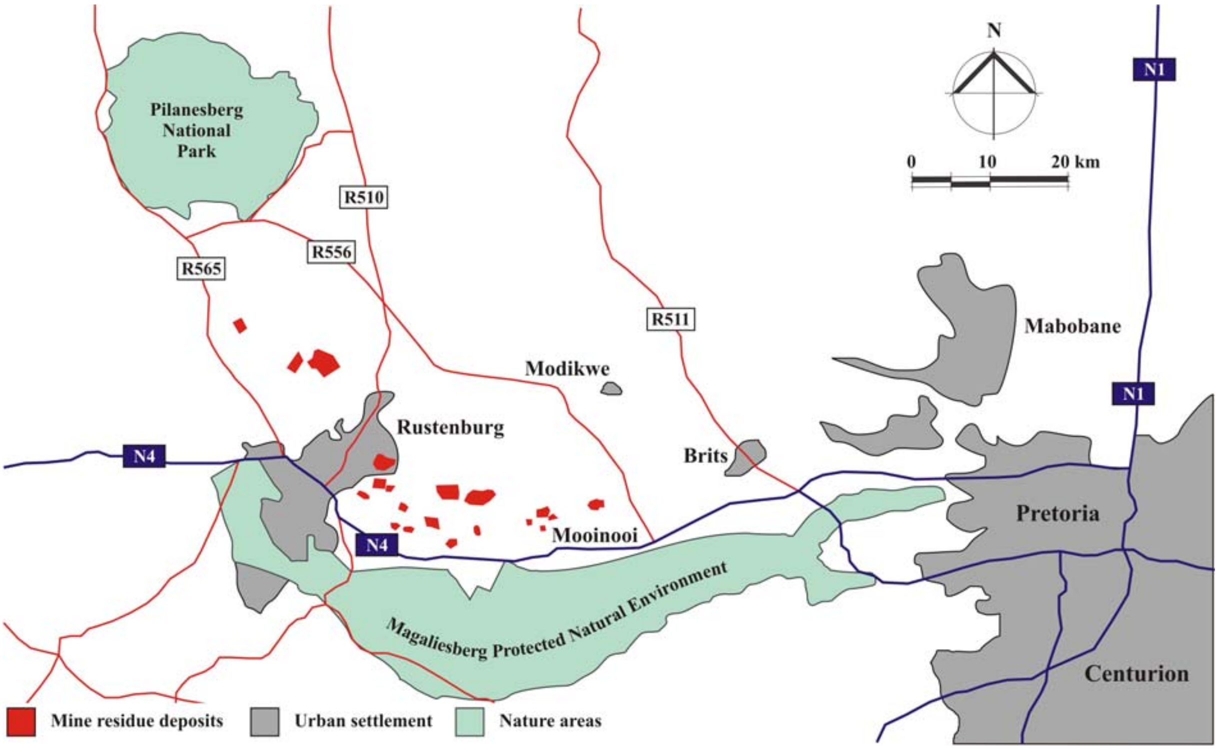


Figure 16: Footprints of mine residue deposits in and around the Rustenburg Region, South Africa.

Considering the nature and the scale of mine residue disposal it is not surprising that the image in the mind of the public is that mining is a dirty and dangerous activity that leaves the environment irreparably scarred and degraded. Historically, economic rather than environmental factors have governed the mining industry. However, issues of safety, pollution and rehabilitation of the environment are now of major concern. Responsible environmental management must balance the negative environmental effects and the positive developmental and financial benefits that result from the optimal exploitation and utilisation of raw materials (Wilson and Anhaeusser, 1998:12).

Detailed geological investigations are required in order to decide on the placement and design of such facilities at the onset of mining. Geology is considered significant to the placement of tailings impoundments for the following reasons:

- it influences the geotechnical founding of impoundment structures;
- geological composition of the reefs mined may be characterised by high levels of sulphide minerals and heavy metals which upon milling, concentration and exposure to water and oxygen can result in seepage characterised by low pH and high sulphate levels;
- it is important not to locate impoundment in close proximity to aquifers in which groundwater may be susceptible to contamination; and
- the lithology and structure of the underlying formations determine the direction and rate at which contaminants migrate migrate away from the tailings impoundment.

In response to changes in environmental legislation the location, design, construction and management of tailings impoundments have received much attention in recent years. Several methods of tailings disposal exist such as the disposal of tailings slurry in impoundments, dry or thickened tailings in impoundments or free-sanding piles, backfilling underground mine workings and open-pits as well as sub aqueous disposal.

The most common method within the South African landscape is slurry impoundments and more specifically the upstream method ring-dyke type raised embankment impoundment. The ring-dyke is best suited to flat terrain in the absence of topographic depressions. These impoundments are also usually laid out with a regular geometry, resulting in a uniform configuration (Figure 17).

[1] View of one of the Grootvlei Proprietary Mine ring-dyke tailings impoundment's which lies to the north-east of Springs, Gauteng.

[2] View of one of the many gold tailings impoundments in the Welkom Region, Free State.

Figure 17: Views of upstream constructed ring-dyke impoundments.

2.3 Tailings characterisation and disposal

2.3.1 Introduction

The previous section describes the scale at which gold and platinum are exploited which results in a substantial amount of fine-grained mining waste. The waste can be disposed of using either temporary or permanent solutions, one of which includes the containment of the waste slurry in a tailings impoundment. Tailings impoundments are some of the largest earth structures in the world and require an in-depth understanding of geotechnical principles. Impoundments receive intense regulatory attention and public scrutiny and can be considered as one of the most important sources of environmental impacts related to mining projects.

Historically tailings disposal began as the practice of dumping tailings into nearby streams which progressed to empirical design of impoundments based on trial and error. Since the early 1960's geotechnical engineering design principles based on water retention dam design practices have been applied.

More recently the configuration is the result of multidisciplinary input over many and diverse fields considering aspects such as:
- metallurgical processes;
- materials characteristics and chemical nature;
- engineering behaviour of tailings; and
- environmental impacts.

2.3.2 Mineral processing

Vick (1983) states that fundamental steps in mineral processing includes:
- initial crushing and grinding;
- concentration of those particles that contain the highest mineral value; and
- separation of mineral values in the concentrate which leaves the remaining particles as tailings.

The final step is the disposal of tailings (Figure 18).

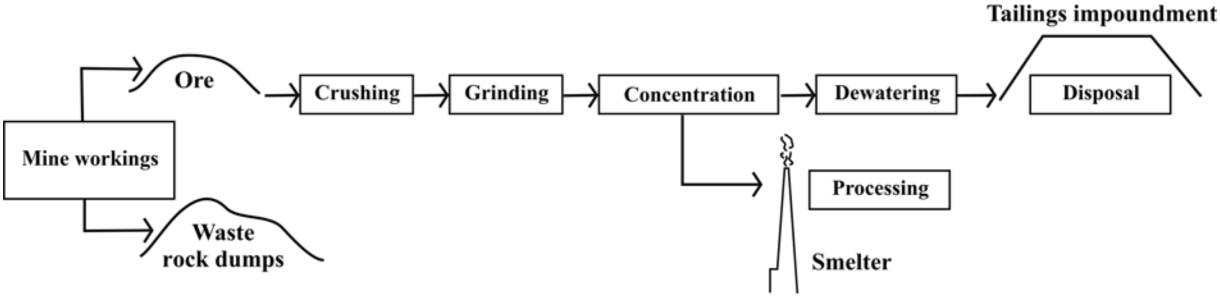


Figure 18: Typical mineral process indicating the context of tailings disposal.

2.3.3 Engineering characteristics

The engineering behaviour of tailings is determined by aspects such as the characteristics of the material, the nature of the deposit, and the method used for tailings disposal. The particle size distribution of the tailings is important as this determines the possibility of separating the material into coarse and fine fractions. The coarser fraction of the slurry is used to construct the outer slope of the impoundment while the finer and less free-draining material is deposited within the outer retaining embankment. Figure 19 provides typical illustrative gradation envelopes for gold and platinum tailings.

Actual particle size distribution depends on factors such as the:

- fineness of the milled ore;
- degree of weathering of the ore;
- type of milling process; and
- separation and concentration process.

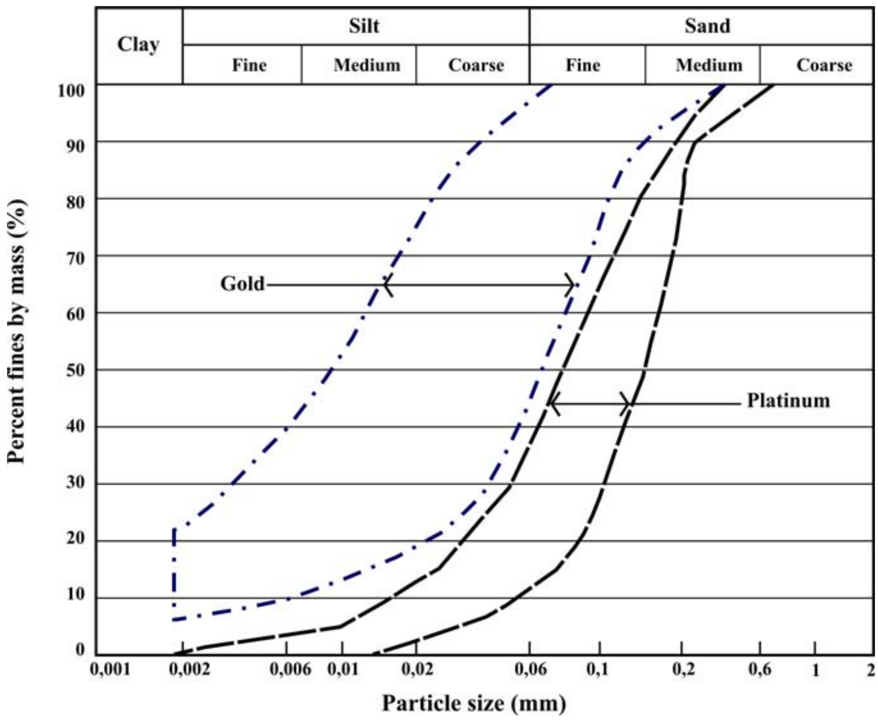


Figure 19: Typical particle size envelopes for gold and platinum tailings (CM, 1996:19).

Depositing tailings hydraulically can lead to the stratification of material within the impoundment which influences the shape of the phreatic surface and the seepage losses. The shear strength and coefficient of consolidation of the tailings affects the rate at which the impoundment may be built. Further, the material may exist in a loose state and when the loose structure is combined with a high state of saturation this may reduce the strength of the material especially if it is subjected to shear stresses such as those resulting from seismic events which can result in liquefaction and subsequent flow of material (CM,1996:18-22).

Layout

Some general tailings impoundment layouts are:

- cross valley - similar to conventional water storage reservoir;
- side hill - generally where hydrology and topography precludes cross valley layout; and
- ring-dyke - suitable for relatively flat terrain with a high ratio of embankment fill to storage volume and illustrated in Figure 20.

The fine sand and silt-sized tailings (coarse fraction) from the gold and platinum mines are used to construct ring-dyke impoundments which is used to contain the slurry.

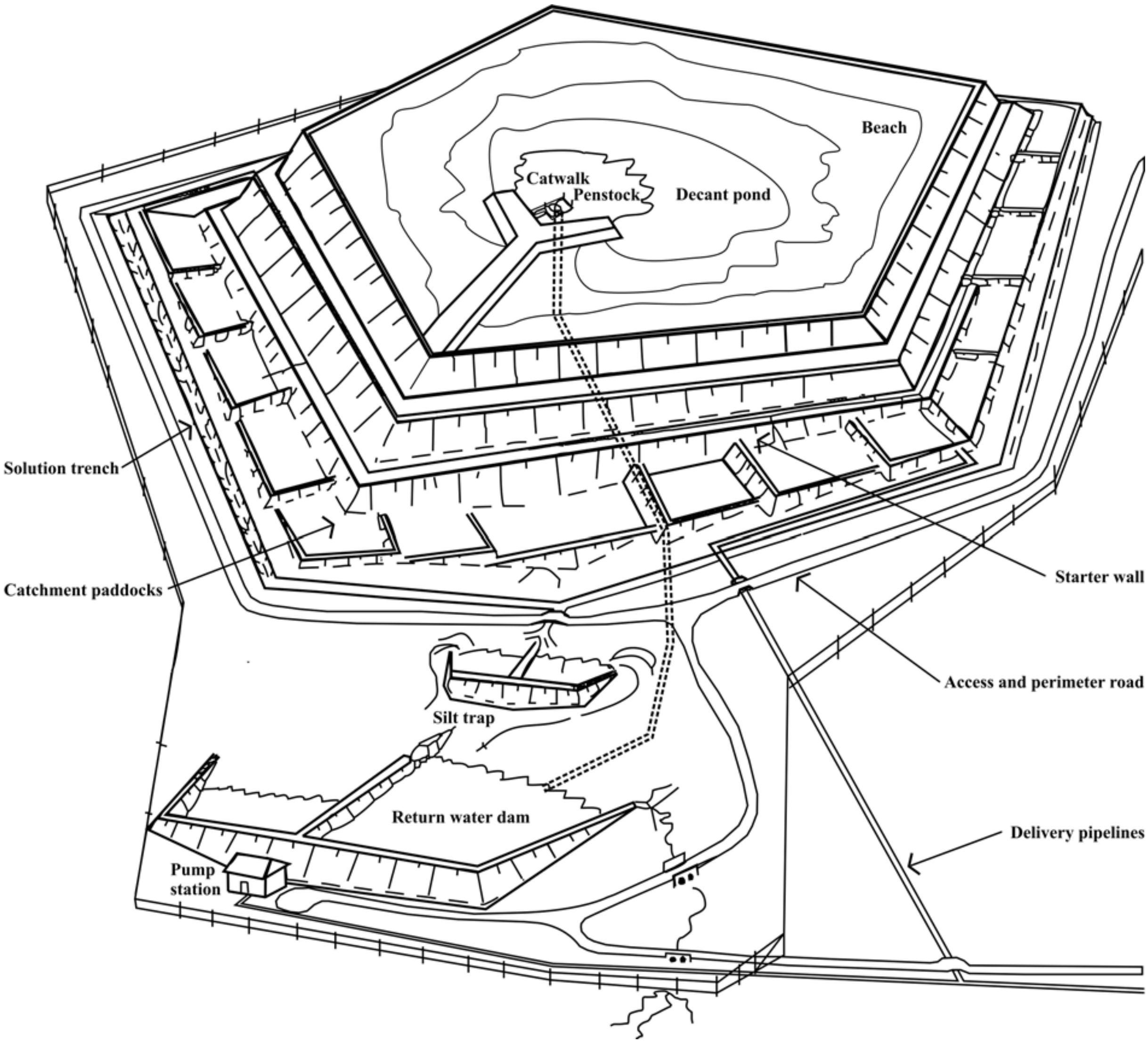


Figure 20: Schematic of upstream deposited ring-dyke tailings impoundment (CM, 1996:169).

Construction method

Surface disposal of tailings is widely used in South Africa and can take a variety of forms but are generally characterised by the fact that they impound hydraulically placed fine grained material. This thesis focuses on upstream ring-dyke impoundments as this has been and still is used widely by both the gold and platinum mining industries. The embankment method designation refers to the direction in which the crest moves. The most common raised embankment methods of disposal include:

- downstream;
- centre-line; and
- upstream.

Upstream ring-dyke raised embankment impoundments usually require a starter wall constructed from borrowed material in order to allow for the initial storage of flood inflows. Deposition of tailings proceeds upwards and inwards to form the final profile of the impoundment as the level rises. The tailings is discharged around the periphery to form a beach and pond (Figure 21). A competent beach is required to support the subsequent perimeter dyke.

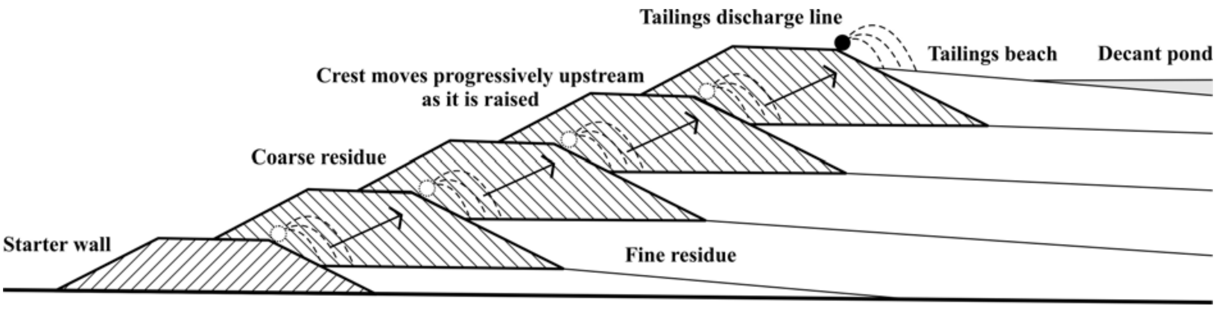


Figure 21: Cross-section through an upstream deposited ring-dyke impoundment embankment.

Factors such as phreatic surface control, water storage capacity, and seismic liquefaction susceptibility constrain the application of the upstream raising method. As with any homogenous dam the location and management of the phreatic surface is in crucial determining the embankment geotechnical stability. It is essential to keep the phreatic surface away from the downstream slope. Once the phreatic surface reaches the slope, the positive pore pressure acting close under the surface of the slope and where the total pressure is small, can so reduce the effective stress that the strength falls sufficiently to permit shallow rational slips to occur.

Important factors that influence the phreatic surface location are the:

- permeability of the foundation relative to the tailings;
- degree of grain-size segregation and lateral permeability variation within the deposit; and
- position of the pond water relative to the embankment crest.

Upstream embankment, while a simple and cost efficient raising method, can only be justified if the constraints discussed above can be adequately addressed. Tailings deposited by spigotting usually results in two distinct classes of material namely sands and finer grained slimes. Spigot deposition is generally used when tailings has a wide grading curve and especially where it also has a fairly high percentage of fines such as is the case with platinum tailings. The sands are controlled by mechanical hydraulic sorting mechanisms and the slimes are deposited by sedimentation. The tailings is spread on to a gently sloping beach leading to the decant pond with the sand sizes settling out first.

Slope stability

For any earth material, there is maximum angle, called the angle of repose, at which it can be safely inclined and beyond which it will fail (Marsh, 1997:80). The angle of repose varies widely for different materials, from 90 ° in strong bedrock to less than 10 ° (1:6) in some loose, unconsolidated materials. Moreover, in unconsolidated material it may vary substantially with changes in water content, vegetative cover, and the internal structure of the particle mass. This is especially so with clayey materials. A poorly compacted mass of saturated clay may give way at angles as low as 5 ° (1:12), whereas the same mass of clay with high compaction and much lower water content may be able to sustain angles greater than 45 °(1:2). In most surface materials the angles of repose are difficult to define with much accuracy because influencing factors, such as moisture content, vary a lot.

In surface deposits of homogenous composition the angle of repose can be defined with some confidence (Marsh, 1997:80). This is especially so for coarse materials, such as sand, pebbles, cobbles, boulders, and bedrock itself, which are less apt to vary with changes in water content and compaction. Representative angles of repose for some of these materials and others are given in Figure 22. Beyond the angles shown, these materials are susceptible to failure in which the slope ruptures and slides, slumps, falls, or topples, or in the case of saturated materials of clay, silt, and loamy composition, flows down slope.

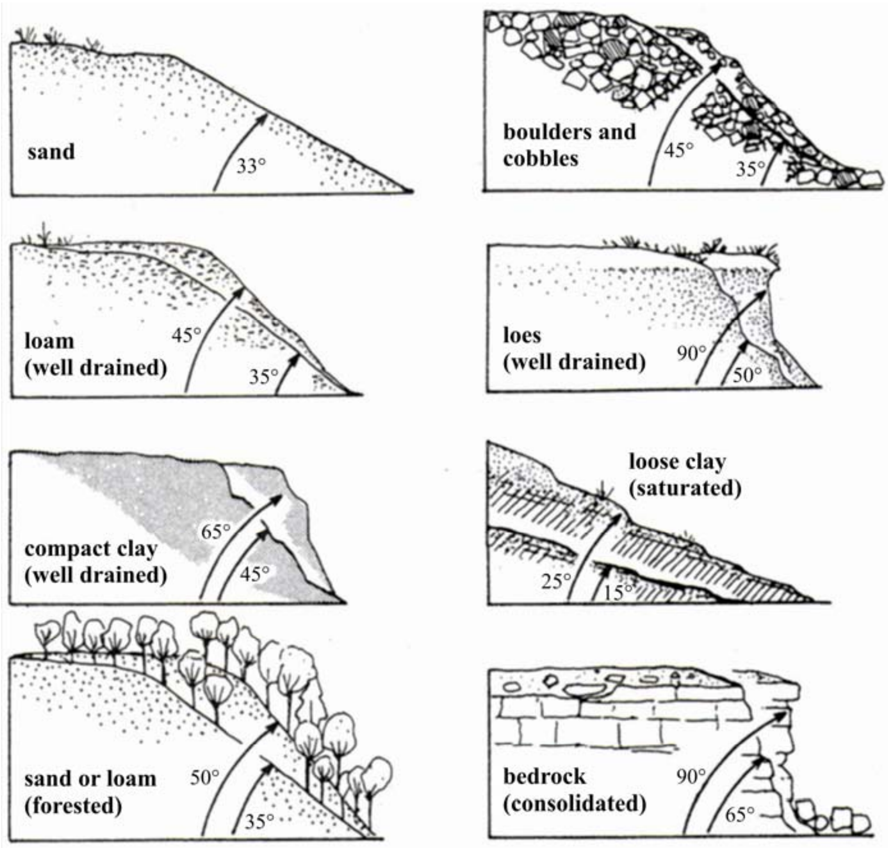


Figure 22: Angles of repose for various types of slope materials (Marsh, 1997:81).

The influence of vegetation on slope is highly variable depending on the type of vegetation, the cover density, and the type of soil (Marsh, 1997:87). Vegetation with extensive root systems undoubtedly imparts added stability to slopes composed of clay, silt, sand, and gravel, but the influence is limited mainly to the upper 1 to 2 m where the bulk of the roots are concentrated. For very coarse materials such as cobbles, boulders, and bedrock blocks, the influence of vegetations is typically not significant unless large trees buttress loose rock. On sandy slopes such as sand dunes, the presence of a forest cover can increase the slope by 10 to 15 ° to above 33 ° producing a metastable slope condition. Such slopes are sometimes marked by a distinctive convex profile.

In addition to the overall angle, form or shape can also be an important factor in slope analysis (Marsh, 1997:82). Form is expressed graphically in terms of a slope profile, which is basically a silhouette of a slope drawn to known proportions with distance on the horizontal axis and elevation on the vertical axis.

Five basic slope forms are detectable on contour maps:

- straight;
- S-shape;
- concave;
- convex; and
- irregular.

These forms often provide clues about a slope's makeup, past behaviour, and potential stability. For resolving land use planning and landscape management problems it is necessary to understand the relationship between slope form and various geologic, soil, hydrologic, and vegetative conditions in order to identify typical and atypical slope shapes and conditions in different areas. In areas where slopes are comprised of unconsolidated materials (soils and various types of loose deposits), and where bedrock is not a controlling factor, slope form is often the product of the interplay and balance among vegetation, soil composition, and runoff processes.

Understanding phreatic surface conditions is an important step in evaluating slope stability. Tailings impoundments contain a lot fines which may impede drainage. A combination of a high fines content and hydraulic deposition can result in the build-up of a phreatic surface within the impoundment which could adversely affect its stability. The evaluation of tailings impoundment embankment slope stability, using analytical procedures, comes after the assessment of the phreatic conditions.

The following typical factors contribute to uncertainties in the analysis of slope stability:

- variation in tailings properties that are difficult to predict and measure;
- variation in the properties of an impoundment which depend on method of deposition, operation and maintenance practices, and climate;
- the difficulty to predict pore pressures and phreatic surfaces which vary with time, seasons and weather; and
- the difficulty and inherent problems due to shortcomings in sampling, test procedures and test equipment.

The engineering behaviour of tailings is complex, is determined by the characteristics of the material itself and the nature of the deposit, and must be interpreted in the context of classical soil mechanics theories for behaviour of natural soils. However, proper application of these theories requires taking into account that tailings have unique characteristics (Vick, 1983:68).

Slope stability analysis for tailings embankments concentrates on initial rational-type slides incorporating the rigid-body assumptions of limiting-equilibrium analysis. These analyses represent only conditions of incipient failure and are not intended to describe the behaviour of the embankment after failure has been initiated (Vick, 1983:187).

Stability analysis using the most critical slip surface, which is unlikely to be simply circular, is sensitive to slope angle. At the design stage a safe slope can be chosen using the available knowledge about the strength and deformation parameters of the tailings assuming that the pore pressures will be controlled by the planned drainage.

A number of methods are available to model the stability of embankment slopes. The end product of analysis of a given trail or potential failure surface is the factor of safety (F). A factor of safety of more than 1,0 will theoretically not fail and less than 1,0 failure must have occurred. A minimum factor of safety of 1,3 is viewed adequate for tailings impoundments operated under close and continual supervision. However, a long-term safety factor of 1,5 is preferable (CM, 1996:65).

For dry cohesionless tailings a shallow critical failure surface will be found. This can be simplified by considering an infinite-slope. With an infinite-slope it is assumed that the potential failure surface is parallel to the surface of the slope and at a depth that is small compared with the length of the slope and in such cases the slope is considered to be of infinite length with the end effects being ignored (Craig, 2004:357). The following infinite-slope relationships for dry and saturated slopes are useful in conjunction with simplified analysis for cohesionless materials (Vick, 1983:189).

This approach is only taken to demonstrate the relationship between factor of safety and slope angle.

No pore pressure

$$F = \frac{\tan \phi'}{\tan \beta} \tag{1}$$

Where:
F = factor of safety for conditions with no pore pressure
ϕ' = friction angle
β = embankment slope angle

Seepage parallel to the slope

$$F = \frac{\gamma' \tan \phi'}{\gamma_{sat} \tan \beta} \tag{2}$$

Where:
F = factor of safety for saturated conditions or seepage parallel to the slope
γ' = buoyant density of tailings = $\gamma_{sat} - \gamma_w$
γ_{sat} = saturated density
γ_w = density of water

Using Equations (1) and (2) a graph can be drawn to demonstrate the expected general trend in terms of embankment safety factor for various slopes (Figure 23) given a friction angle of 37°, buoyant density of tailings as 1000 kg/m^3, and the saturated density of tailings taken as 2000 kg/m^3.

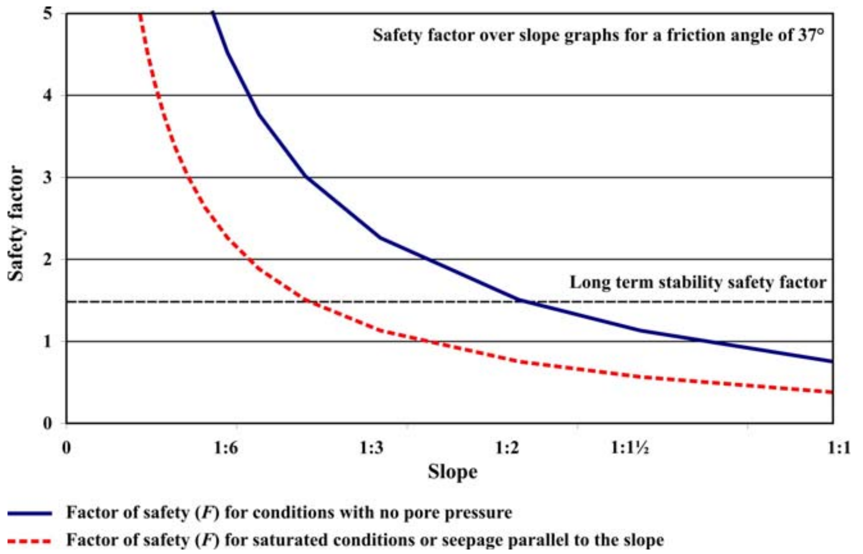


Figure 23: Typical slope safety factors for various slopes given a critical state parameter for the tailings of 37°.

There is an increase in the safety factor with the flattening of the slope for both unsaturated and saturated conditions. In most instances the phreatic surface will be kept as far away as possible from the outer surface of the embankment ensuring unsaturated conditions. It becomes apparent that for tailings with a friction angle of say 37° a slope of approximately 1:2 and flatter will result in a safety factor of 1,5 which is considered adequate for long term slope stability.

No tailings impoundment with a slope flatter than 1:4 to 1:5 has had a failure attributable to a "spontaneous" static liquefaction event. Whereas there are several upstream constructed tailings impoundments of overall or intermediate 1:2 to 1:3 slopes that have failed in this manner (Hustrulid, McCarter and van Zyl, 2000:370).

An embankment slope must be flat enough to ensure adequate stability but not too flat as this may result in very large footprints and cause excessive quantities of fill material being required for the construction of the initial starter wall. As upstream spigotted tailings embankment uses the hydraulically placed tailings to construct the outer embankment and occurs simultaneously to the disposing of the remaining fines, the disposal costs are therefore fairly insensitive to slope angle and design for a flatter slope such as 1:4 compared to say a 1:2 slope. There is therefore little or no economic incentive for over steep slopes if only considering tailings placement cost. It is imperative that an embankment slope angle satisfies safety constraints and achieves economic design as well as minimising erosion problems.

If space is not a problem it would be possible to construct the overall outer slope as flat as 1:4 (approximately 14°). This could:

- contribute to the reduction in erosion of material due to surface runoff;
- simplify the vegetation of the outer surface; and
- reduce the maintenance after closure.

Where space is limited and steep impoundment slopes are required the rate at which the impoundment has to rise becomes critical. The rate of rise largely determines the rate of gain of strength of the deposited tailings. Sun-drying of the material on the beach together with the complete consolidation of tailings seldom see rises exceeding 2 m per year. It is important that theoretical calculations, based on and in some instances confirmed by measured coefficients, indicate a safe rate of rise.

2.3.4 Tailings dam failures

Many tailings dam failure case histories indicate that the failure was entirely predictable in hindsight and that there were no:

- unknown loading causes;
- mysterious soil mechanics; and
- substantially different behaviour in materials.

In all of the cases over the past 30 years the necessary knowledge existed to prevent the failures. There is lack of design ability and poor stewardship or a combination of the two, in every case history. If basic design and construction considerations are ignored, a tailings impoundment's candidacy as a potential failure case history is immediate (Hustrulid et al., 2000:367).

Tailings impoundment failures can have any or all of the following impacts:

- loss of life;
- environmental damage;
- extended production interruption;
- damage to company and industry image;
- economic consequences to the company and even industry as a whole;
- forcing higher standards for subsequent projects; and
- legal responsibility for companies.

For a mining company, the most tangible impact after ensuring public safety is the immediate and longer-term financial impact of their operations. Public now has instantaneous access to tailings dam failures by means of the news, media, and internet and given the frequency of tailings dam failures over the past 30 years, public perception is that such events are on the rise. Public sentiment and regulatory perceptions can quite easily drive project design decisions, as opposed to appropriate experience and technical logic. Failures of tailings impoundments tend to be viewed as events caused by the collective mining industry and it is naive to think that an individual corporation or regulatory jurisdiction is not affected by the tailings impoundment failures of others (Hustrulid et al., 2000:378).

Hustrulid et al. (2000:384) also state that in all of the cases over the same period, the necessary knowledge existed to prevent the failures. Four of the most basic requirements for the safety and stability of ring-dyke impoundments are that:

- the rate of rise must be moderate so that each successive deposited layer of tailings can drain and consolidate under its accumulating overburden;
- embankment side slope angles must be moderate and consistent with shear stability;
- a minimum quantity of water must be retained in the basin of the impoundment;
- the decant pool must be located as far as possible from the outer perimeter wall.

The last two requirements aim at keeping the phreatic surface in the embankment slopes as low as possible.

Case studies

Following is a discussion on two tailings impoundment failures. The one occurred at Bafokeng in 1974 and the other at Merriespruit in 1994. The discussion focuses on the extent of the physical zone of influence as a result of tailings flow. The slurry flow zone of influence is something tangible and can be mapped, assessed and the costs relating to the devastation determined.

Bafokeng

The south-western wall of the No. 1 Bafokeng tailings impoundment compartment failed on the morning of 11 November 1974 resulting in the deaths of 12 miners (Hustrulid et al., 2000:384). The flood of slurry spread to a width of 800 m and 10 m deep at a distance of 4 km from the breach in the impoundment (Figure 24). The flood continued down the Kwa-Leragane River into the Elands River. An estimated 2 million m^3 of tailings eventually flowed 45 km downstream into the Vaalkop reservoir.

Aerial photograph downloaded from GoogleEarth.com. Slurry zone of influence information, sourced from Hustrulid et al. (2000), has been superimposed over the aerial photograph to illustrate the extent of the flow.

Figure 24: Bafokeng tailings impoundment slurry flow zone of influence.

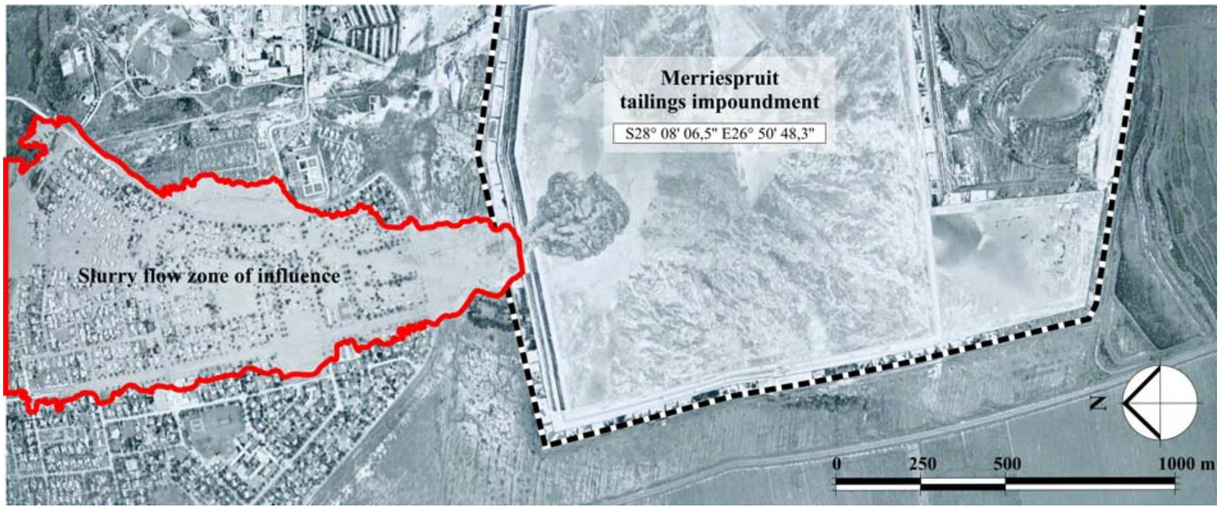
It appears that the Bafokeng impoundment failed as a result of overtopping that was triggered by a form of erosion failure caused by either:

- localized liquefaction caused by vibrations set up by a front-end loader working on the perimeter of the impoundment; or
- the dislodgement of rings from the temporary penstock shaft.

Piezometers were not installed in the tailings impoundment embankment making it difficult, if not impossible, to monitor the phreatic surface. This coupled with the decision to store large volumes of water on the top of the impoundment and that examination by knowledgeable geotechnical engineers were irregular contributed to a failure which may otherwise have been prevented. After the Bafokeng failure the Chamber of Mines of South Africa (CM) commissioned the preparation of the Handbook of Guidelines for Environmental Protection. This technical guideline was published in 1979 and revised in 1983 and 1994.

Merriespruit

The Merriespruit failure occurred on the evening of 22 February 1994 (Figure 25). The 31 m high tailings impoundment upstream of Merriespruit, a suburb of the town of Virginia failed with disastrous consequences. A massive failure of the northern wall occurred following a heavy rainstorm. More than 600 000 m^3 of tailings and 90 000 m^3 of water were released. The slurry travelled about 2 km covering nearly 50 ha. Given the downstream population and the volume of material released, it is fortunate that only 17 people lost their lives in this tragedy. Several points emerged from the enquiry that followed the failure and included aspects such as unauthorised deposition of water and tailings which reduced the freeboard to dangerous levels and the encroachment of the pool to the outer wall. Analysis of the piezometer readings rule out overall shear failure as a result from a high phreatic surface as the primary cause of the disaster. The impoundment had insufficient capacity to safely store the additional rainfall which resulted in the overtopping of the northern embankment. The overtopping resulted in a series of slip failures retrogressively cutting into the slope leading to a massive slope failure and releasing the tailings flow (Hustrulid et al., 2000:365).



The aerial photograph was taken on 23 February 2004, the day after the failure occurred (photograph courtesy of the DME).

Figure 25: Aerial photograph showing the slurry flow physical zone of influence after failure at Merriespruit tailings impoundment.

2.4 Sphere of influence

2.4.1 Introduction

The environment can be described as the surroundings in which a scheme is proposed including the visual, air, water, soil and landform aspects (i.e. the resources) providing suitable habitats for humans, animals and plants (i.e. receptors) and their interaction (Figure 26).

The National Environmental Management Act No. 107 of 1998 (NEMA, 1998) defines the environment as the surroundings within which humans exist and are made up of:

- the soil and landform, water, and atmosphere of the earth;
- micro-organisms, plants, and animal life;
- any part or combination of the above and the interrelationships among and between them; and
- the physical, chemical, aesthetic and cultural properties and conditions of the foregoing that influence human health and well-being.

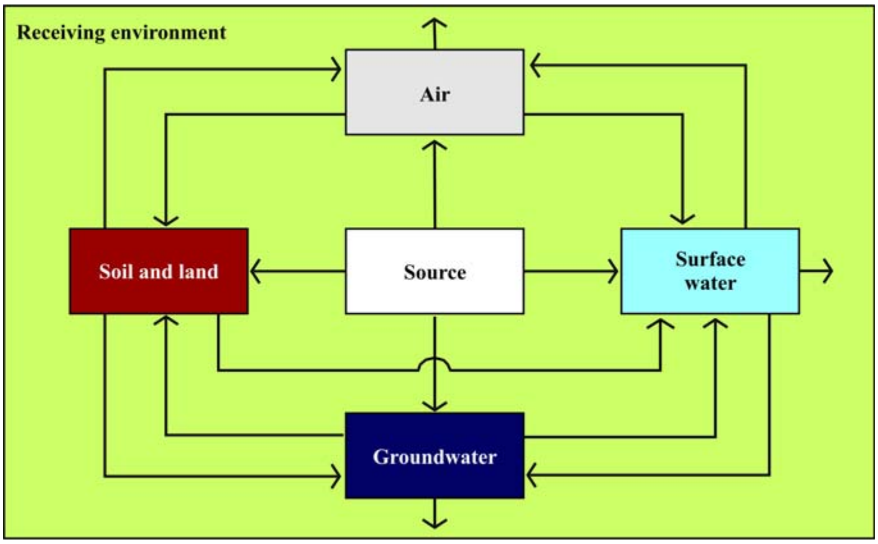


Figure 26: Biophysical environmental aspect pathways.

There is a need to systematically assess tailings impoundments in terms of the potential to pollute and impact on the receiving environment. The receiving environment can be simplistically categorised as the:

- biophysical environment (air, water, soil and landform, fauna, and flora);
- socio-cultural environment (people, visual, heritage and land use); and
- economic environment.

2.4.2 Environmental sphere of influence

The term sphere of influence is used in this study to describe the three-dimensional tailings impoundment impact zone on the environment. This sphere is the spatial overlay or sum of the different environmental aspect zones of influence. It is useful in the quantification and valuation of environmental impacts related to tailings impoundments. When a tailings impoundment (external effect) influences the environment, these are referred to as environmental impacts.

Historically economic rather than environmental factors have informed the positioning and configuration of impoundments. At present the location and impacts are governed by legislation and guidelines. The main aspects traditionally have been water and dust pollution. However with the rapid loss of land and the increase in population density, visual impact and change of land use have become more important. The impacts disperse into the social and economic spheres and are responsible for impacts on health and the loss and sterilisation of land. Resolving these issues can potentially be burdensome. This requires either an indefinite maintenance liability or a rehabilitation commitment until regulatory authorities relieve the proponent from blame or obligation by issuing an exoneration or closure certificate.

A report on the environmental consequences of the scheme is known as the environmental impact assessment (EIA) report or in some countries also referred to as the environmental impact statement. Turner (2003:32) makes a distinction between two sub-categories of environmental impact, namely landscape impacts and visual impacts (Figure 27). Landscape impacts refer to changes to the fabric, character and the quality of the landscape as a result of the scheme. Visual impacts, a subset of landscape impacts relate to the changes in available views of the landscape and the experiences of affected parties.

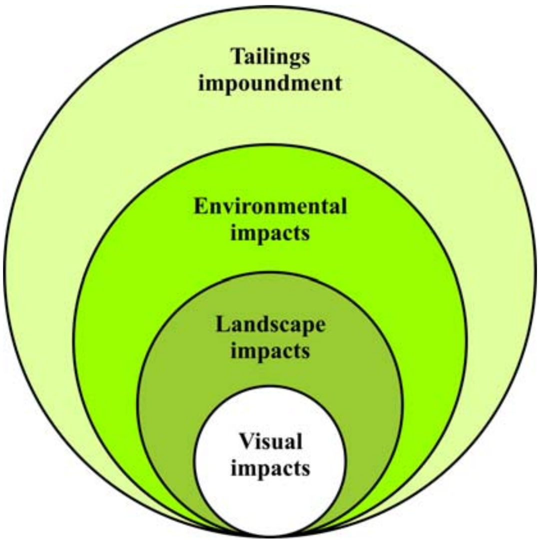


Figure 27: A tailings impoundment impacts the environment resulting in landscape impacts and finally leading to visual impacts (Turner, 1998:34).

It is important to understand the potential impacts of an impoundment on the environment. It is understood that a scheme could cause changes in the environment which in turn will impact either on the health or comfort of people, plants or animals. This however does not tell how these impacts occur or how they are measured but are simplistic descriptions only, but hopefully sufficient to start addressing the problem. It is necessary to consider the mechanics of the process of how the impact on air quality takes place -i.e. fugitive dust generated from exposed surface areas and how, for example, this causes the adverse impacts on the receiving environment.

One need to consider the contaminants associated with the scheme, the contaminant source release, environmental transport mechanisms and transformation, human exposure and dose, and the potential risk of each contaminant. Depending on the type of source zone (impoundment, vadoze zone or aquifer for example) it can be assumed that the environmental transport pathway could be by means of seepage (groundwater pathway), wind suspension (atmospheric pathway) and lastly water erosion and overland flow (surface water pathway). In addition with gold tailings, contaminants could be lost from the zone by radioactive decay or degeneration from the zone (Streile, Shields, Stoh, Bagaasen, Whelan, McDonald, Droppo and Buck, 1996).

2.4.3 Land use zoning

When dealing with land uses such as tailings disposal facilities which could impact significantly on adjacent land uses it is important to take the necessary steps to ensure that such land use conflicts are managed prudently. The following sections discuss regulatory mechanisms such as zoning and title deeds, and recent approaches to managing conflicting land uses by means of using and implementing buffer distances.

Zoning

Zoning is a form of policy power delegated by the state to local governments to ensure the welfare of the community by regulating the most appropriate use of the land. The zoning ordinance is the mechanism by which new development is controlled as growth occurs. As such, zoning is a classification of land uses that limits what activities are allowed to take place on a property by establishing a range of development options. The traditional concept behind zoning is to separate potential conflicts among incompatible land uses. Typically, the zoning ordinance will include the following categories of use:

- residential,
- commercial,
- industrial,
- office,
- public/institutional, and
- agricultural.

Each zone is regulated by a number of conditions in addition to use including aspects such as density, or physical restrictions such as height, area coverage, parking requirements, and screening. In addition, as indicated above, there may be zones based upon environmental conditions such as open space, flood plains, and steep slopes (Lodi, 2005). For example, the Department of Water Affairs and Forestry (DWAF) stipulates that no person may locate or place any mine residue disposal facility within the 1:100 year flood-line or within a horizontal distance of 100 metres from any watercourse or estuary, borehole or well, or on water-logged ground, or on ground likely to be undermined (DWAF, 1999).

Origins of zoning

Zoning stipulations are contained within the relative ordinance of each municipality and this is a legal document similar to a by-law or an act which can be enforced by the courts. Therefore, whether or not the owner of a piece of land agrees with the zoning placed on the property, it is required, by law, to act within such restrictions. Zoning places restrictions on a piece of land for three main reasons:

- to sustain the identity of an area or neighbourhood;
- to protect the natural environment; and
- to protect the rights of adjacent land owners.

Other land use controls

Land use controls are also contained within the Title deed of a property. These controls are registered at the deeds office. These were originally designed by the government to protect the environment.

2.4.4 Buffer distances and conflicting land uses

A buffer zone or buffer distance is any area that serves the purpose of keeping two or more areas distant from one another. The term 'buffer distance' is used rather than 'buffer zone' to avoid confusion with the word 'zone' in a statutory planning context. Buffer distances can be set up to prevent violence, protect the environment, and protect residential and commercial zones from industrial accidents or natural disasters (Wikipedia, 2006). Buffer distances are also used to manage disputes over development. Inevitably, conflict emerges between social forces promoting development, increased population, and those sectors of society that want to preserve natural resources or indigenous cultures (Smith, 2003).

A buffer distance can be an area of mainly open undeveloped land between sensitive land uses. If sensitive land uses are not sufficiently buffered, amenity and quality of life in the adjacent area may be reduced, due to odour, dustfall, noise, and aesthetics (EPA, 1990). It is not always possible to completely eliminate impacts on adjacent areas, hence the importance of instituting buffers between for example land used for housing, and land used for the disposal of mining residue which has the potential to cause conflict or nuisance. Each buffer distance is typically defined on the basis of the unique characteristics of the use and can restrict the development of certain other uses adjacent to this area.

Conflicting land uses

Both ecological considerations and land use conflicts must be addressed when finding a suitable site to construct a tailings impoundment. Ecological considerations typically include the potential disturbance of sensitive areas that are important to wildlife and include wetlands or wildlife habitats. It is also important to minimize conflicts with other surrounding land uses. Tailings impoundments are considered by some as a locally and sometimes even as a regional undesirable land use. Land use conflicts can generate significant public opposition to a new or proposed tailings impoundment. If residential development encroaches upon an impoundment it may result in nuisance impacts or in certain instances result in ill-health. At the rate of development, especially low cost housing, it can be anticipated that there is a potential for conflict. Low cost housing is frequently located on low cost land close to polluting industries and uses. Environmental concerns must be addressed to avoid legal challenges. Laws protect sites of heritage importance and it is important that such sites are identified during the site selection process to avoid a delay in the project development. Also, in the wrong location, tailings impoundments can be to the detriment of an area’s scenic beauty.

Using buffers to manage land use conflicts

Imposing buffer distances between certain land uses can be used to manage the conflict that exist or could be foreseen to exist should the uses not be separated. The Gauteng Department of Agriculture Conservation and Environment (GDACE) initiated a project in 2002 with the aim to assess proposed developments in areas regarded as sensitive, or where such developments may result in potentially harmful effects on human health and well-being (GDACE, 2002). Two generic buffer distances are provided. The best-case scenario buffer distance translates into a large buffer distance and the worst-case scenario buffer distance translates as a smaller buffer distance. GDACE can use these guidelines to establish the large buffer as the preferred option around potentially harmful or nuisance activities and the smaller buffer as the absolute minimum based on the information gathered and the legal requirements in terms of national, provincial and local legislation and policies where applicable.

GDACE buffer distances for mine residue deposits are given as 1000 m and 500 m for the best-case and worst-case buffers respectively. Mphephu (2004:181) concludes that a buffer distance of 1500 m is realistic around mine residue deposits. GDACE provides the best-case buffer of 1000 m as it is contended that beyond this distance dust from residue deposits cannot be distinguished from ambient dust pollution. It is also stated that dust levels are generally acceptable at a distance of 500 m provided that adequate management practices are implemented (GDACE, 2002) (Table 4).

Table 4: Typical buffer distances.

		Buffer distance	
Reference	**Land use**	**Best case**	**Worst case**
South Africa[1]	Industrial (Heavy industry and power stations)	1500 m	750 m
	Industrial (Manufacture and noisy operations)	500 m	250 m
	Industrial (Clean manufacturing and high-technology research)	100 m	50 m
	Sewage treatment works	800 m	500 m
	Landfill sites (General landfill sites)	400 m	200 m
	Landfill sties (hazardous waste landfill sites)	2000 m	1000 m
	Mine residue stockpiles and rock dumps	100 m	0 m
	Mine residue disposal facilities and ash dumps	1000 m	500 m
South Africa[2]	Mine residue deposits	1500 m	500 m
Australia NSW[3]	Mining (Mining for coal)	1000 m	-
	Mining (Quarrying of hard rock with blasting)	500 m	-
	Industrial (Manufacture of non-metallic products such as tiles)	200	-

[1] GDACE (2002). [2] Mphephu (2004:181). [3] EPA (1990).

The GDACE policy document uses dustfall as the only criteria to buffer sensitive land uses from adjacent mine residue disposal facilities. However, the document does state that specialist studies may still be required for new developments in these buffers around pollution sources to take account of specific environmental impacts and risks. The following environmental specialist studies may be required:

- analysis of toxicity of chemicals contained in the tailings and the potential of the material to disperse into the environment and impact on adjacent land uses;
- detailed analysis of the dispersion of tailings through surface water runoff and wind; and
- geo-hydrological study to determine levels of soil and groundwater pollution.

2.4.5 Summary

Sphere of influence is a term that describes the three-dimensional tailings impoundment zone of influence within which an effect on the environment is predicted or measured. This zone is the spatial overlay or sum of the different environmental aspect zones of influence and is also representative of a particular configuration at a specific moment in time. All the regulatory mechanisms used to manage conflicting land uses within zones of influence are of great importance even only to reduce conflict.

There are many variables that influence the determination of a site specific sphere of influence for tailings disposal sites, such as:

- characteristics of the tailings;
- disposal methods;
- underlying geology;
- climate;
- wind regimes; and
- topography.

However most of the problems with conflicting land uses can be dealt with effectively before the development takes place. While buffer distances are a means of reducing the effects of environmental impacts, they are not an alternative to source control. If an activity has been allocated on site with an inadequate buffer distance, subsequent remedial action to alleviate off-site effects either within or beyond the buffer distance may be required. It must however be realised that such management interventions can be costly and may not be economically feasible or fully effective. Reliable buffer distances for tailings disposal facilities ought to be determined in consultation with the relevant government agencies through undertaking site specific assessments. Figure 28 illustrates how typical buffer distances can be applied. The shortcoming of rigorously applying buffer distances such as provided in Table 4 (p. 42) is that it does not take cognisance of variables that can determine the true sphere of influence.

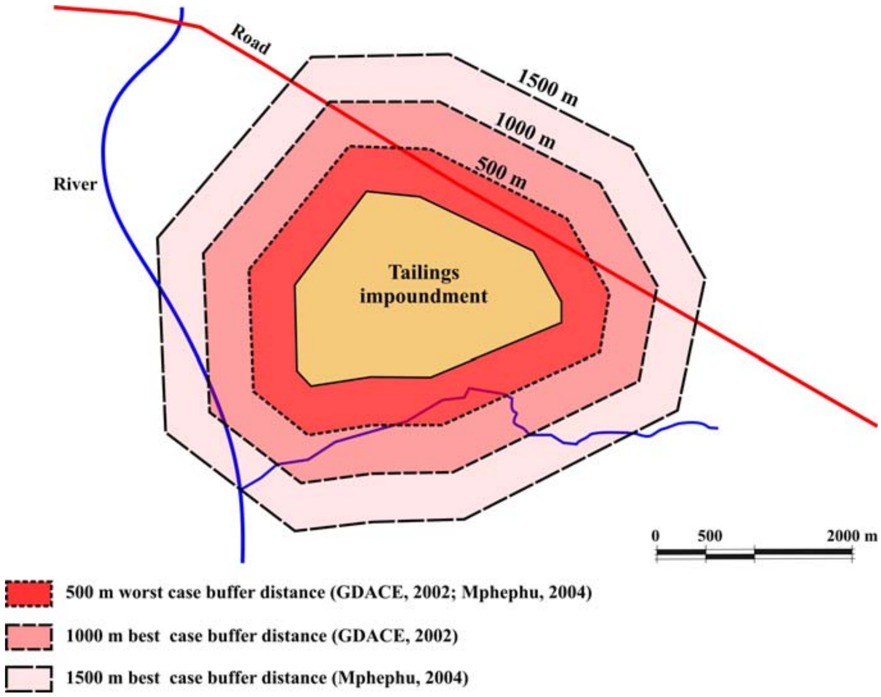


Figure 28: Schematic representation of typical buffer distances.

2.5 Sustainable development

> "Environmentally sustainable development is probably the most important aspect of future growth and the process of creating a better life for all the inhabitants of South Africa. Development with disregard for, or neglect of, the environment, has throughout the world proven to be short-sighted, short-lived and detrimental to both humans and natural resources. It is therefore necessary to view all aspects of development holistically in their relation to the environment."
>
> van Riet et al.(1997:59)

2.5.1 Defining sustainable

"Sustainable" has become laden with so many meanings that it has almost no readily defined meaning. In this context, however, it could be taken to mean that the tailings impoundment should comply with all the environmental requirements. Whether these requirements in themselves result in sustainability may well be a different issue. In this context sustainable is understood to mean, "for ensuring compliance with the relevant criteria and good practice".

Two definitions such as "…sustainable development is development that delivers basic environmental, social and economic services to all without threatening the viability of natural, built and social systems upon which these services depend." Walmsley and Botten (1994:5), and "…meeting the needs of the present without compromising the ability of future generations to meet their needs…" (Map21, 1999) underlines the importance of sustainable development. In other words, a process of social and economic development that can be sustained, not one that will ruin the world for our children (Map21, 1999).

Sustainability is about individual duty, responsibility and attitudinal change. It can also be described as a system that survives for some specified (finite) time.

This implies:

- consumption cannot exceed rate of production in the ecosphere;
- economic production cannot exceed the ecosphere's capacity to assimilate waste; and
- no element of the ecosphere can be depleted beyond rejuvenation.

Achieving sustainable development is dependent on the notion of Caring for the Earth. This means protecting and safeguarding the fertility and productivity of our planet, which can be achieved by:

- maintaining essential ecological processes and life-support systems; and
- using natural resources or ecosystems sustainably or, where this is not possible in the case of non-renewable resources, wisely.

Human welfare and the preservation of Earth's life-supporting systems are dependent on ecologically sustainable development, in which total human population size and resource use in the world (or region) are limited to a level that does not exceed the carrying capacity of the existing natural capital and is therefore sustainable (Miller, 2001).

Most action to achieve sustainable development has to be formulated and implemented locally. The fact that every environment and its place in the local, regional and global economic system is unique implies the need for optimal use of local resources, knowledge and skills. Sustainability implies different solutions for different places. Like the word "appropriate", "sustainability" is qualified by its context.

2.5.2 Context of sustainable development

Late in 1983 the secretary-general of the United Nations asked Norway's Mrs Gro Harlem Brundtland, the only politician in the world to proceed from the post of Environment Minister to Prime Minister, to put together an independent commission to look at the environmental degradation and suggest ways which would allow the planet's rapidly growing population to meet its basic needs. In other words, to form an ecological sustainable environment (Hinrichsen, 1989). The group – ministers, scientists, diplomats and law-makers – studied and debated and held public hearings on five continents over almost three years. In April, 1987, the commission published Our Common Future. It was to be submitted to the United Nations General Assembly for consideration during its 42nd Session in the autumn of 1987. Brundtland wrote in the foreword to that report:

> 'Our message is directed towards people, whose well being is the ultimate goal of all environment and development policies. Unless we are able to translate our words into a language that can reach the minds and the hearts of people young and old, we shall not be able to undertake the extensive social changes needed to correct the course of development.'
>
> Brundtland (1987)

The Commission's main task was to come up with 'a global agenda for change'. Its mandate spelled out three objectives:

- to re-examine the critical environment and development issues and to formulate realistic proposals for dealing with them;
- to propose new forms of international co-operation on these issues that will influence policies and events in the direction of needed changes; and
- to raise the levels of understanding and commitment to actions of individuals, voluntary organisations, businesses, institutes and governments.

The report describes a future that will not work, given the present international economic systems, population growth rates, agricultural systems, species extinction rates, energy technologies, industrial processes, urban development, procedures for managing global 'commons' and present world 'arms culture'. It describes many of the changes required to provide a future basis for development founded on enhanced environmental resources and popular participation in decision making. Its conclusions offer hope that any responsible leader, once exposed to the realities of the various inter-locked environment and development dilemmas, would see the need for dynamic new policies to build a workable world future.

The recent World Summit on Sustainable Development (WSSD) highlighted a growing consciousness of the need to protect the planet, but at the same time emphasised that the noble concepts can easily result in little more than stirring speeches obfuscated by excessive jargon.

2.5.3 Tailings impoundments and sustainable development

The recent view of leaving impoundments simply in a "safe" state is no longer acceptable and this state is maybe best described as semi-desirable. The desirable outcome is now seen as requiring sustainability and for this to be realisable it is necessary to define sustainable in the particular context.

Sustainable can have many meanings but in this context the extremes range from self sustainable, perhaps best exemplified as returning the area to wilderness for wild life grazing and habitat, to managed sustainable, which could entail anything from vegetable gardens to factories. In both cases it may well be that the stewardship of the land passes from the mine owner to the subsequent owners or occupiers and that there is a net benefit in that the usage value could exceed the cost of any maintenance of the land.

These sustainable outcomes, either self or managed, could involve either total reshaping of the tailings impoundment or simple stabilising of slopes and providing convenient access.

The choice of rehabilitation method will depend on the projected end use and this in turn should be informed by an overall local or regional land use development plan. In a developing country regional planning is not yet sufficiently advanced in many places to allow it to impact on the current design of tailings impoundments which may only be closed in a decade or two. Nevertheless cognisance could still be taken of the broader planning initiatives which are likely to prevail at closure.

Thus far consideration has only been given to rehabilitation of conventional tailings impoundments. The implicit assumption is that the process of constructing them, followed by closure and then rehabilitation to currently a semi-desirable state - but in future to a desirable sustainable state - is an optimum process. This is not necessarily so and it may well be that if the final result can be envisaged during the initial planning then the tailings impoundment could be designed differently. This could result in lower final rehabilitation costs possibly at the expense of higher initial costs.

These considerations lead to a number of interrelated questions, which cannot satisfactorily be resolved individually. For example it is not possible to decide that after closure a tailings impoundment should revert to:

- wilderness,
- woodlot,
- recreational and educational purposes,
- crop cultivation,
- a township, or
- a factory site

without taking into account the location, the costs and the benefits and whether these are sustainable.

If such a decision could then be made, it may be beneficial to change the design of the tailings impoundment or even the location to better suit the end use. This overall process of planning, design, construction, operation, closure, and rehabilitation to a sustainable end use has become more complex and should be viewed essentially as a linear system with major iterative loops.

2.5.4 Summary

Sustainability is not simply about creating ecologically correct buildings, cities or open spaces; it is about creating unique places that express the continuity of our habitation and the interconnectedness of all people and things. This underlying philosophy, together mixed land use, regenerative design, and resource-conserving technology, constitutes truly sustainable development.

Let us go back to the beginning of the idea of duty and responsibility and again remind ourselves that if sustainability is going to work, and become normal practice, a concerned and environmentally literate community is required, which means that every person is responsible for putting the principles of sustainability into practice and that we should:

> *non noli nocere* – "First cease doing harm."
>
> First oath of Hippocrates in
>
> Goodland, Daly and Kellenberg (1994)

2.6 Decision making

> "According to the classical decision theory, decisions should be assigned to the lowest competent level in an organisation. This theory is based on the fact that the closer a decision maker is to the problem, the quicker the choice can be made."
>
> Moody (1983:18)

> "In the real world we usually do not have a choice between satisfactory and optimal solutions, for we rarely have a method of finding the optimum...
> ...we look for alternatives in such a way that we can generally find an acceptable one after only a moderate search."
>
> Simon (1969:64)

> "...a decision is a judgement and, as such, is rarely a choice between right and wrong but at best a choice between 'almost right' and 'almost wrong'."
>
> Drucker (1967)

2.6.1 Introduction

This thesis is about making decisions regarding the configuration of tailings impoundments and on how the concept of decision making can be applied to the judgement of the environmental acceptability of tailings impoundments. This section provides a general commentary on making decisions and systems, frameworks and tools used to support the process. Hence terms such as decision-support system (DSS) and decision-support tools are used.

Any model, no matter what its form or use, is an attempt to represent a situation in a simplified form. The purpose therefore is to represent some sort of real-world situation in a more simplistic and potentially more easily understood form to assist with the making of decisions. This is usually achieved by developing a model that focuses on the key aspects of the situation and ignoring the rest (Wisniewski, 1997:7). However, it is important that models are developed and understood by those concerned with making such decisions; in this case the configuration of tailings impoundments and consequent impacts on the environment. Care must be taken not to oversimplify a problem. Decision makers should also be cautious not to look at an environmental problem and assume that some sort of existing generic approach can be made to fit the problem. This can quite easily result in a model being forced to fit the problem; generating information and results that are at best incomplete or at worst misleading to decision makers.

2.6.2 Decision-making theory

Decisions, ranging from elementary to complex, are continually made by everyone. A DSS supports decision making by assisting with organizing the relevant aspects within a rational framework (Sage, 1991:1). The framework provides support to decision makers through increasing the effectiveness of the decision-making process.

The rational choice process allows for:

- the formulation of a number of different alternatives;
- cause and effect analysis of each alternative, as each alternative will have a set of consequences; and
- interpretation and selection of the preferred outcome for the scheme by ranking the consequences according to a system of preference.

A key question to developing a DSS is:

> "What specific decision or decision process are we trying to support?"
>
> Keen and Morton (1978:58)

Decisions range between the simple choices between two alternatives and more complex multi-alternative decision-making processes where each alternative has a number of factors influencing the final selection. As a decision becomes more complex, so does the process involved in making a selection.

A DSS should at least:

- support decision makers in the formulation, framing, or assessment of the decision situation in the sense of recognising needs and identifying appropriate objectives by which to measure acceptable resolution of issues;
- provide decision makers with the ability to understand the consequences of different choices; and
- provide guidance to determine the environmental acceptability of alternatives leading to choosing a preferred tailings impoundment configuration.

The purpose of a DSS is to support people in the processing of primarily cognitive tasks that involve decisions, judgements and choices (Sage, 1991:4). Associated with these three steps of decision making must be the ability to acquire, represent, and utilize information or knowledge and the ability to implement the chosen alternative course of action. This must be accomplished with a rational perspective of the decision-making process used.

Fundamental to the notion of a DSS is assistance provided in:

- assessing the situation;
- identifying alternatives;
- formulating the decision problem; and
- structuring the decision

in such a rational way that using the system will result in an outcome relating to the acceptability of an alternative.

The following key ingredients are required for effective decision making:

- availability of quality, factual and defendable data;
- knowledgeable and experienced decision makers understanding the scope of the problem;
- best practice methods to analyse problems; and
- expert judgement to combine facts, knowledge, experience and analysis.

Variability in information relative to decision making

Keen and Morton (1978:83) discusses the variables that influence the information that should be obtained relative to any given decision-making situation. Although the variables are task dependent it is important that the available information deals with the following:

- Inherent accuracy- Information for strategic planning situations is often uncertain and incomplete.
- Level of detail - Aggregated information is often sufficient for strategic planning situations whereas more detailed information is required to answer specific operational questions.
- Time frame for information requirements - Strategic decisions are often founded on information and predictions based on long time frames where the nature of control is infrequent.
- Frequency of decision making – Although strategic decisions are usually made less frequently than operational decisions, it could be required to refine strategic decisions more often.
- Information source – Strategic decision making uses information from many external sources.
- Scope of information - Strategic decisions are based on information with a broad scope. Sometimes certain factors cannot be fully anticipated or quantified prior to the need for a decision.
- Ability to quantify information - Information required for strategic planning decisions is initially likely to be qualitative with quantitative information only becoming available as the planning process progresses.
- Recentness of information - It is often difficult to obtain recent and current information necessary to make strategic planning decisions.

Decision loop

Decision makers, such as environmental practitioners, are often required to follow some sort of rational planning process to arrive at objectives, policies or strategies. While there is no single set of rules, they all relate to decisions of different sorts. Although decision making ranges between being simplistic and complex and may even relate to different fields of management such decisions can be guided by the simplistic closed loop decision-making process illustrated in Figure 29. The closed loop decision-making process incorporates typical steps common to most decision-making circumstances.

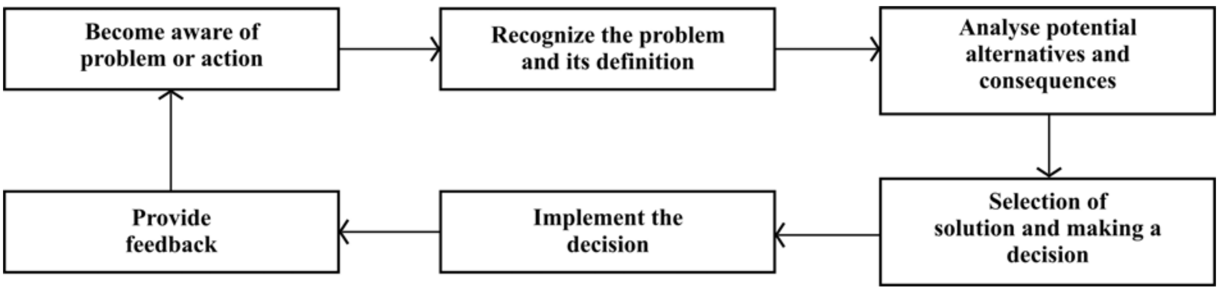


Figure 29 Closed loop decision-making process comprising typical steps common to most decision-making circumstances (Moody, 1983:1).

Time, cost and benefit, and uncertainty of decisions

It is important to be able to decide when enough facts have been gathered to make an informed and rational decision. Gathering facts takes time, requires resources and costs money. Moody (1983:4) provides useful graphs indicating the conceptual relationship between cost and benefit over time (Figure 30). The more time spent gathering information and facts to make a decision the greater the total related cost would be. There is a point in time when the cost of gathering information outweighs the derived benefit. In addition, facts are gathered to limit uncertainty in decision making. Uncertainty decreases as time passes and the amount of data increases. At a certain point the cost of collecting data does not increase the effectiveness of the final decision and further delays would pass the optimum decision-making point and increase the total cost of the process.

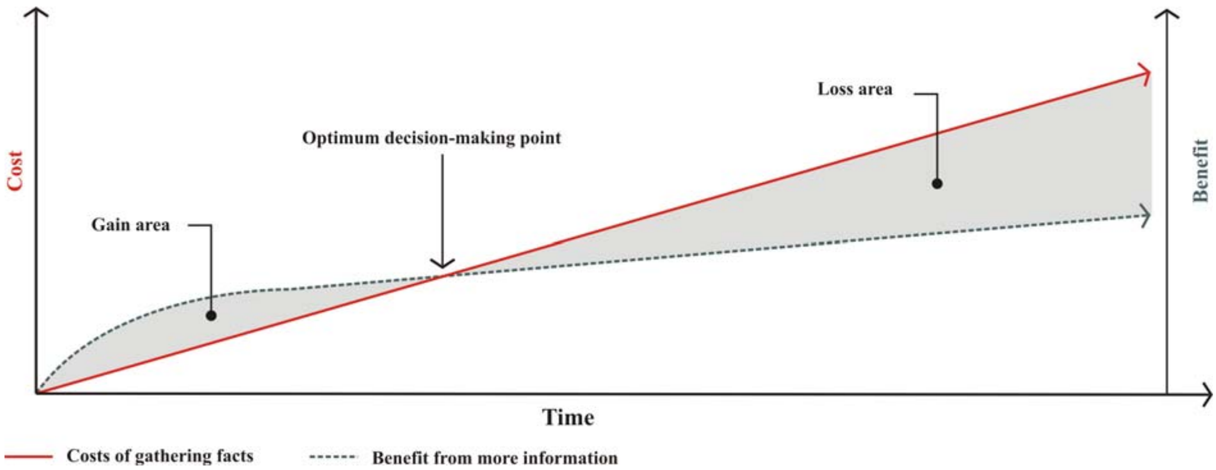


Figure 30: The theoretical optimum decision-making point lies at the cross over point of cost and benefit (Moody, 1983:5).

Rational decision making

Rational decision making involves:

- growing awareness and identification of the problem;
- determining who and what the stakeholders are;
- whether a solution is possible;
- identification of alternatives;
- considering of consequences;
- selection of the most acceptable solution;
- implementation of the decision; and
- providing feedback from monitoring

in order to close the dynamic decision-making loop (Moody, 1983:60).

Political decision making, on the other hand, can be seen as a personalised bargaining process between organisational units and it is argued that power of influence determines the outcome of any given decision (Keen and Morton, 1978:63).

2.6.3 Decision-support system

A preliminary decision support system for the sustainable design, operation and closure of metalliferous mine residue disposal facilities and commissioned by the Water Research Commission (WRC) discusses that the term "decision-support system" relating to the sustainable configuration of tailings impoundment requires that several environmental aspects are addressed and that numerous questions to determine whether or not a scheme will comply with various criteria are posed. The nature of the criteria is typically set in government regulations although specific measurable criteria may not be. The evaluation process is in a sense an integration of the responses to typical questions initiated by regulators and the process must result in a decision of the type that the tailings impoundment configuration is acceptable, unacceptable or some conditional response where additional information is needed (Rademeyer, Wates, Bezuidenhout, Jones, Rust, Lorentz, van Deventer, Pulles and Hattingh, 2007).

It is essential that the process to address and evaluate the responses to the questions must be rational and transparent. To this end the DSS is a framework of questions comprising a network in series and parallel. The series elements concern individual environmental aspects which may require a succession of questions to produce a definitive answer and the parallelism lies in addressing different issues (Figure 31).

In general the system questions must be in the form of:

> "Does the particular situation comply with a set of predetermined criteria?"

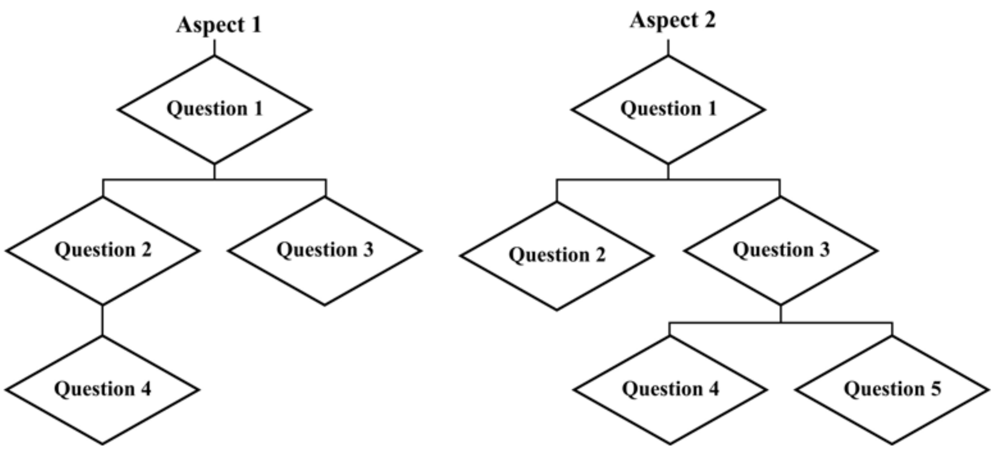


Figure 31: Top down structure of questions for the environmental aspects being considered.

The system itself poses these questions within a rational hierarchical framework (Figure 32, p. 53). Perhaps the emphasis should be on the word support since it is not intended that the system should generate decisions, it must guide the decision maker through the problem of issues which need to be considered and addressed in order to ensure all relevant issues are adequately dealt with. It is anticipated that the user of the system is knowledgeable on all issues being addressed and could have addressed them outside of the system. The system will therefore provide a rational method for addressing all the issues and for recording the outcomes so that transparency is achieved.

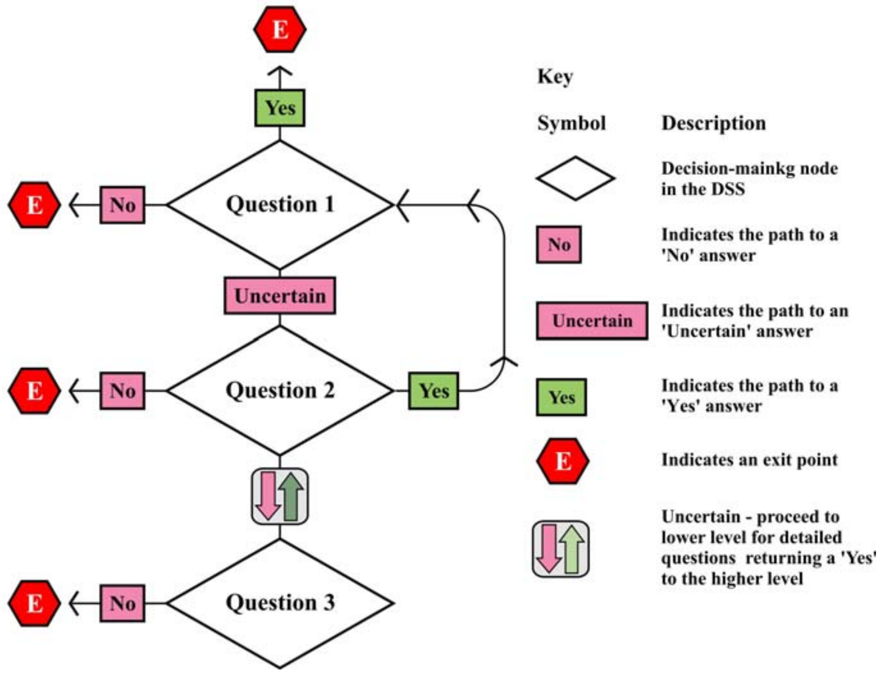


Figure 32: Conceptual DSS framework indicating decision-making paths (Rademeyer et al., 2007).

The second term in the phrase is support. A DSS supports decision making and does not replace decision makers. This emphasis is important as it stresses the fact that decision making utilises models and tools appropriate for the problem and leaves the rest to the decision maker. The third term used is in the phrase is system. A system in this context does not necessarily imply a fully automated computer system, but rather a rational framework with access to some form of interaction with computerised tools and models.

Decision-making points

Tailings disposal facilities pass through at least four distinct management stages namely the development, operation, closure, and lastly the post-closure stage. The development stage typically includes aspects such as conceptualisation, preliminary planning, site selection, detailed planning and design whereas the operation stage includes construction, deposition and decommissioning. Maintenance and follow-up audits are part of the post-closure stage (Figure 33).

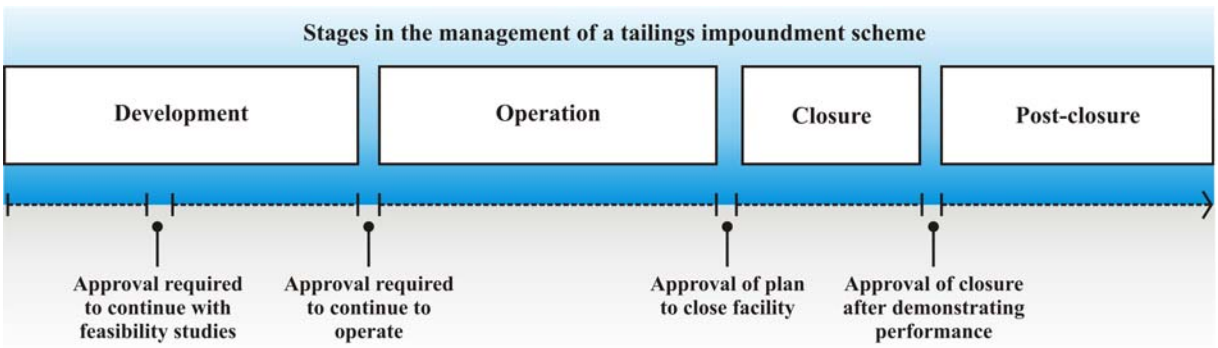


Figure 33: Important decision-making points during tailings impoundment configuration (Rademeyer et al., 2007).

2.6.4 Summary

The development of a decision framework comprising questions supported by decision guidance and decision criteria to examine key questions such as whether or not seepage from a proposed tailings impoundment exceeds water quality criteria has been developed by Rademeyer, Wates, Bezuidenhout, Jones, Rust, Lorentz, van Deventer, Pulles and Hattingh (2007). Although various factors influence the ultimate decision as to the acceptability of a scheme, it is believed that the overall framework and modelled environmental aspects described by Rademeyer et al. (2007) provide sufficient structure to answer the relevant questions. The preliminary framework is robust enough to allow the addition of information and knowledge if and when it becomes available. It can also be said that as more information becomes available the risk of uncertainty will decrease.

The overall objectives of the decision framework are:

- to represent some sort of real-world situation of tailings impoundment configurations that is simplistic and understandable;
- to assist decision making with regard to the acceptability of the proposed scheme's impact on the environment;
- to provide decision makers with a framework for the decisions related to the former point that involve decisions, judgements and choice; and
- to contextualise some of the factors which influence such decisions.

2.7 Environmental planning and design

South Africa's integrated environmental management procedures rely on international experience in environmental policy and the application of environmental assessment and management tools. It is also generally recognised that the globally applied term "environmental assessment and management" is comparable with the South African term "integrated environmental management" (IEM). DEAT (2004:2) defines IEM as the way of thinking that provides an holistic framework that can be embraced by all sectors of society for the assessment and management of environmental impacts and aspects associated with each stage of the activity life cycle, taking into consideration a broad definition of environment with the overall aim of promoting sustainable development. IEM provides a set of underpinning principles and a suite of environmental assessment and management tools aimed at promoting sustainable development. Achieving the goal of sustainable development requires co-operation between all spheres of government, community-based organisation, non-governmental organisations, researchers and academics, industry and environmental practitioners.

IEM applies to the planning, assessment, implementation and management of any activity that has the potential to significantly effect the environment. Its implementation relies on the selection and application of appropriate tools to a particular proposal or activity.

Tools for IEM may include:

- environmental assessment tools such as strategic environmental assessment (SEA) and risk assessment (RA);
- environmental management tools such as monitoring, auditing and reporting; and
- decision-making tools such as multi-criteria decision-support systems.

IEM is the direction for environmental management in South Africa. All stages of the project must be evaluated in terms of sustainability, alternatives for development must be identified, and development benefits viewed in the light of environmental impacts.

IEM is designed to ensure that the environmental consequences of schemes are understood and adequately considered in the planning, implementation and management stages. The purpose of IEM is to resolve or lessen any negative environmental impacts and to enhance positive aspects of schemes.

Some of the relevant IEM principles are (DEAT, 2004 S0:9):

- accountability and responsibility;
- alternative options;
- environmental justice;
- informed decision-making;
- integrated approach;
- polluter pays;
- precautionary approach; and
- sustainability.

2.7.1 Planning for sustainability

With the economic benefit, the mining industry is also responsible for environmental degradation resulting from large quantities of waste deposited and inadequate waste management practices. Increasing environmental awareness and the movement towards sustainable development place strict demands on the mining industry to disclose potential environmental and social impacts and alter current mining practices accordingly. The promulgation of the Constitution of the Republic of South Africa No. 108 of 1996 and the National Environmental Management Act No. 107 of 1998 (NEMA) are seen as progressive steps towards practicable legislation to the benefit of the social and natural spheres.

Although there are numerous and varied definitions of the term "sustainable development", the common elements include the need to integrate social, economic and environmental features as well as to address intra- and inter-generational equity. Brundtland (1987) defines sustainable development as development that meets the needs of the present without compromising the ability of future generations to meet their needs and aspirations and NEMA (1998) defines such as meaning the integration of social, economic and environmental factors in to planning, implementation and decision-making so as to ensure that development serves future and present generations.

2.7.2 Mining legislation

The Mineral and Petroleum Resources Development Act No. 28 of 2002 (MPRDA, 2002) and its regulations (MPRDA, 2004) set out the process whereby a mine owner is required to decommission and apply for closure at cessation of operations (Figure 34).

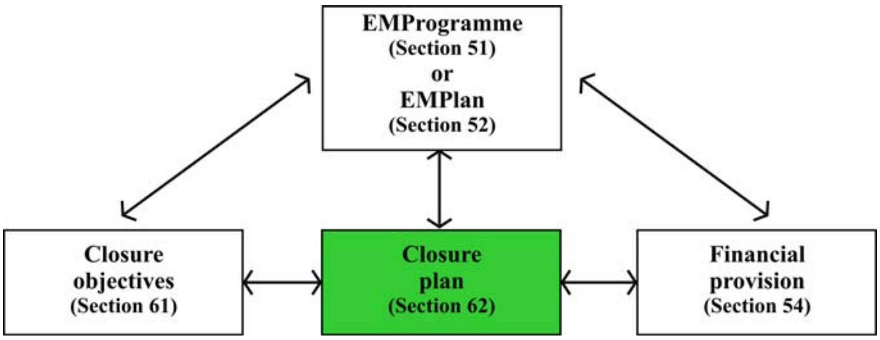


Figure 34: MPRDA closure planning process.

The closure objectives which form part of the required environmental management plan must inter alia identify key objectives, define future land use objectives and provide financially for the remediation of environmental damage.

Section 38(1)(d) of the Act obligates the holder to rehabilitate the environment to either:
- a natural state;
- a predetermined state; or
- a land use which conforms to the generally accepted principle of sustainable development.

Section 38(1)(e) states that the holder is responsible for any environmental damage, pollution or ecological degradation inside and outside its boundaries.

Further, the Act:

- reiterates that the State has an obligation to protect the environment for present and future generations – i.e. support sustainable development;
- gives effect to Section 24 of the Constitution of the Republic of South Africa – mineral and petroleum resources developed in ecologically sustainable manner;
- obligates the holder to rehabilitate the environment;
- states that the holder is responsible for any environmental damage, pollution or ecological degradation inside or outside boundaries;
- applies the IEM principles such as:
  - a cradle-to-grave approach;
  - the consideration of alternatives;
  - stakeholder involvement and public participation;
  - the adoption of the polluter-pays principle;
  - the adoption of the pre-cautionary principle; and
  - in consultation decision-making process.

The Mineral and Petroleum Resources Development Act Regulations (MPRDA, 2004):

- provides principles of mine closure in Section 56;
- requires that the incorporation of the closure process begins at commencement of the operation and continues throughout its life-cycle; and
- obligates the holder of the right to quantify the environmental risks and liabilities.

Section 51 and 52 and states that the EMProgramme or EMPlan must include:

- environmental objectives and goals for mine closure;
- a closure plan (refer regulation 62 for obligation);
- the management of identified environmental risks and liabilities; and
- both the methods and the quantum for financial provision.

Section 61 and states that the closure objectives in the EMProgramme or EMPlan must:

- identify key objectives for mine closure to guide planning and implementation;
- provide broad future land use objective(s) for the site; and
- provide proposed closure costs.

Section 62 requires that the closure plan must include:

- closure objectives;
- identification of long-term management requirements;
- a sketch plan indicating final and future land use – i.e. final land use plan; and
- a summary of environmental risks and liabilities.

Section 54 necessitating that the quantum of financial closure must include costs required for:

- premature closure [old approach of contributing towards future objective no longer suffices];
- decommissioning and final closure; and
- post-closure management for residual and latent environmental impacts.

To achieve the desired objectives most efficiently and comply with the relevant legislation it is contended that a paradigm shift is required so that the total life of tailings disposal from planning through construction, operation, decommissioning, rehabilitation, closure, and post-closure maintenance for a designed end land use, is seen as an integrated system.

2.7.3 Typical rehabilitation practices

Typical tailings impoundment good practice rehabilitation includes:

- Removal of supporting infrastructure
  Once pumping of tailings and water stops, all pipelines, pumps and electrical facilities are removed and sold. Any civil structures are removed down to 1 m below natural ground level. Collector and return water dams are kept in operating condition for use as evaporation ponds for seepage. Solution trenches are kept in operating condition to allow seepage from the filter drains to flow down to the return water dams or evaporation dams to evaporate.

- Ongoing seepage and rain water control
  Ongoing seepage from the filter drains will flow to the collector and return water drains to evaporate. Paddocks at the toe of the dams are designed to contain the 1:100 year storm. The reduced amount of solids in the run-off from successfully vegetated embankment side slopes should ensure that the capacity of the paddocks is maintained.

- Long-term stability
  Safety factors used in the design of the tailings disposal facility as well as the proposed vegetation of the embankment side slopes and the reduced amount of water on the tailings impoundment pond should ensure that there are no long-term stability concerns. In order to establish vegetation on a tailings impoundment, it is often necessary to leach the surface in order to leach soluble salts or acidity to below the root zone. The objective of establishing vegetation on the surface of an impoundment is much easier to achieve if the surface can first be covered by a soil growing layer. Vegetation is also often irrigated to maintain it during periods of drought. Leaching or irrigating the slopes of the tailings impoundment has the effect of reducing the capillary stresses that enhance the stability of the slopes. In South Africa, it is very common to find slopes in mine residue deposits with an angle steeper than the angle of shearing resistance. The only way this is possible is through the presence of capillary tensions in the pore water. If these tensions are reduced too far, surface sloughing of the slope may occur. This sloughing, by steepening the slope locally may result in deeper seated shear instability (CM, 1996:72).

- Final rehabilitation
  Erosion by wind and water will be effectively controlled by the vegetation of the side slopes of the impoundments. Wind erosion and the generation of dust from the top of the impoundments will be controlled by ridge ploughing until a permanent rehabilitation method has been found. Vegetation of the whole of the top surface of the impoundment ought to be considered.

2.7.4 Closure

The objectives for successful closure of a mining facility as stipulated in the November 1998 edition of Mining Environmental Management, is as follows:

> "Minimising long-term environmental liability, attaining regulatory compliance and maintaining geo-technical stability, while closing as quickly and cost effectively as possible. All this should materialise within the general goal of returning the land to a safe and stable condition for the purpose of post-mining alternative functions. A successful closure procedure is a combination of innovative concepts, long-term commitment and multiparty cooperation."
>
> Mudder & Harvey (1998:1)

Tailings impoundments could be stabilised to ensure public safety and restrict adverse environmental impacts to an acceptable level before the proponent will be exonerated by the permitting regulatory authority. Only when this level of closure is achieved is it possible to transfer ownership of the site and liability will rest upon a new owner. When entering the closure stage, the mining company is faced with a series of options. All the options concern the management of waste and the exercising of the company's environmental liability and moral obligation. Stakeholders apply constant pressure on mining companies to comply with increasingly stringent environmental standards and policies. An approach of environmentally sensitive mining and engagement on a socially responsible level is appropriate from a sustainable development point of view.

2.7.5 Energy flow and sustainability

Sustainability in the mining industry is greatly focussed on energy efficiency. The bulk of energy utilised during the life-of-mine is concentrated during the ore extraction and processing phases. The disposal of tailings requires relatively little energy whereas the rehabilitation could quite easily require a lot depending on the final landform envisaged. Large scale earth moving and soil preparation is required to transform the barren and lifeless tailings impoundment into a stable and sustainable landform.

The energy that 'shapes' a natural landform is caused by geomorphologic processes. The material responds to the impact of dynamic energy flows and over time creates a unique landform. This combination of material with specific characteristics and energy of particular intensity and time results in landforms that progress to a state of equilibrium, most likely not in terms of geological time scale but at least in terms of human time scale.

An example of such an attained equilibrium is the effect of erosion on most inclined terrains. A rounded crest, steep rocky faces and concave foot slopes are the result of continuous climatic forces impacting on the surface of a landform. Soft material is easily displaced from the higher areas down into the valleys due to its poor resistance to erosion forces. The steep rock faces are more resistant and can therefore withstand the impact of energy and maintain vertical postures.

Energy usage ties in closely with money expenditure and a reduction in energy usage will inevitably result in a reduction in expenses. The energy that is used to deposit the tailings should be utilised in such a way that the final desirable landform can be achieved with minor or no additional energy application.

2.7.6 Integrated environmental planning and design

Integrated environmental planning and design (IEPD), however similar to IEM, necessitates planning across traditional specialist fields with the aim of achieving a sustainable project outcome. The project outcome should be informed by a broad and inclusive knowledge base of every influencing aspect in order to reach a desired goal. Landscape architecture is one such specialist field that is novel in the planning, operation and rehabilitation stages of mining and quarrying industries and it can provide valuable insight to formulating a sustainable approach for the disposal of tailings.

The American Society of Landscape Architects (ASLA, 2001) defines landscape architecture as the art and science of analysis, planning, design, management, preservation and rehabilitation of the landscape. "Landscape" is an encompassing term including all natural and human introduced elements of the living and perceivable environment. Mutually beneficial interaction and co-existence between humans and the natural environment are known since the earliest eras and can be seen as a crude origin of the profession.

The term "landscape" is described as a tract of land with its distinguishing characteristics and features, especially considered as a product of shaping processes and agents (Burchfield, 1976). Oxford (2002) describes landscape as all of the visible features of an area of land.

The term "landform" refers to an element of and within the landscape with specific shape characteristics. This term also refers to an artificial element such as a tailings impoundment, which can be compared to a natural landform and is subject to the same dynamic geomorphologic impacts.

The challenge is to manage, combine and integrate knowledge of various specialist aspects to satisfy not only engineering but also environmental, social and economic criteria. The design of a tailings impoundment if considered as a landform planning and design exercise must be informed by guidelines originating from natural systems and technical considerations. The ultimate goal and overall aim is to configure an impoundment which will be acceptable in terms of its short term as well as long term impacts on the environment and to create a landform which will be usable and sustainable. In order to formulate an integrated environmental planning and design (IEPD) approach an understanding of current mining processes is required. It has been stated that:

> "...social construction of reality is a defining criterion in the creation of environmental values."
>
> Vatn and Bromley (1997)

This implies that the acceptable level of environmental impact is necessarily subjective, as what constitutes an acceptable impact depends on the wants and needs of that society. For example, economies in transition have a real need for economic growth and development, and their comparative advantage over developed countries is often, at least in part, founded in that society's willingness to accept a higher level of environmental impact in exchange for social and economic benefits.

When the endeavour of mining is entered into by a mining company, an approximate volume of waste is pre-determined, the appropriate methods for waste deposition are decided and life of deposition is estimated. An expectation regarding rate-of-deposition exists to achieve the goal of viable economic return. Once the projections are finalised an appropriate site is allocated to accommodate the volume of tailings in a suitable facility. The selected site is either in a pristine condition or it supports a developed land use which requires a passive or active maintenance strategy. Subsequently, active mineral extraction and tailings disposal occur while the site is under continuous active maintenance and care for an extended period of time.

In entering the closure stage, the mining company is faced with a series of options (Figure 35). In a few cases impoundments are vegetated in order to provide surface stability, this approach has proven ineffective and unsustainable. Total reclamation and restoration can be achieved when the impoundment is removed for reclamation (i.e. reworked). In most cases the only suitable option is to rehabilitate in accordance with a pre-defined closure plan.

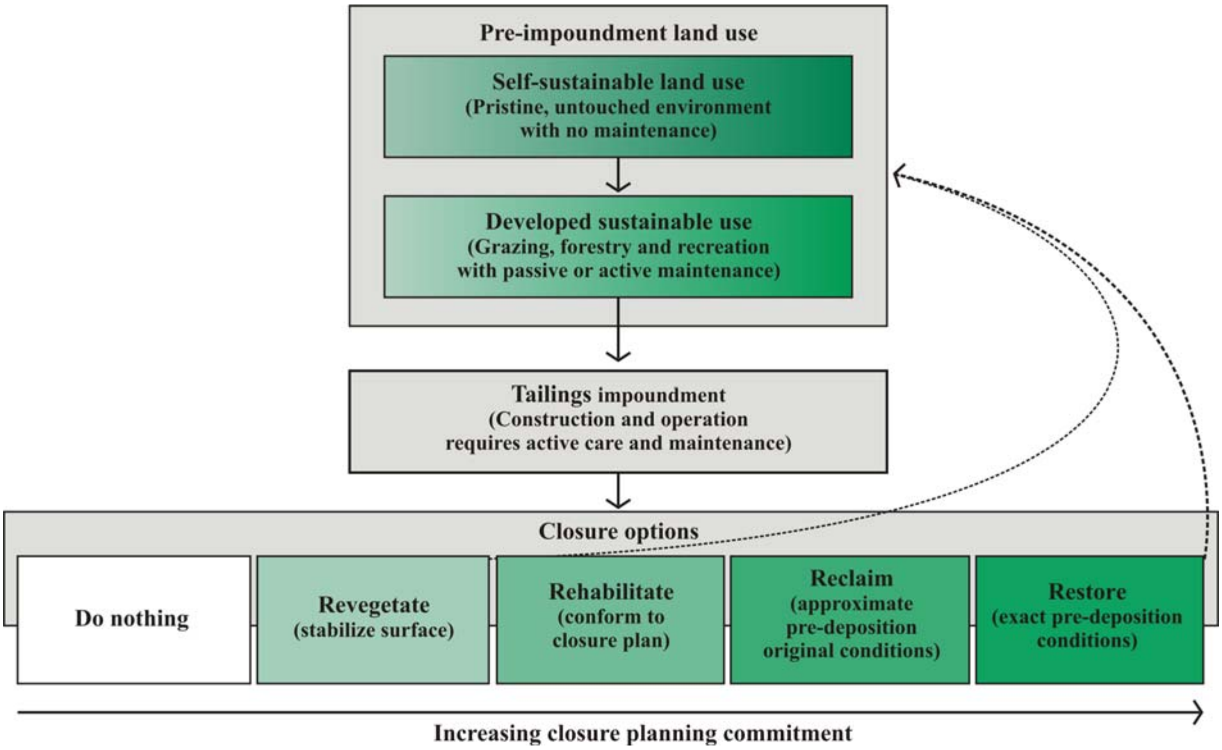


Figure 35: Closure options (Robertson, Devenny and Shaw, 1998b).

Integrated tailings impoundment planning requires the completion of a closure plan along with the impoundment design before the construction of the impoundment is allowed. It must be clearly communicated what the anticipated long-term land use of the tailings impoundment will be (Figure 36, p. 62). It is an interaction between the present need and the future goal and requires an iterative process in the design stage and continuous revision during operation of the mine.

Integrated impoundment planning incorporates an IEPD approach and will determine the success of the desired long-term land use. The decision for a long-term land use is based on the:

- anticipated life of deposition;
- municipal or local authority development programmes; and
- existing local natural and social environments.

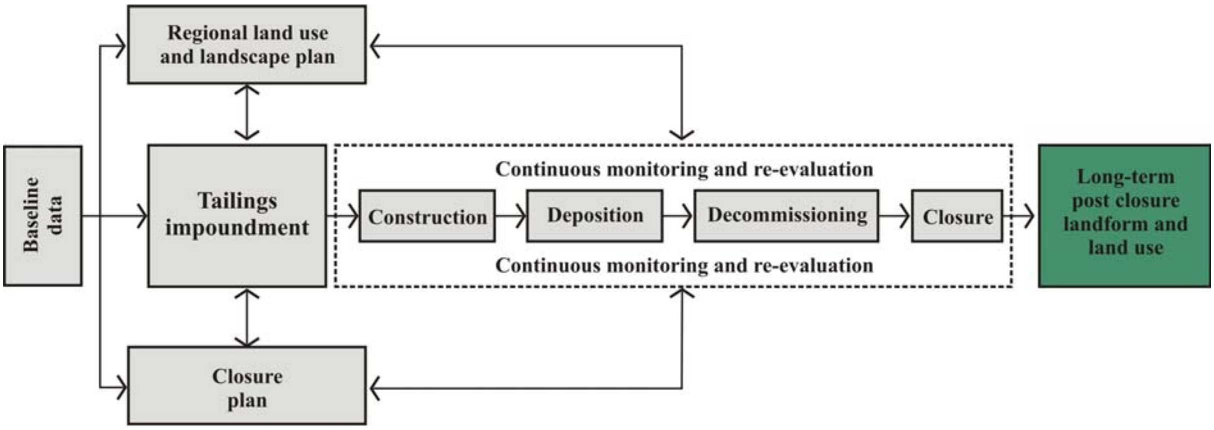


Figure 36: Integrated impoundment environmental planning and design process (Rademeyer and van den Berg, 2005).

The IEPD approach is grounded on the argument that the main function of tailings impoundment is to contain slurry within the parameters of safety and stability standards as well as economic feasibility. However, this can be defined as a short-term function concluding when the mine enters the closure phase. Following decommissioning, the impoundment undergoes an alteration in function. It is no longer a facility for the disposal or storage of waste but a permanent man-made landform located within a specific natural landscape.

2.7.7 Summary

The inference therefore is that if a tailings impoundment is designed with the short- and long-term land use of storing tailings and functioning as an acceptable natural landform in its context, it will potentially increase the rehabilitation success, support a future alternative land use and shorten the closure application period. The implementation of the integrated environmental planning and design approach will result in environmental, social and economic benefits in the long-term. This requires the design to respond in changing either the geometry and/or cover of the impoundment (Figure 37).

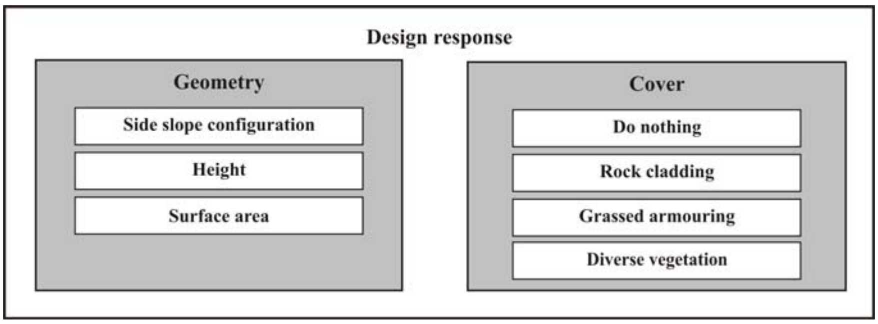


Figure 37: Context of design (Rademeyer and van den Berg, 2005).

Geometric alterations must however occur within the parameters of safety and geotechnical stability along the guidance of the ultimate goal of a regenerative sustainable landform. Tailings impoundments with varying slope gradients, slope lengths, bench widths and which imitate natural landforms may result in something which is truly sustainable. This may result in a profile similar to adjacent natural landforms with diverse slope configurations and varying microclimates necessary to sustain a diversity of floral and faunal species.

2.8 Environmental planning framework

The overall objective of achieving sustainable development of tailings impoundments is controlled by legislation. The term "sustainable" has become laden with so many meanings that it has almost no readily defined meaning. In this context, however, it could be taken to mean that the tailings impoundment should comply with all the environmental requirements. Whether these requirements in themselves result in sustainability may well be a different issue. In this context sustainable is understood to mean, "for ensuring compliance with the relevant criteria and good practice".

The Mineral and Petroleum Resources Development Act 28 of 2002 (MPRDA, 2002) and its regulations (MPRDA, 2004) set out the process whereby a mine owner is required to decommission and apply for closure at cessation of operations. The closure objectives (Section 52(2)(f)) which form part of the required environmental management plan must identify key objectives, define future land use objectives and provide financially for the remediation of environmental damage. Section 38(1)(d) of the Act obligates the holder of a right or permit to rehabilitate the environment to either:

- its natural state;
- a predetermined state; or
- a land use which conforms to the generally accepted principle of *sustainable development* (own emphasis).

Section 38(1)(e) further states that the holder is responsible for any environmental damage, pollution or ecological degradation inside and outside its boundaries.

Vick (1983:324) states that while different emphases are often placed on various priorities, the following are usually considered to be fundamental objectives of tailings impoundment rehabilitation:

- long-term mass stability of the impoundment;
- long-term erosion stability of especially the embankments;
- long-term prevention of environmental contamination; and
- eventual return of the disturbed area and constructed landform to productive use.

To achieve the former desired objectives most efficiently and comply with the relevant legislation it is contended that a paradigm shift is required so that the total life of tailings disposal; from the planning through construction, operation, decommissioning, closure, and post-closure stages; integrate a designed post-closure end land use from the start.

Envisaging the final tailings impoundment configuration during the initial planning stage should allow optimization of the design possibly resulting in lower final rehabilitation costs at the expense of higher rehabilitation costs. High decommissioning and closure costs can easily negate short-term benefits of disposal strategies which do not facilitate easy rehabilitation (DME (QLD), 1995:2)).

Courtnage (2001) states that environmental legislation and regulation is becoming increasingly stringent, thereby increasing company exposure to environmental risks, with Directors being held liable for environmental damage. Environmental liability aims at making the polluter pay for remedying the damage that he has caused. Environmental regulation lays down norms and procedures aimed at preserving the environment. Without liability, failure to comply with existing norms and procedures may merely result in administrative or penal sanctions. However, if liability is added to regulation, potential polluters also face the prospect of having to pay for restoration or compensation of the damage they caused (European Commission, 2000).

One way of addressing the risk of negative environmental impact is to impose liability on the party responsible for the activity resulting in such impact. This means that when an activity results in an environmental impact, the party in control of the activity (i.e. the polluter) has to pay:

- the costs of that impact;
- the cost of remediating the impact; or
- compensate society for the impact incurred.

This then is the foundation of the polluter pays principle – that the costs of environmental impact should be borne by those responsible for the impact (DWAF, 2006).

Not all forms of environmental damage can be remedied through liability. For the latter to be effective:

- there needs to be one or more identifiable polluters;
- the damage needs to be quantifiable; and
- a causal link needs to be established between the damage and the identified polluter(s).

Therefore, liability can be applied, for instance, in cases where damage results from:

- incidents;
- from gradual pollution caused by hazardous substances; or
- waste coming into the environment from identifiable sources.

In theory it may be possible to make the 'polluter pay' principle operational but in practice it is difficult. It has been proposed that regulatory authorities should ensure effective decontamination and restoration or replacement of the environment in cases where there is a liable polluter, by fitting the cost of remedial action to the polluter and also making sure that the funds acquired to undertake the remediation will be properly and effectively used to this effect.

Figure 7 (p. 10) illustrates the hypothetical tailings impoundment life-cycle cost model which represent total project costs through the life cycle of a tailings impoundment. The total costs comprise both environmental aspect costs and basic engineering costs; whilst the latter are conventionally estimated – the former require the development of value scales to assess intangibles such as aesthetics or perceived social benefits.

The environment can be divided into biophysical and socio-cultural elements which together with the economic aspects comprise the triple bottom line. Initial environmental aspects that must be built into the model are (Figure 38, p. 65):

- visual aspects;
- air quality aspects; and
- water aspects.

Estimating the environmental aspect costs can include:

- cost of water pollution control systems;
- health risk and associated costs of treatment and time loss from dust pollution; or
- the cost of implementing effective mitigation measures.

These environmental and engineering cost sets are not of course independent since in general the extent of the mitigation will depend on the potential damage or loss of amenity caused by the particular environmental hazard.

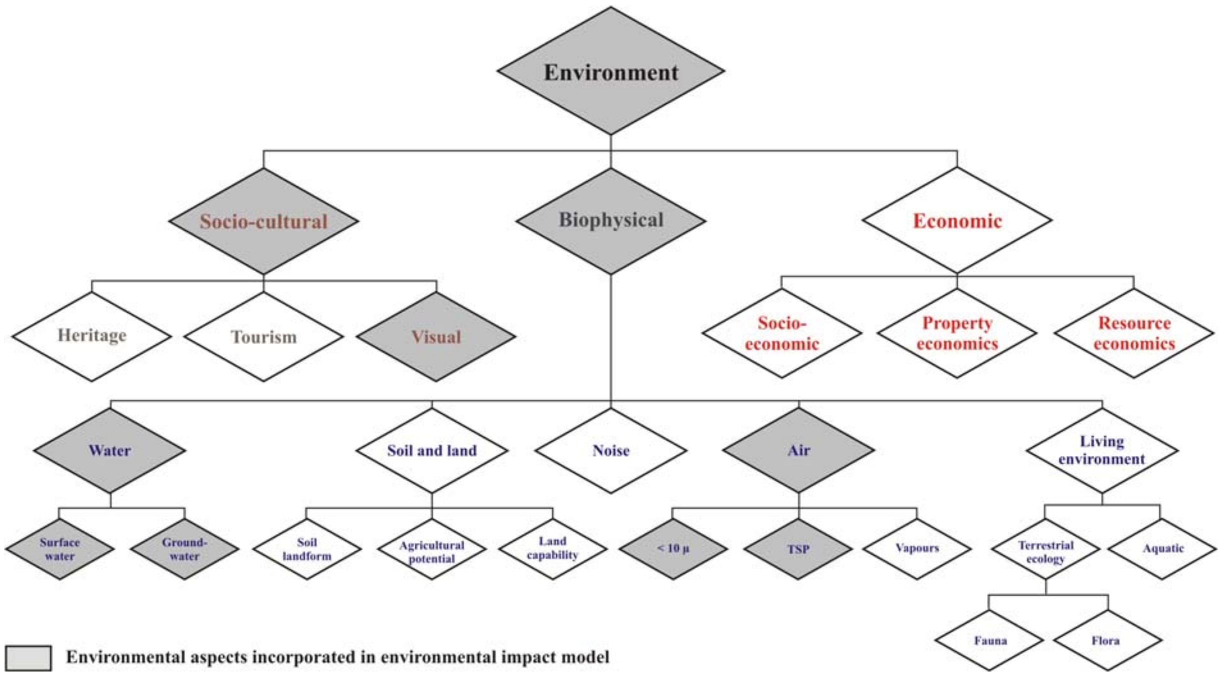


Figure 38: Overall simplified environmental aspects diagram. Highlighted blocks indicate the environmental aspects that must be built into the initial model.

A model that can be used as a planning and design tool for future tailings impoundments in order to optimise the selection of a sustainable land use and the process to achieve this is required. The models must be able to represent different end uses - from return to a pre-mining environment to a range of alternatives.

The overriding concept however has to be that the tailings impoundment design, construction, operation, and closure process should be seen as an integrated system in which the desired end result – sustainable land use – informs the process from the start. Figure 36 (p. 62) illustrates the integrated planning process within an environmental and legal framework.

2.9 Environmental impact estimation

> "We shall never understand the natural environment until we see it as a living organism. Land can be healthy or sick, fertile or barren, rich or poor, lovingly nurtured or bled white. Our present attitudes and laws governing the ownership and use of land represent an abuse of the concept of private property... Today you can murder land for private profit. You can leave the corpse for all to see and nobody calls the cops."
>
> Paul Brooks (Brooks, 1971)

2.9.1 Introduction

The placing of monetary values on environmental goods or services, or the impacts of environmental quality is commonly referred to as the process of valuation. Two major elements to be considered when valuating environmental impacts are:

- identifying the environmental impacts and measuring them;
- determining the processes needed to place monetary values on these impacts, so that they can be included in the final cost analyses for projects.

The purpose of this section is to discuss the use of analytical approaches and to provide insight into techniques, which could be used to determine monetary values for the environmental impacts of tailings impoundments.

2.9.2 Valuation of impacts

The following general guidelines can be followed to valuate environmental impacts (Dixon, Scura, Carpenter and Sherman, 1995:28):

- Start with the most obvious and easily valued environmental impacts. For example where air quality impacts can result in increased respiratory hospital admissions.

- Understand the useful symmetry in benefits and costs. A benefit foregone is a cost and a cost avoided is a benefit. It is intended that both the benefit and cost sides of actions will be considered and evaluated in the most feasible and cost-effective way. The value of improved seepage water quality could be approached from both the direct cost (largely capital and operation, maintenance and replacement costs) and the costs avoided i.e. reduced requirements of downstream users to replace or supplement potable water.

- The economic analysis should be done in a with-and-without project framework. It is important that only additional or incremental benefits and costs due to the implementation of the project be considered. This will be practically implemented by comparing the desired long term tailings impoundment configurations as defined in the section discussing the study method.

- All assumptions should be stated explicitly. This is particularly important in valuing effects on the environment especially if the results will be used comparatively to inform decision-making.

Table 5 presents some of the different valuation techniques, examples of the types of effects valued, and the underlying basis for the valuation. For example, the cost-of-illness approach can be used to evaluate the health impacts of dust fallout from impoundments; the approach is based on underlying damage functions, which relate the degree of physical health impact such as incidence of respiratory disease to the level of pollution.

Table 5: Valuation methods for environmental impacts (Dixon et al., 1995:30).

	Valuation method	**Effects valued**	**Underlying basis for valuation**
	Objective valuation approaches (OVA)		
1	Changes in productivity	Productivity	Technical/physical (behaviour assumed)
2	Cost of illness	Health (morbidity)	Technical/physical (behaviour assumed)
3	Human capital	Health (morbidity)	Technical/physical (behaviour assumed)
4	Replacement/restoration costs	Capital assets and natural resource assets	Technical/physical (behaviour assumed)
	Subjective valuation approaches (SVA)		
1	Preventative/mitigative expenditures	Health, productivity, capital assets, natural resource assets	Behavioural (revealed)
2	Hedonic approaches		
	Property/land value	Environmental quality and productivity	Behavioural (revealed)
	Wage differential	Health	Behavioural (revealed)
3	Travel cost	Natural resource assets	Behavioural (revealed)
4	Contingent valuation	Health and natural resource assets	Behavioural (expressed)

Two distinctive sets of approaches are distinguished in Table 5. The first set, objective valuation approaches (OVA), is based on physical relationships and provide objective measures of damage resulting from various causes. The OVA use ‘damage functions’ which relate the level of offending activity (for example, the level and type of air pollutants) to the degree of physical damage to a natural or man-made asset (for example, soiling of buildings), or to the degree of health impact (for example, incidence of respiratory disease) (Dixon et al., 1995:31).

In contrast to OVA, the second set of approaches, subjective valuation approaches (SVA), are based on more subjective assessments of possible damage expressed or revealed in real or hypothetical market behaviour. Using revealed behaviour involves examination of real markets for goods or services, which are affected by environmental impacts, such as air or water pollution, in which people actually make trade-offs between the environmental impact (pollution) and other goods or income. For example, people are sometimes required to take actions to prevent damage from pollution, such as having to purchase potable water after the contamination of existing groundwater resources. Also, the examination of housing markets has revealed that in many cases that property values are higher in areas where air quality is good as compared with areas where air quality is bad. The difference in the property values between these two areas is a proxy measure of willingness to pay for good quality air. Similarly it can be argued that there is a willingness to pay for visual quality.

As previously described, it is imperative that environmental impacts should be identified prior to the valuation process. Table 6 lists typical environmental impacts and mitigation measures which must be addressed during the life cycle of tailings impoundments as part of the cost models.

The choice of the appropriate method of measurement depends on what is being measured. Figure 39 (p. 69) presents a simplified valuation flowchart, which indicates the analytical process. The flowchart starts with the environmental impact and depending on whether there is a measurable change in production or environmental quality, the appropriate flow path is indicated. Changes in crop yields are easy to evaluate whereas environmental quality changes are usually more difficult to value. In the case of habitat change, for example, the opportunity-cost approach, the replacement-cost approach, the land-value approach or the contingent valuation method could be used to estimate benefits and costs. Similarly, air and water quality can be valued by several cost-based approaches and health impacts are handled with other methods. Non-use values and less tangible impacts such as recreational or aesthetic effects are frequently valued by contingent valuation methods.

Table 6: Environmental impacts and typical mitigation measures.

	Environmental impacts	**Typical mitigation measures**
1	***Visual impact and aesthetics***	
	Visual intrusion within the zone of visual influence	Locating project infrastructure with excessive vertical dimension within zones with high visual absorption capacity. Planning must take cognisance of surrounding landforms. Landform engineering is increasingly applied to surface contouring (Robertson, 2000:9). The objective is to create landforms, which, to the extent practicable, mimic the natural landforms of the area.
2	***Air pollution / dust fallout***	
	Dust fallout and increase in PM_{10} concentration resulting from dust blows off tailings impoundment	Control measures to combat dust pollution include suppression by water and/or detergent and enclosure of source such as using a suitable cover.
3	***Water pollution***	
	Surface – sediment load	Separate clean and dirty water systems by constructing stabilised diversion or perimeter cut-off drains to intercept run-off from disturbed areas and to divert run-off from undisturbed areas.
	Groundwater seepage – contaminant plume	Construct facilities and implement measures to prevent seepage/infiltration and contain groundwater seepage.
4	***Soil disturbances***	
	Soil erosion	Construct soil conservation measures and avoid bare, disturbed surfaces for long periods and undue stormwater concentration. Minimise compaction during stockpiling of material in dry state and avoid unnecessary trafficking. Ripped compacted areas to reduce run-off and aid re-vegetation.
	Soil contamination	Seepage of chemical (including heavy metals) can hardly be controlled unless expensive sealing liners are installed over large areas. Contingency plans should be made to avoid unnecessary spills.
5	***Land use / Land capability***	
	Permanent loss of wilderness, arable land or grazing	Slopes must reflect the natural form of the landscape, providing a natural appearance with varying slopes.
6	***Faunal and floral habitat displacement***	
	Land void of floral and faunal diversity	Disturbance of habitats should be restricted to the actual project area. Vegetation should take place with indigenous species, encouraging habitat creation.

Although objective valuation techniques rely on observable environmental changes, use market prices, and are easier to present to decision makers, subjectively based techniques such as using surrogate markets are increasingly accepted for decision making. It is important to remember that the simplest techniques are usually the most useful and often includes those that rely on actual changes in production, on replacement costs or preventative expenditures, or on information about impacts on human health such as cost of illness. All these deal with physical changes that can be valued using market prices (World Bank Group, 1999:56).

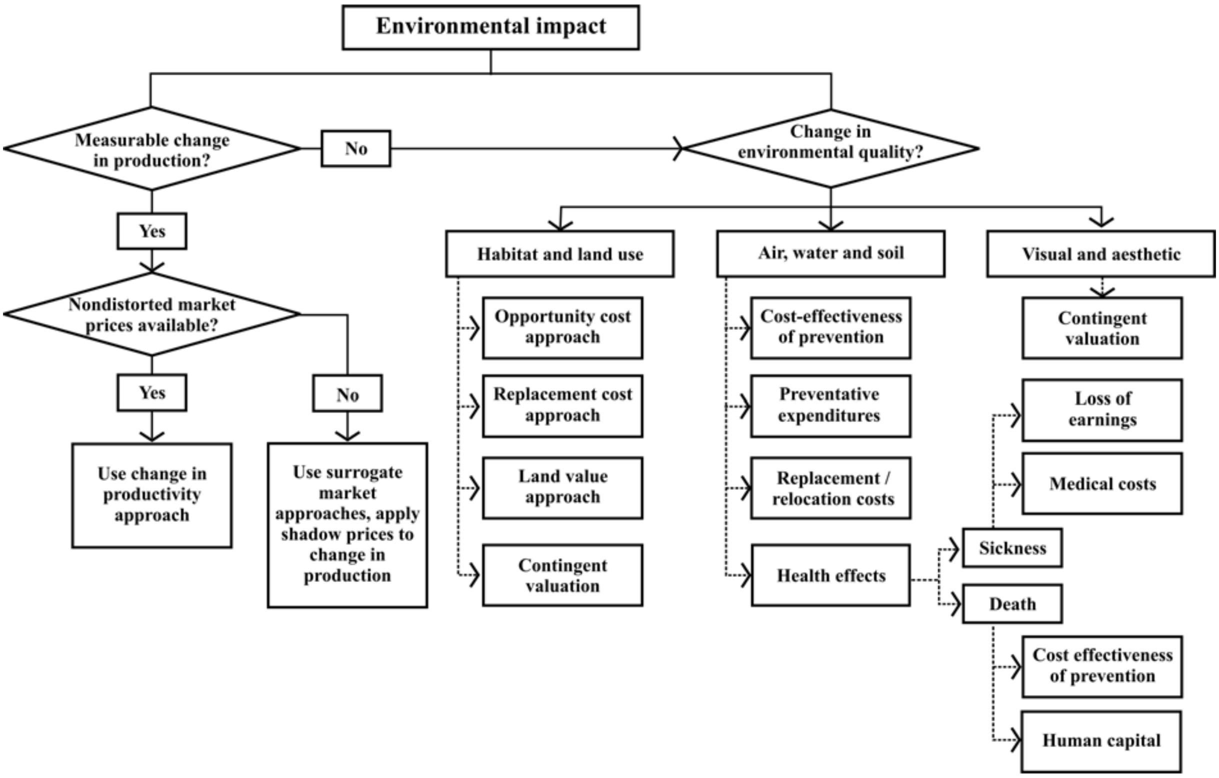


Figure 39: Simplified valuation flowchart for environmental impacts (Adapted from Dixon and Sherman, 1990).

Besides the task of identifying the impacts on the environment and determining their monetary values, two important conceptual problems remain:

- determining the boundary of analysis; and
- setting an appropriate time horizon.

Boundaries of analysis are, to a large extent, determined by the confines of the environmental impacts under consideration. Boundaries differ for the various environmental impacts and are dependent on the locality of the impoundment within the landscape. For example, Figure 40 (p. 70) indicates that the tailings impoundment is confined by:

- the road to the North;
- the river and its tributaries to the West and South;
- geological structures, i.e. dykes to the West and South; and
- transmission lines to the East of the impoundment.

The permanent loss of land and habitat occurs mainly under the physical footprint of the tailings impoundment, while it is expected that a contaminant plume will develop outside the immediate boundaries of the tailings disposal facility. Setting up of an appropriate time horizon is a major conceptual problem. The time horizon should be long enough to encompass the 'life of project'. This poses the question as to the inclusion of just the 'life of mine' or the 'life of tailings disposal' with specific reference in both instances to the post-closure stage. With typical tailings life cycles it is expected that benefits and costs will accrue over very long periods. At any positive discount rate the present day magnitudes of benefits and costs will, say after 50 years, be very small in the calculations of net present value. A discount rate of 10 %, for instance, would mean that most benefits and costs would become inconsequential after only 20 years. The environmental impacts, however pose a special challenge.

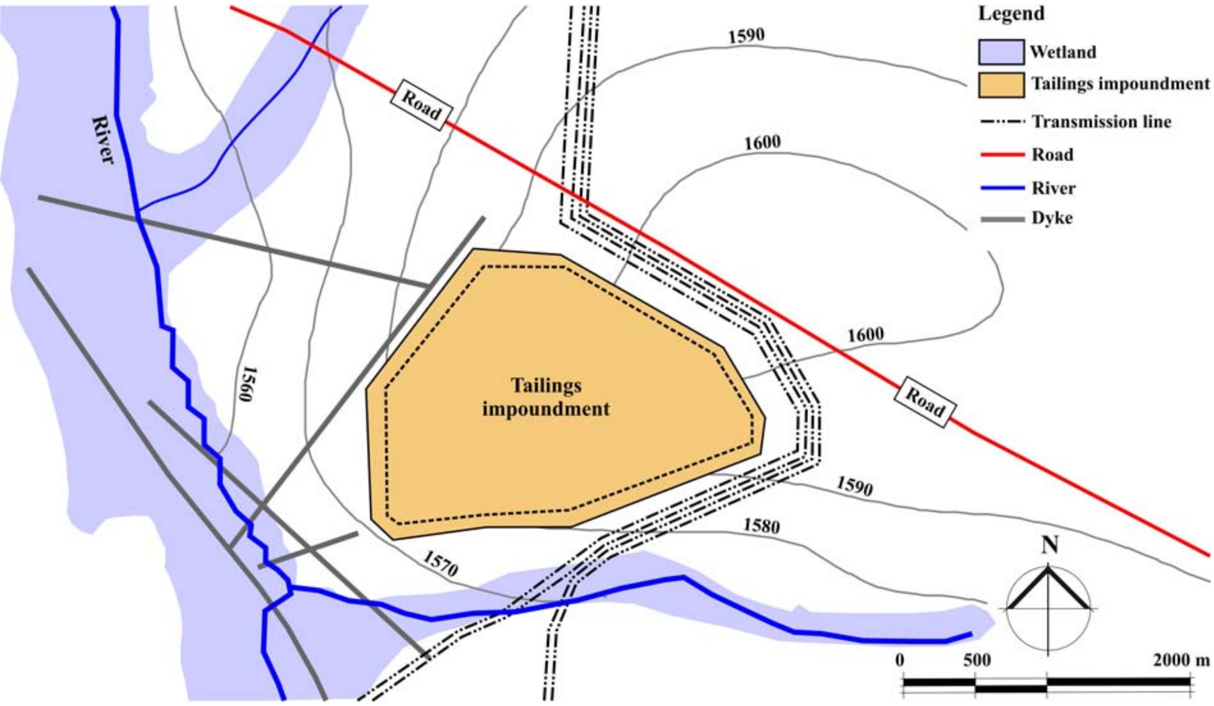


Figure 40: Simplified illustration of boundaries limiting tailings impoundment locality.

If the duration of the impact is less than the economic life of the project, then the effects on the environment can be included in the standard economic analysis. The construction of access roads to an impoundment may cause an increase in soil erosion during the initial construction stage, with the consequent sedimentation downstream in irrigation canals. After five years the road cuts have been stabilized, erosion has stopped and extra costs for cleaning/dredging the canal have come to an end. In this case the project's impacts on the environment can be included in the standard analysis with a time horizon equal to the project's expected life.

With tailings impoundments, however certain impacts on the environment are expected to last beyond the lifetime of the mining activity (funded project generating income), the time horizon over which the project must be considered must thus be extended. It is most likely that the time horizon to be considered can be accommodated within the analysis by adding a capitalized value of net benefits (or costs) at the normal end of the mining operation (i.e. end of tailings deposition). This approach implicitly assumes that the impact on the environment (either the benefit or cost) extends to infinity. In essence this method is the establishment of a kind of 'environmental salvage value' for the project which could be negative or positive.

2.9.3 Multiple accounts analysis

Robertson and Shaw (1998a) state that multiple accounts analysis (MAA) provides a value-based analysis in which numerical values are assigned to the indicators in each account using ranking and scaling techniques. Tradeoffs are achieved by weighting each account to accumulating the numerical values in all accounts.

The MAA approach has been used to evaluate impoundments and determine the environmental advantages and disadvantages of different construction, operation, closure and rehabilitation methods. The process provides a clear, transparent and defensible framework, which can determine the relative ranking of these methods.

MAA is used in industry to determine the preferred alternatives for tailings site, design and management options by means of:

- Identifying the impacts (benefits and losses) to be included in the evaluation (assessment accounts and sub-accounts).
- Quantifying the impacts (benefits and losses) for each of the accounts and sub-accounts.
- Assess the combined or accumulated impacts for each option and compare these with other options to develop a preference list (ranking, scaling and weighting) of options.

A method of evaluating environmental impacts for impoundment site selection has been developed by Shaw, Robertson, Maehl, Kuipers and Haight (2001). The lessons learnt from this approach can be adopted for this research.

Shaw et al. (2001) states that in mining, the diversity of impacts that must be considered makes integrated (combined and cumulative impacts) assessment difficult. How does one compare the ‘apples and oranges’ in one fruit basket with the ‘plums and bananas’ in another to decide which is the preferable. To a large extent any comparison is subjective and depends on the flavour preference (value basis) of the analyst. It is not possible, and probably not desirable, to remove this subjectivity as each analyst seeks to have his/her value basis applied in the analysis. It is therefore an advantage if the evaluation methodology (analysis) is systemized and transparent, allowing the various analysts to clearly indicate their value basis and results.

If the results of analyses from two analysts are similar, despite differences in value basis, then there is likely to be consensus on the alternative selected. If results are materially different, then the root cause of the difference can be identified and discussions and/or additional studies focused on the material, value basis, and issues to determine if a consensus resolution can be reached.

Multiple accounts analysis framework

MAA is structured such that the four broad based categories of issues, referred to as ‘accounts’ are defined (Figure 41, p. 72). These are:

- the technical account;
- the project economic account;
- the environmental account; and
- the socio-economic account.

The technical account typically covers engineering aspects, the project economic account would deal with financial aspects characteristic of the proposed project component, the environmental account addresses typical biophysical aspects and the socio-economic account encompasses socio-cultural impacts.

All the stakeholder issues (called ‘sub-accounts’) are grouped under one of these main accounts and listed on the MAA ‘ledger’. Sub-accounts were defined as any material impact (benefit or cost) associated with any of the alternatives being evaluated. Within each sub-account, indicator values of that particular issue are defined in order to give a clear, understandable description of the impacts. An ‘indicator value’ is a measure or descriptor that provides the reader with some concept or ‘picture’ of the degree of impact, allowing the reader to measure or compare impacts between alternatives. Some sub-accounts will have more than one indicator while others could be represented by just one. Typical indicators for land use are shown in Figure 41.

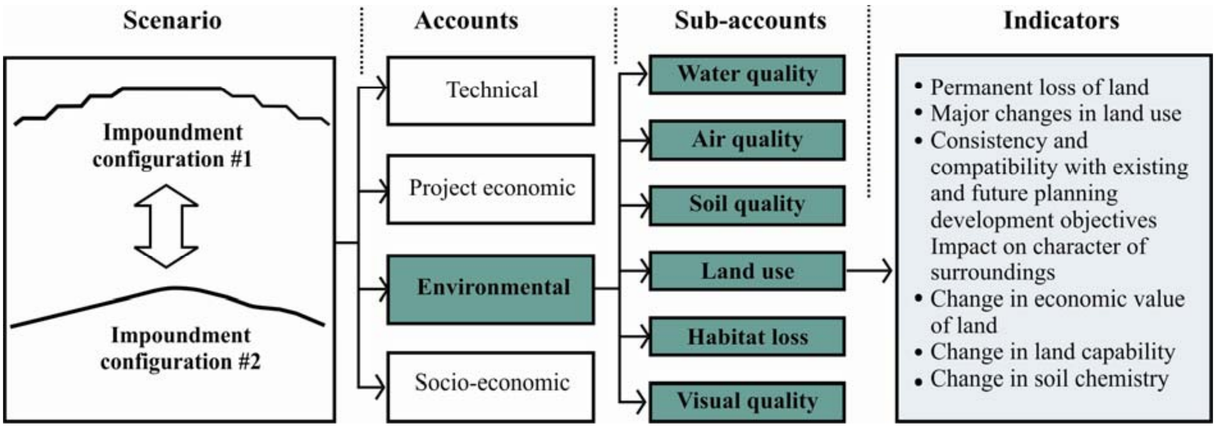


Figure 41: Fundamental accounts for comparing configurations using the MAA methodology.

Some indicators will most likely be straightforward and quantitative (e.g. costs), however many indicators, particularly environmental and socio-economic indicators, are difficult to accurately describe or quantify without a large amount of investigation and analysis. Cognisance has to be taken that the appropriate effort for any indicator should be a function of the significance of the impact; hence an iterative approach will be followed. For example, within the environmental account, the sub-account ‘surface water quality protection’ can be identified. The predictive values for long term water quality ‘protection’ are difficult to quantify, therefore the indicator and measure, of the surface water protection value by necessity will be qualitative. Based on the current level of understanding of issues such as the likely water quality in a specific drainage and the reliability of the collection systems, a qualitative ‘protection value’ will then be assigned to each alternative. A descriptive value of ‘high’, ‘somewhat high’, ‘intermediate’, ‘somewhat low’ or ‘low’ is given to each of the alternatives depending on the reclamation measures included in each alternative. For instance, installation of high infiltration reduction efficiency (higher cost) covers in one alternative would provide greater protection to water quality than installation of lower infiltration reduction efficiency (lower cost) covers in another alternative.

As a result of uncertainties such as long-term water quality predictions, much of the assessment is necessarily based on judgment rather than deterministic analysis. Judgment however is based on some modelling and analyses and the experience of experts in the topic. The anticipation and assessment of the performance of engineered structures, natural processes at work and environmental impacts require a sound understanding of the current technologies as well as considerable experience on a wide variety of similar projects in order to recognize and identify potential impacts, issues and risks. Therefore, having participants who are experienced with similar projects and/or dedicated to understanding and learning the realistic benefits and limitations of certain measures are critical to the success of these evaluations.

It is believed that a great deal of understanding and information transfer can be accomplished during the task of filling out MAA ledgers. It is during this stage that the differences of the alternatives and critical flaws (not the meeting of threshold values such as water quality standards or cost limitations) are highlighted. Numerical evaluations begin once the ledgers are complete. This involves ranking, scaling and weighting the indicator values in each of the sub-accounts. This numerical normalization allows comparison of indicators and different sub-accounts.

Ranking, scaling and weighting of aspects

Outcomes are ranked, in order from best to worst, with respect to the indicators for each sub-account (Table 7). Ranking is a simple ordered list and makes no attempt to distinguish how great the difference in impact is between alternatives on the list. In practice, there may be very little or very large differences in the impact from the best to the worst.

Table 7: Subdivision of the scaling system (indicator value) (Robertson and Shaw, 1998a).

Scaled Factor			Scaled Factor	
9	***BEST***		9	
8	*Very good*		8	Impoundment Alternative #1 (e.g. 85% vegetation cover)
7	***GOOD***		*7*	
6	*Good'ish*		6	
5	***INTERMEDIATE***		5	
4	*Poor'ish*		4	Impoundment Alternative #2 (e.g. 45% vegetation cover)
3	***POOR***		*3*	
2	*Very poor*		2	
1	***WORST***		1	

Since the separation of the best alternative from the worst may be either very slight or very significant, scaled values are assigned to each alternative for each of the indicators using a nine point scale (Table 7). Shaw et al. (2001) found a nine point scale is readily understandable and provides a range and discretion suited to these evaluations. The 'best' alternative in the ranking will always be given the value of 9. If the 'worst' alternative is considered to be half as good as the best, it should be given a value of 5 (Shaw et al., 2001:6).

A weighting factor (W) is applied to each indicator to allow the introduction of value bias between individual indicators. A weight of '5' indicates a 'high value' or important indicator. The process of assigning weights to the various indicators on the ledger (Table 8, p. 74) serves two purposes.

First, it serves to clearly identify those issues that are most critical to the different stakeholders. For instance, while aesthetics might be of utmost importance to one stakeholder, capital cost might be most important to another.

The second level of understanding achieved in this process is that each evaluator has the opportunity to defend his/her weightings and more often than not a compromise between extremes is reached as the complexities of the task at hand are stripped down, issue by issue, and the issues are assessed relative to one another.

The cumulative 'score' of one outcome compared to another in any one sub-account is obtained by adding together the products of the scalar value and weight for each indicator in a sub-account and normalizing by the division of the sum of the weights for all indicators of that sub account. The higher the score, the more favourable the outcome in any one category.

$$\text{Sub-account merit rating} = \frac{\text{sum of Scalar Values x Weights (for each indicator in the sub-account)}}{\text{sum of Weights for indicators in the sub-account}}$$

The process of adding together the sub-account scores to obtain the account scores for the main accounts and the overall MAA score follows the same procedure of weighting and normalization.

Table 8: Example of a ledger with indicators for sub-accounts (Robertson and Shaw, 1998a).

Account: Environmental								
Sub-account: Land use, land capability and landscape character								
Multiple Accounts Evaluation ⟵⟶						**Value-based Decision Process** ⟵⟶		
	Indicators	**Indicator parameter**	**Unit**	**Critical flaw threshold**	**Indicator Quantity**	**Indicator Value (S)**	**Weight (W)**	**S x W**
1.	Permanent loss of land	Area	ha		350	3	1	3
2.	Major changes in land use	Value	-	None	LDO/IDP – qualitative	6	2	12
3.	Consistency and compatibility with existing and future planning development objectives	Value	-	None	LDO/IDP – qualitative indication	5	2	10
4.	Impact on character of surrounding area	Value	-	None	EIA/VIA and Visual Absorption Capacity – qualitative	2	2	4
5.	Change in economic value of land affected	Value	-	None	LDO/IDP – qualitative	6	3	18
6.	Change in land capability	Value	-	None	EIA - qualitiave	2	1	2
							Sub-account Merit Score Σ(SxW)	49
							Sub-account Merit Rating Σ(SxW)/ΣW	4.5

2.9.4 Summary

Pollutants produced as a result of tailings deposition – solid wastes, leaching of toxic substances, and substances that pollute the air and water – may impose costs on society and individuals. The identification and quantification of these impacts and the assessment of their monetary and non-monetary impacts are important elements in a broader economic analysis of the benefits and costs of tailings impoundments. Such information is important in helping decide what level of pollution control is economically justified, and being able to make informed decisions as to 'internalising' environmental impacts. If the monetary values can be determined for each environmental impact by means of existing valuation techniques it may be possible to enter these into an overall account for the different tailings impoundment stages.

Understanding the environmental costs will serve to rationally inform decision making as to:

- managing environmental impacts by means of mitigation; or
- to consider implementing measures in order to completely prevent an impact from occurring.

If the environmental impact is completely prevented, the cost of the prevention can be taken into consideration in the financial analysis of the tailings impoundment. An example would be to decide between installing an impermeable liner to prevent contamination of the groundwater resource, or only using in situ clay reducing the pollution potential when locating the impoundment. If the decision is taken to merely mitigate, and not eliminate water pollution, the cost of the mitigation action is a direct and identifiable cost of the project, but the value of the residual environmental impact also needs to be considered in the costs of the project. Valuating tailings impoundment environmental impacts could assist authorities and proponents with deciding whether a particular alternative's benefits (including all of the environmental benefits) exceed its costs (including all of the environmental costs).

2.10 Visual

The visual aspect literature review covers:
- visual impact assessment (VIA); and
- the generation of photorealistic computer images.

The environment can be divided into biophysical and socio-cultural elements and economic aspects. Visual aspects is a sub-account under the socio-cultural account (Figure 42).

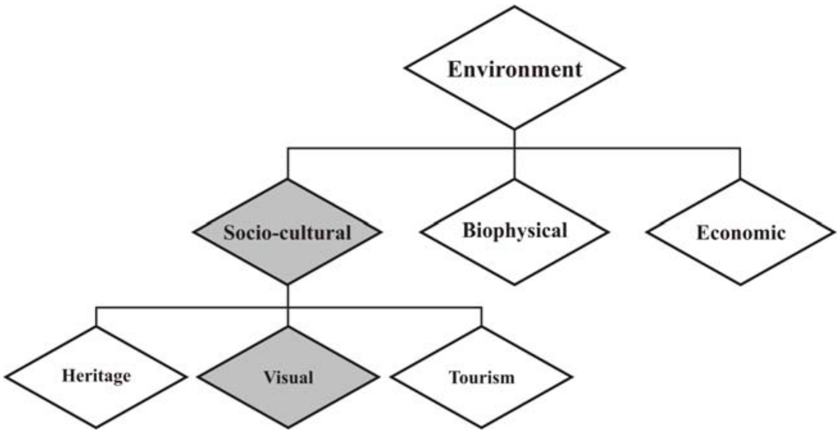


Figure 42: Simplified environmental aspects flow-diagram indicating the context of visual quality.

2.10.1 Visual impact assessment

Visual impact assessment (VIA) is an increasingly important part of environmental impact assessment (EIA). Following an integrated iterative design process, environmental constraints and opportunities must be taken into account at each stage of decision making. The objective is to avoid or minimise the potential negative visual effects of a scheme and, where appropriate, to seek opportunities for landscape enhancement (Landscape Institute, 2002:13).

Visual impact assessment methodologies are often criticised for their subjectivity. A prime motivation for this research is to substitute subjective evaluation with objective measurement.

Stamps (1997:251) states that VIA studies require two judgments, namely:
- an estimation of the severity of the impact; and
- an assessment of the necessity for and extent of impact mitigation.

Discroll, Gray, Blair, and Ady (1976) state that an existing or proposed scheme's visual impact is influenced by the following factors:
- physical and visual characteristics of a scheme;
- visibility of a scheme;
- distance from the scheme when observed;
- the environmental setting (environment around the scheme); and
- disposition and visual preference of people viewing the scheme (viewer sensitivity).

Smardon, Palmer, and Felleman (1986:206) mention that the visual impact of a scheme may be estimated through:

- describing the visual characteristics of the scheme;
- delineating viewing zones around the scheme;
- identifying sensitive viewing populations within the zone of visual influence; and
- evaluating the scheme's visual impact on foreground and background landscape.

Hull and Bishop (1988) and Young (2002:13) state that visual impact of a scheme can be determined using visual intrusion, visibility and visual perception criteria and is concerned with the:

- direct impacts of the development upon views of the landscape through intrusion or obstruction;
- overall impact on visual amenity, which can range from degradation through to enhancement; and
- reactions of viewers who may be affected.

Smardon (1986) provides an outline procedure for a six step VIA:

- conduct a landscape description or inventory;
- assess user or viewer characteristics;
- make preliminary line-of-sight determinations;
- establish key viewpoints;
- assess impacting activity/land use characteristics; and
- prepare a visual impact assessment and mitigation summary.

Visibility

Felleman (1986a:48) states that visibility analysis is concerned with determining those portions of the landscape which can be seen as well as the content and composition of available views. Visibility mapping is central to the prediction and communication of landscape and visual elements. A visibility map indicates the visibility of an existing or a proposed scheme within the landscape. The existing or baseline visibility of a site contributes to the visual amenity of the surroundings (Landscape Institute, 2002:101). When determining the visibility of a scheme it is preferable that the worst-case scenario be assessed, that is the visibility of a scheme should be analysed for the anticipated final design height, shape, side slope configuration, size and cover. The surface topography, within which an impoundment is located, affects the part(s) which are visible at a given point (ESRI, 2000:128). This is known as the zone of visual influence (ZVI) also referred to as the viewshed, visual envelope or visual basin.

Zone of visual influence

The zone of visual influence (ZVI) is the area from which the actual or proposed scheme or structure is visible. The zone is generally shown on a visibility map. The line of sight is the line between two points that show the parts of the surface along the line that are visible to or invisible from an observer across the surface topography. This line determines the zone of visual influence (ZVI) (Figure 43). The principle is that if the vertical angle between the observer and the scheme is bigger than the angle between the observer and the intermediate objects then the scheme is visible; if not, it is hidden or invisible (Smardon et al., 1986:57). The extension of this algorithm, applied to an area, can generate a ZVI map. Further, Felleman (1986a) states that these sightlines can be assumed to be straight except in views involving heated surfaces, which may cause mirages, or over large areas of water.

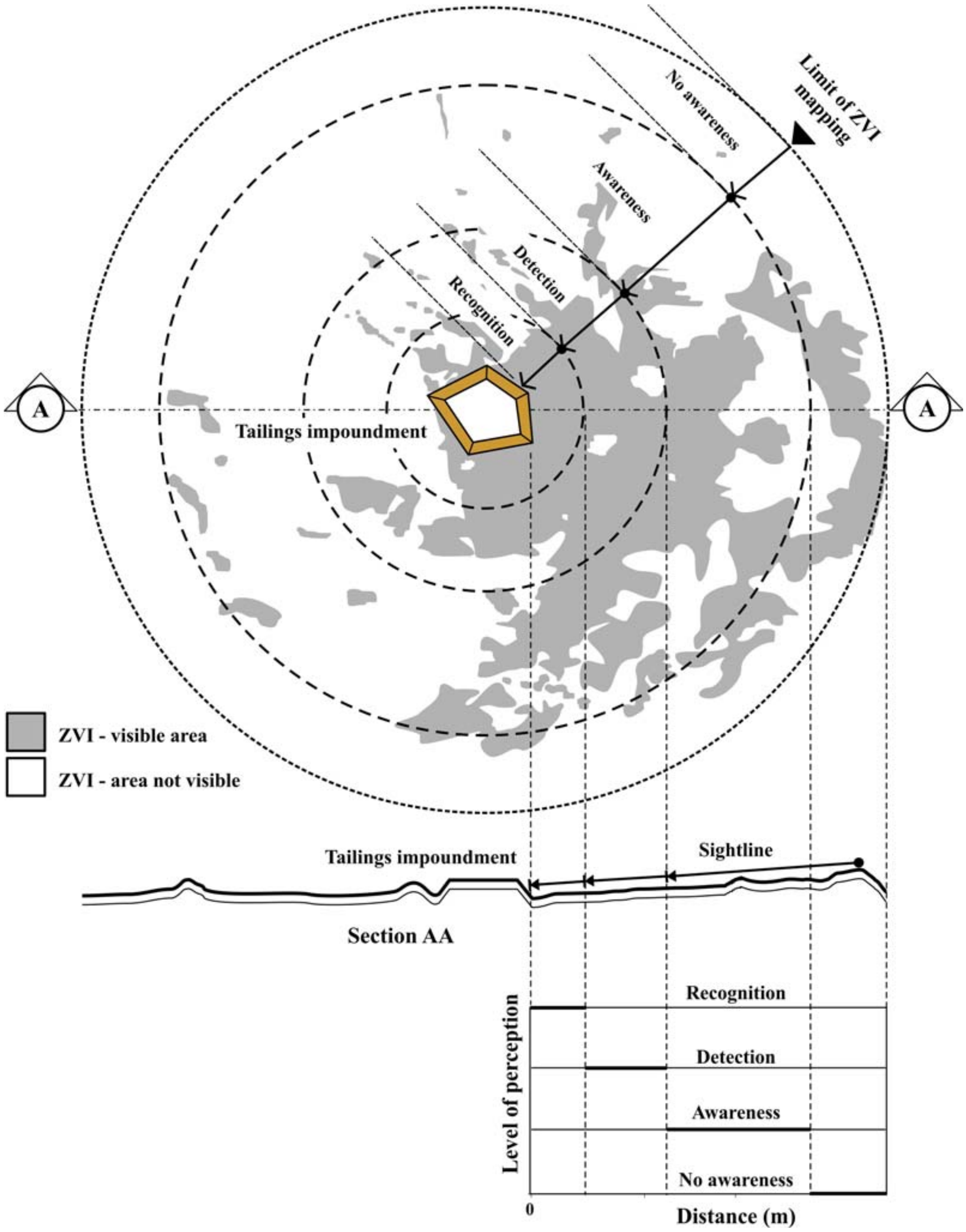


Figure 43: Zone of visual influence terminology and concepts.

The simplest and oldest analytical methods for determining the ZVI may be traced back to the early 1970s and are summarised by Kent (1986:103). The basic desk-based approach developed by Weddle (1973) involves the plotting of topographic sections and sightlines at ten degree intervals around proposed schemes. Although inevitably crude (due to the limited number of sections used), slow, and laborious, this approach enables the identification of so-called "dead ground" (areas from which a development is hidden or invisible) and provides an explicit spatial indication of the ZVI. Today, the ZVI is determined by means of running queries with Geographic Information Systems (GIS) software.

Techniques of visibility impact assessment are largely concerned with the extent to which a scheme can be seen from the surrounding area and generally do not attempt to quantify human reaction or perception of the intrusion (Wohlwill, 1978). The key element in a visibility analysis is determining the ZVI. The ZVI, when extended and applied to elements with appreciable dimensions such as tailings impoundments, can be defined as the portion of the landscape which can be seen from the impoundment (Alonso, Aquilo and Ramos, 1986:293). The reciprocal is also true. The ZVI therefore delineates the surface area around an existing or proposed impoundment from where the scheme will be visible. The ZVI is an important element of predictive visual impact assessment since it serves not only to define the area from which a scheme will be visible, or to whom or what the scheme is visible (Fels, 1992), but also because it is used as a precursor to the selection of individual views for more detailed visual and landscape impact assessment.

The physical limits of the process of intersection are refelcted in two dimensions in the form of a ZVI map and are influenced by elements of the macro- and micro-environment. The macro-environment includes surface topography (terrain), surface features that project above the terrain, and the atmosphere, where conditions related to visibility include clarity and the intensity and direction of illumination. The micro-environment refers to the nature of the environment in the immediate vicinity of the observer and includes features such as buildings, vegetation, or windows, which effectively serve either to block, filter, or frame a view.

In addition to the screening influences of the macro- and micro-environment the extent of the ZVI can be influenced by the curvature of the earth and the loss of visual sharpness that occurs with increasing distance from a project (Alonso et al., 1986:292). Alonso also states that the further an observer moves from a scheme, the less noticeable the details become. This fact has two immediate consequences:

- visual perception decreases as the distance increases; and
- it is possible to determine a distance, related to the conditions of the terrain and the scheme, beyond which it is not necessary to pursue visibility analysis.

Visual distance zones

The zone of visual influence (ZVI) can be divided into subzones which can be defined as visual distance zones (Driscoll et al., 1976:84). The subdivision may be on the basis of visibility distance or the delineation of a foreground, middleground and background (Figure 44, p. 79). Since visibility distances are a function of many factors, the subdivision distances will be case dependent.

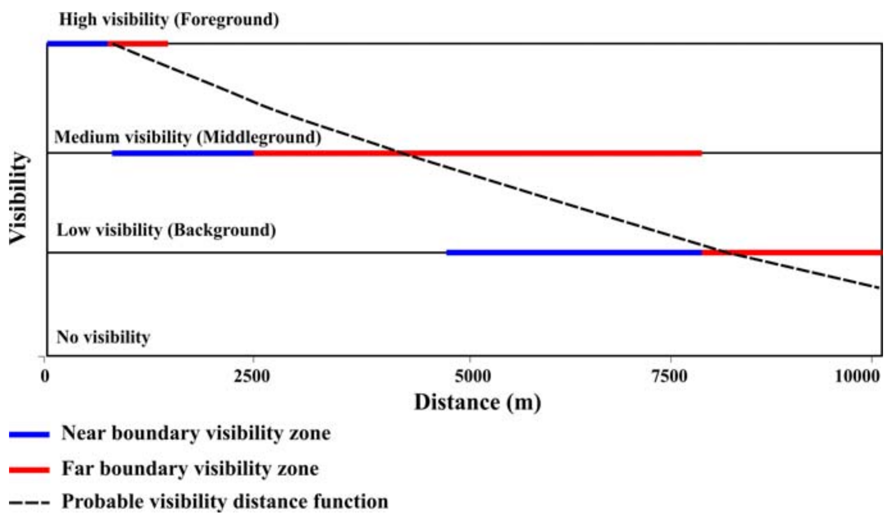


Figure 44: Subdivision of zone of visual influence into visibility distance zones.

Felleman (1986a:54) recommends that visibility distance zones should be established on a case-by-case basis rather than adopting a single scale. The visibility-distance relationship given by Smardon et al. (1986) provides a useful guide and illustrates that a rational visibility-distance function can be established.

The foreground (high visibility) is the zone where recognition of surface textures and the fullest range of surface colours are possible. Cognitively, in this zone human scale plays a key role in judging spatial relationships (Smardon et al., 1986:54; Alonso et al., 1986:292).

In the middleground (medium visibility) texture is characterised by the visualising of complete surface features such as a uniform stand of trees and building clusters and small landforms (Smardon et al., 1986:54). This scale is a function of local surface geology and development patterns. The middleground plays the most significant role in understanding the perceived landscape due to its integrative role in defining compositional content (Alonso et al., 1986:292).

The background (low visibility) stretches to infinity and is mostly dominated by the horizon. Typically the atmospheric conditions reduce colours to blue-greys and textures are seen as groups of patterns (Alonso et al., 1986:292).

Visual perception

Visual perception is not just a seeing activity but also an act of interpretation, albeit largely subconscious. People actively scan the visual field to obtain detail and sample the ambient array by moving the eyes, head, and body. In general, perception involves the concurrent awareness of persistence and change in the ambient array. Information concerning persistence comes from various invariants such as ratios, gradients, discontinuities and other relationships in the ambient array that are due to persisting features of the environment (Smardon et al., 1986:70).

People are dependent on senses to attain an awareness of their environment. The smell, taste and tactile senses are used to familiarise ourselves with our immediate surroundings. Our visual and auditory senses are much more developed and are capable of perceiving both immediate and distant environments.

Senses are rarely used in isolation, but in some cases there is a deliberate reliance on the visual sense to make reason of what is perceived because the other senses are incapable of adding clarity to the observed element. This usually happens when distance between the observer and the element is so great that sensory information becomes redundant. In this case we rely strictly on our visual sense to acquire the necessary information needed to recognise the element.

The subconscious mind progresses through a series of stages when a scene is viewed, the different elements are analysed, each with its own character in terms of shape, colour and texture and then correlated with a data base. Photographs 1 and 2, Figure 45, demonstrate this process and illustrate just how complex the visual perception process is. Both landforms within the photographs may at first glance seem out of place and only when viewed closer does it become apparent that the elements are not man-made but natural landforms in a very flat landscape. The landform in photograph 1 has a similar appearance to a waste rock dump and the landform in photograph 2 could quite easily have been some sort of mine residue deposit.

[1] Photograph of an outcrop of dark intrusive rocks to the south-east of Kakamas, Northern Cape.

[2] Photograph of an inselberg-type flat-topped mountain East of Pofadder, Northern Cape.

Figure 45: Photographs demonstrating how shape, colour and texture influence the visibility of natural landforms in the landscape.

Thresholds of the sensory system are used to study the link between variation in specified characteristics of environmental stimulation and subjective experience. The visual threshold is the minimal quantity that can be perceived, a boundary one crosses from not detecting to detecting. However, a threshold is rarely an absolute event (Shang and Bishop, 2000:125).

Although the concept of visual threshold has long been used in psychophysics it has not been used in landscape research with respect to tailings impoundments. Perception is the central concern of the area of psychological inquiry forming the impressions of the qualitative and quantitative aspects of external objects and their spatial positions (Dember, 1979:2). Psychologists generally agree that perceptual experience as it generally occurs in people, is a process whereby stimulus information is elaborated and interpreted so as to yield organisation and meaning (Dember and Warm, 1979:6).

Dember and Warm (1979:21) states that there are a variety of perceptual tasks and that their ordering occurs according to the amount of information required to perform them successfully. A stimulus which is below-threshold is one which contains insufficient information for a particular task to be successfully accomplished. In contrast an above-threshold stimulus contains the necessary amount of information for such a task to be completed. Thus, the point of transition between the below-threshold and above-threshold is called the threshold.

After a subconscious awareness, noticing the presence of a stimulus is called detection and requires the least information of any perceptual task a person might be able to perform. The stimulus required for something to be detected requires much less information than for it to be recognised.

A recognition threshold can be obtained in a similar manner as the detection threshold through finding the minimal amount of information necessary for correct recognition. Also, a recognition threshold for a given stimulus will require a higher level of information than a detection threshold for the same stimulus. The relationship of distance and visual perception is well recognised in visual analysis literature (Hull and Bishop, 1988:104). The principles are illustrated in Figure 46.

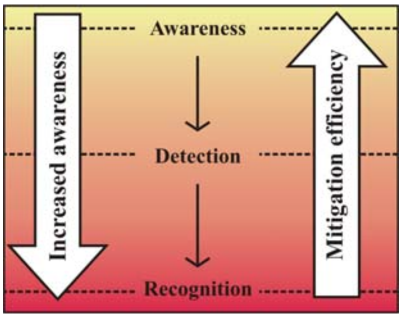


Figure 46: Visual perception thresholds (Shang and Bishop, 2000:126).

Although the process is the interpretation of a continuum, in practice a series of thresholds occur which may be described as progressing from awareness through detection to recognition. These three perception thresholds are applied in this study and illustrated in Figure 43 (p. 78). The first threshold is becoming aware of a stimulus, i.e. being aware but not detecting the stimulus. The second threshold is where detection of the stimulus in its environment takes place. It could be that the object is undetectable due to the distance between the observer and the object or merely due to the lack of contrast with its environment. This is not to say that there is no stimulus - it is just not detectable. The third and last threshold is where recognition of the detected stimulus takes place. If the stimulus is a familiar object, like a tree, recognition is the effortless comparison and matching of the detection stimulus with a similar object in the human memory.

If it is an unusual stimulus for the specific scene it could be either unrecognisable or misinterpreted. This could happen where the distance to the object is so great that the specific element cannot be perceived for what it truly is. This perception is also a function of the contrast-factor between the element and its environment, the ability to camouflage an object. Camouflage is the reduction in contrasts to such a level that recognition and even detection is disabled. Therefore the quantity of information and knowledge we receive depends on the diversity and degree of contrast of the sensory data we obtain and the ability to differentiate between them (Bell, 1999).

Tailings disposal facilities typically represent regular forms with regular geometries. Regular form, as compared with irregular form, is more readily perceived as one continuous entity according to the Gestalt theory and potentially provides stronger stimuli to the viewer (Shang and Bishop, 2000:128). Gestaltists elect to study perception in terms of inherent organisation and configurational properties and suggest that perceptual events must be understood in terms of their holistic nature.

> "The whole is greater than the sum of its parts" typifies this conceptual approach toward the investigation of perceptual processes.
>
> Dember and Warm (1979:18)

2.10.2 Photorealistic computer imaging

Two functions of visual impact assessment (VIA) are:

- to assess the impact of a scheme; and
- to assess the mitigation of a scheme

and visual simulation is generally required for both.

A range of visual simulation (visualisation) techniques are available for landscape and environmental practitioners engaged in all aspects of environmental impact assessment (EIA). For the purpose of this research, simulation is given the definition:

> "...to create a representative and accurate two-dimensional image of a future or proposed scheme through the use of computer modified photographs and computer graphics."

Visualisations are the preferred means of communicating visual effects of a scheme, however it is imperative that they are representative and accurate.

Representative simulation

It is essential that simulations should be as realistic as possible (Lange, 1994). Often the aim is to illustrate worst-case situations at different stages in the life of the scheme especially if conditions are expected to change. In order to visualise the worst-case scenario it is necessary to carefully consider the following:

- location;
- season;
- time of day;
- lighting;
- weather conditions; and
- age of the scheme (Smardon et al., 1986:192).

Accurate simulation

It is important to aim for visual accuracy with regard to the photo simulations and it is incumbent upon the creative person to justify any and all known inaccuracies. Visual simulation is integral to visual analysis and must be:

- objective;
- defensible; and
- understood with ease (Smardon et al., 1986:199).

Alternative visualisation techniques

Visualisation techniques range from using photomontages and panoramic photographs of similar schemes through to constructing virtual reality three-dimensional computer simulations using topographical data, digital terrain maps and data from aerial photography.

Three-dimensional computer simulations

This technique requires the modelling of a three-dimensional environment and the applications of different texture maps on the created objects. This approach requires a skilled person and highly advanced computer hardware and software in order to be executed properly. Even then three-dimensional computer environments have been found to be inadequate and lacking realistic representation.

Photomontage

A common visualisation technique is to place an image onto a photograph for the purpose of creating a realistic representation of proposed or potential changes to the view. Traditionally these were created manually by hand rendering. Recently with advancements in computer technology and software objects can be computer-generated and inserted into a photograph. A constraint for this method is the precise determination of the position and scale of the object inside such a photo environment. The following is required to correctly place an object within a photograph:

- locations and dimensions of the scheme;
- accurate location and height from which the photograph was taken;
- camera focal length; and
- precise direction of view of the camera.

The realistic rendering of an object to correlate with the context of the photograph is often time consuming and needs to be performed by a suitably skilled person.

Electronic manipulation of panoramic photographs

Panoramic photographs can be taken from key viewpoints to an existing object and altered using computer simulation techniques to visualise differences. The resultant visual change to the landscape can then be observed and assessed. The electronic manipulation of panoramic photographs to create photorealistic representations of various impoundment configurations from key viewpoints is the most appropriate technique for this study.

2.10.3 Summary

Visual impact assessment (VIA) is becoming increasingly important in the overall environmental impact assessment (EIA) process. VIA addresses a component of the social-cultural aspect of the environment and focuses specifically on the visual effects of a scheme on the environment. The methodologies used to determine visual impacts are often criticised for its subjectivity. A visual impact methodology that is objective and contains defensible measurements is required to assess the impact of tailings impoundments on the receiving environment.

Stamps (1997:251) states that a VIA study requires the following two judgements:

- the estimation of the severity of the impact; and
- the assessment of the necessity for and extent of impact mitigation.

Numerous methods exist to determine the severity of an anticipated visual impact. Discroll et al. (1976) states that visual impact is influenced by the following factors:

- physical and visual characteristics of a scheme;
- visibility of a scheme;
- distance from the scheme;
- environmental setting; and
- disposition and visual preference of people viewing the scheme.

The five factors provide a basis for visual impact determination. Factors two and three are fundamental to the quantitative assessment of visual impacts. These two factors are required to calculate the zone of visual influence (ZVI) and delineate the extent of the visual impact. A geographic information system (GIS) can be used to generate a two-dimensional map which spatially represents the zone of visual influence of a scheme within the landscape.

Visual perception should be incorporated into the VIA methodology. Visual perception is a psychophysical process and is not just a sensory activity, but also includes an act of interpretation, albeit largely subconscious. Quantification of a visual impact requires linking visual perception and distance. Alonso et al (1986:292) states that detail of an object becomes less noticeable with the increase in distance between an observer and object.

Visual perception studies can be used to study the link between variation in specified characteristics of environmental stimulus and subjective experience. A visual threshold refers to the minimum quantity of stimulus required to enable the observer to cross the boundary from one level of perception to another. Although the process is the interpretation of a continuum, in practice a series of thresholds can be used which describe the progression from awareness through detection to recognition.

This process can simplistically be described with an example. Suppose an observer detects an object at the end of a road. At this point the observer has crossed the threshold from not detecting to detecting. As the observer moves closer to the object, the threshold of recognition is crossed. At this point the observer's ability to recognise the object as a familiar element is influenced by distance and the consequent clarity of detail enabling accurate recognition.

Photorealistic computer imaging can be used as a visualisation technique to assess the visual impact of a tailings impoundment and entails the realistic simulation of an impoundment in the visual environment. Electronic manipulation of panoramic photographs, as a visualisation technique, can be used by taking panoramic photographs from key viewpoints to an existing impoundment. The photographs can then be altered through the use of computer simulation software to represent different configurations.

2.11 Air

> "The management of mine residue deposits is an integrated process that relies upon the implementation and management of all applicable design assumptions and principles during the life cycle of the facility."
>
> Mine Residue Code of Practice (SABS, 1998)

2.11.1 Introduction

Environmental protection is a priority for society. Regulators set environment standards, requirements, and targets and ensure that these are met. Decision makers need to work together as partners protecting the environment to meet the needs of the present without compromising the ability of future generations to meet their own needs...

A wide variety of airborne pollutants are of concern in terms of health and environmental impacts. Dust is a problem for almost all forms of mining and associated activities and is a generic term used to describe fine particles that are suspended in atmosphere and is non-specific with respect to size, shape and chemical make-up of the particles. Dust can contribute to a reduction in visibility, stain and soil surfaces, or pose a threat to human health. Certain types of dust also contain metals which are potentially hazardous or contain particles known to cause diseases (McGranahan and Murray, 2003).

Particulates include total suspended particulates (TSP) and particulate matter of 10 µ or less in aerodynamic diameter (PM_{10}) (Environment Australia, 1998; World Bank Group, 1999) which are indicated as sub-accounts under the air account in Figure 47.

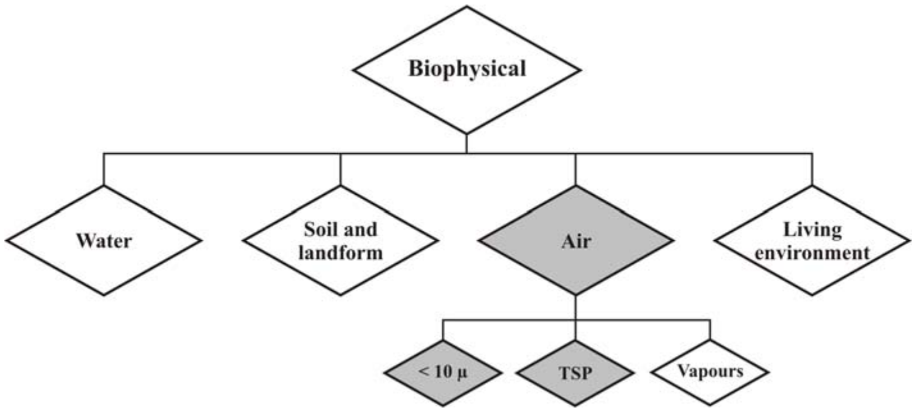


Figure 47: Simplified environmental aspects flow-diagram. The highlighted blocks indicate the context of the air quality aspects relevant to most tailings impoundments.

Impact of fugitive dust

Tailings impoundments change elements of the receiving environment such as air and water which in turn affect the health or cause discomfort to people, plants or animals. It is therefore necessary to understand the mechanics of the air quality impact process and how fugitive dust generated from exposed impoundment surface areas causes adverse impacts on the receiving environment.

When assessing the impact of tailings impoundments on air quality, the main source of inhalable particulates (PM_{10}) is as a result of wind entrainment of particulates from exposed impoundment surface areas (Scorgie and Randell, 2002). Fugitive dust sources are emissions of solid particles by the forces of wind or machinery acting on bare, sparsely vegetated or unsuitably covered areas. The level of dust generated, travelling distance, and types of health risks and environmental impacts depend on factors such as:

- climate;
- topography;
- tailings mineralogy and metallurgical characteristics;
- impoundment geometry and cover; and
- land use of the area surrounding the impoundment.

This section describes the impact of wind blown dust off tailings impoundments on the air quality and includes:

- literature on best practice predictive modelling approaches and techniques;
- typical remedial measures that reduce the air quality zone of influence; and
- a process for quantifying the zone of influence and linking such to the overall environmental impact and engineering cost model.

Fugitive dust can be divided into nuisance dust and dust that can cause harm. Fugitive dustfall levels greater than 2000 mg/day/m² may result in repeated complaints whereas levels higher than 5000 mg/day/m² could prompt angry responses. The DME uses the 1200 mg/day/m² threshold level as an action level. Finer dust fractions (PM_{10}) are important in terms of possible health risk. South African guidelines provide a 24 hour average concentration value of 180 µg/m³ and annual average of 60 µg/m³ for PM_{10}. Metals and silica content can also be used to determine the toxicity levels of liberated dust. Tailings impoundments, through the fallout of fugitive dust and increase in suspended particulate matter concentrations, can impact on air quality (Figure 48).

[1] and [2] photographed by Johan Fourie, Johan Fourie and Associates, as part of an air quality assessment in the Rustenburg Region.

Figure 48: Wind entrainment of particulates from exposed tailings impoundment surface areas.

The purpose of this section is to describe the possible effect of tailings impoundments on the air quality and will focus on:

- the discussion of technologies for estimating fugitive dust emissions,
- presenting methods to model and plot the dust dispersion of the aforesaid, and
- implications of air quality on human health.

It is perhaps useful to use one of the aspects for which there are receiving environment limits as an example. Receiving environment limits are also referred to as limiting criteria, maximum standards, minimum requirements, or threshold values. Fugitive dust limits for people in the receiving environment are typically based on published World Health Organisation (WHO) guidelines (WHO, 1987; WHO, 2000 and WHO, 2005). These consider the increase in ill-health effects, such as respiratory illnesses, due to the increase in particulate concentration of fugitive dust by applying published dose-response functions. The criteria have been set on the basis of the records of respiratory related ill health compared with the exposure of particulates – i.e. they are empirical, there is no medical rationale required of exactly why inhalable particulates cause respiratory illnesses – the empirical correlation is sufficient, i.e. the science is statistics not medicine.

It is necessary to predict or measure the amount of particulates generated by the tailings impoundment which causes an increase in concentration in the zone of influence (surrounding area), count the people in the area, and apply dose-response functions in order to estimate the effect of tailings impoundments in terms of ill-health.

Impact estimation and valuation process

The potential air quality impact of dust from tailings impoundment depends on the (US EPA, 1995; US EPA, 1996):

- amount of material entrained from the impoundment surface;
- dispersion of the material in the atmosphere; and
- its removal by deposition.

The above are largely a function of:

- tailings characteristics such as moisture content and particle size distribution; and
- prevailing meteorology and in particular the wind field, atmospheric stability regime, and precipitation and evaporation rates.

Dust mobilisation occurs when wind velocities are higher than the material threshold value. The threshold wind friction velocity is defined as the minimum friction velocity required to initiate particle motion and is dependent in the size of the erodible particles and the effect of the wind shear stress on the surface.

As soon as the threshold friction velocity is exceeded the movement of the particle is dependent on the relationship between the weight of the particle acting downward and the opposite aerodynamic drag on the particle. Once airborne, the drift potential of particles depends to a large extent on the particle diameter, wind speed and the degree of vertical air mixing which is a function of the stability of the atmosphere. Large dust particles tend to settle out near the source whereas finer particles are dispersed over much greater distances.

To estimate the impact of tailings impoundments on air quality the following must be undertaken:

- determine the quantity of wind-generated particulate emissions form the exposed tailings impoundment surface areas by using predictive emission factor equations;
- predict the dispersion patterns of particulates by using appropriate models;
- plot the air quality influence zone isopleths using a computer mapping tool such as Surfer;
- estimate the change in health endpoint by applying published dose-response functions; and
- cost the treatment of respiratory ill-health effect.

Dust control and remedial action

Dust control and remedial measures are expensive and not always efficient enough to stop particles from being released. Typical controls for managing dust release include (CM, 1996):

- improving the mechanical strength of the exposed tailings impoundment surfaces to withstand wind erosion by covering the exposed surfaces with vegetation, rock cladding, or armouring;
- installing sprays on the embankment perimeter of the tailings impoundment and watering down exposed surfaces during windy periods;
- constructing windbreaks; and
- chemical stabilisation.

The dust particles, once airborne, settles at various distances from the source term due a reduction in air speed of the advancing air column. The key objective is to reduce the wind speed on top of the tailings impoundment to below the pick-up threshold friction velocity of the tailings. Watering, the most common and, generally, least expensive method, provides only for temporary dust control. Windbreaks and source enclosures are often impractical because of the size of the exposed areas. The use of chemicals to treat exposed surfaces provides longer dust suppression, but may be costly, have adverse effects on plant and animal life, or contaminate the environment.

2.11.2 Fugitive dust impact assessment

Dust from tailings impoundments can be caused by the following two basic physical phenomena:

- pulverization and abrasion of surface materials by application of mechanical force through implements; and
- entrainment of dust particles by the action of turbulent air currents, such as wind erosion of an exposed surface when wind speed exceeds the threshold friction velocity of the exposed material.

The latter is discussed in this section.

Dust particle size is an important factor influencing its transport and dispersion in the atmosphere, the formation of haze, and its potential effects on human health. Fugitive dust can be divided into the following typical dust particle size ranges (World Bank Group, 1999 and Environment Australia, 1998):

- Total suspended particulates (TSP), as measured by the standard high-volume air sampler, has a relatively coarse size range. Wind tunnel studies show that the particle mass capture efficiency curves for the high-volume sampler is very broad, extending from 100 % capture of particles smaller than 10 µm to a few percent as large as 100 µm. Thus, high-volume samplers do not provide definitive particle size information for emission factors. However, an effective cut point of 30 µm aerodynamic diameter is frequently assigned to the standard high volume sampler. Suspended particulates (SP), which is often used as a surrogate for TSP, is defined as particulate matter (PM) with an aerodynamic diameter no greater than 30 µm. SP can also be denoted as PM_{30}.

- Inhalable particulates (IP), refers to the mass fraction of total airborne particles which is inhaled through the nose and mouth and is defined as PM with an aerodynamic diameter no greater than 15 µm and is denoted as PM_{15}.
- Respirable particulates (RP), the respirable fraction is the mass fraction of inhaled particles which penetrates to the deeper airways and is also referred to as PM_{10}, i.e. particulate matter (PM) smaller than 10 micrometers (µm) in aerodynamic diameter.
- Fine particulates (FP) is defined as PM with an aerodynamic diameter no greater than 2,5 µm. FP may also be denoted as $PM_{2,5}$.

Impact of fugitive dust

The impact of a fugitive dust source on air pollution depends on the quantity and drift potential of the dust particles injected into the atmosphere. In addition to large dust particles that settle out near the source (often creating a local nuisance problem), considerable amounts of fine particles also are emitted and dispersed over much greater distances from the source. PM_{10} represents a relatively fine particle size range and, as such, is not overly susceptible to gravitational settling. There is consistent evidence that health risk increases with exposure (WHO, 2005).

The potential drift distance of particles is governed by the initial injection height of the particle, the terminal settling velocity of the particle, and the degree of atmospheric turbulence. Theoretical drift distance, as a function of particle diameter and mean wind speed, has been computed for fugitive dust emissions. Results indicate that, for a mean wind speed of 4,4 m/s, particles larger than about 100 µm are likely to settle out within 6 to 9 m from the edge of a road or other point of emission. Particles that are 30 to 100 µm in diameter are likely to undergo impeded settling. These particles, depending upon the extent of atmospheric turbulence, are likely to settle within a 100 m or so. Smaller particles, particularly PM_{15}, PM_{10}, and $PM_{2,5}$, have slower gravitational settling velocities and are more likely to have their settling rate retarded by atmospheric turbulence (US EPA, 1996).

Erodibility of material and threshold wind speed

Dust emissions are generated by wind erosion off exposed tailings impoundment surfaces. Field testing of exposed material dumps using a portable wind tunnel has shown that:

- threshold wind speeds exceed 5 m/s at 0,15 m above the surface or 10 m/s at 7 m above the surface; and
- particulate emission rates tend to decay rapidly (half-life of a few minutes) during an erosion event.

In other words, aggregate material surfaces are characterized by finite availability of erodible material (mass/area) referred to as the erosion potential. Any natural crusting of the surface binds the erodible material, thereby reducing the erosion potential.

Air quality assessment

An air quality assessment typically:

- estimates fugitive dust fallout and particulate concentrations; and
- recommends control measures to reduce dust release.

Nuisance impacts due to tailings dust

Nuisance impacts due to dust are associated with soiling impacts and with reductions in visibility. Atmospheric particulates change the spectral transmission which diminishes visibility by scattering light. The scattering efficiency of such particulates depends upon the mass concentration and size distribution of the particulates. Various costs are associated with the loss of visibility, including:

- the need for artificial illumination and heating;
- delays, disruption and accidents involving traffic;
- vegetation growth reduction associated with reduced photosynthesis; and
- commercial losses associated with aesthetics.

The soiling of building and materials due to dust frequently gives rise to damages and costs related to the increased need for washing, cleaning and repainting. Dustfall may also impact negatively on sensitive industries such as bakeries or textile industries.

2.11.3 Dust deposition and suspended particulate standards

Legislation typically requires decision-making authorities to assess the impacts of schemes on the environment. Dust control issues must be assessed at the project planning stage. Regulatory bodies generally accept that reasonable and practicable measures to control dust will be applied. The extent of these measures differs depending primarily on the existing ambient air quality and the proximity to densely populated areas.

South African dustfall deposition standards

Particulate matter has been classified as a criteria pollutant. Various countries have established ambient air quality guidelines and standards in an attempt to regulate the concentrations of this pollutant. Dust deposition levels are evaluated based on these dustfall categories. The Department of Environment and Tourism (DEAT), as part of a set of guideline values for various atmospheric pollutants, has published categories for the classification of dustfall levels (Table 9). The Department of Mineral and Energy (DME) has accepted these values as the reference levels for dust deposition for the purposes of environmental reporting.

Table 9: Dustfall categories published by the DEAT (1994).

Classification	Dustfall (averaged over 1 month)
Slight	less than 250 $mg/d/m^2$
Moderate	250 to 500 $mg/d/m^2$
Heavy	500 to 1 200 $mg/d/m^2$
Very heavy	greater than 1 200 $mg/d/m^2$

Slight dustfall is barely visible to the naked eye. Heavy dustfall indicates a fine layer of dust on a surface, with very heavy dustfall being easily visible should a surface not be cleaned for a few days. Dustfall levels of greater than 2000 $mg/m^2/day$ constitute a layer of dust thick enough to allow a person to "write" words in the dust with their fingers. Local experience, gained from the assessment of impacts due to dust from tailings impoundments in Gauteng, has shown that complaints from the public will be activated by repeated dustfall in excess of 2000 $mg/m^2/day$. Dustfall in excess of 5 000 $mg/m^2/day$ impacting on residential or industrial areas generally provoke prompt and angry complaints (Mizelle, Annegarn and Davis, 1995).

Particulate concentration guidelines

The World Health Organisation (WHO) defines concentrations for particulate matter (Table 10), which if achieved, would result in significantly reduced rates of adverse health effects. These concentrations are based on available scientific evidence and must not be viewed as implying an "acceptable" level of adverse health effects in the population. The quantitative relationship between monitored particulate matter concentration and specific risks to health can be estimated.

Table 10: Air quality guidelines and standards for total suspended particulates and ambient dust concentrations.

Source	TSP (µg/m³)	PM_{10} (µg/m³)	$PM_{2,5}$ (µg/m³)	Averaging period
NHMRC (1986)	90			Annual
NSW EPA[1]	30	to be developed		Long term annual goal
NSW EPA[1]	50	to be developed		24-hour not be exceeded three time in a year
RSA (AQA:2004)		180		24-hour
RSA (AQA:2004)		60		Annual
US EPA (1997)		50	15	Annual
US EPA (1997)		150	65	24-hour
Victorian EPA[1]		40		Annual
Victorian EPA[1]		120		24-hour
WHO (1987)	40			Annual
WHO (2005)[2]		20	10	Annual
WHO (2005)[2]		50	25	24-hour

[1] Environment Australia (1998)

[2] World Health Organisation Air Quality Guidelines

These estimates provide an input for health impact assessments and allow insights into the health burdens at current levels of air pollution and levels that would be achieved under various scenarios. The burden estimates can then also be used to valuate change. General guidelines for threshold dust concentrations are being adopted worldwide with the recent trend towards greater reliance on PM_{10} standards, reflecting the importance on human health issues. Current scientific evidence indicates that guidelines cannot be proposed that will lead to complete protection against adverse health effects of particulate matter and therefore there is a definite hesitance by the WHO to propose thresholds (WHO, 2005).

The WHO states that epidemiological evidence indicates that the possibility of adverse effects remains, even if the WHO air quality guideline value is achieved. It can however be concluded that reducing air pollution would result in significant reductions in health risks. There is little evidence to suggest a threshold below which adverse health effects would not be anticipated (WHO, 2005:7).

2.11.4 Fugitive dust zone of influence

The United States Environmental Protections Agency (US EPA) provides a procedure to predict the emissions and determine the air quality zone of influence for mine residue deposits (US EPA, 1995; US EPA, 1996). Dustfall levels (TSP) and respirable particulates concentrations (PM_{10}) can be predicted with a certain amount of confidence provided the information on the following is available:

- meteorological data;
- physical characteristics of tailings; and
- impoundment geometry.

Some of the factors are only intelligent guesses and require further research and calibration but the overall predictive methodology is satisfactory at least for the level of decision-making required. The measurement and monitoring of TSP (dustfall levels) and PM_{10} (respirable particulates) using appropriate measuring equipment and techniques allows the measurement of effectiveness of control measures as well as comparing the results to local as well as international limit values in order to re-evaluate the scheme's impact on air quality. The impact of dust on ambient air quality can either be determined by prediction or measurement.

Measuring and monitoring dustfall

A monitoring programme typically includes measuring total dustfall out in order to determine the mass/unit area/unit time and must be expressed in terms of the internationally accepted air pollution indices. A health risk monitoring programme requires measuring particulates in the respirable range by using single multi-stage low volume suspended dust sampling train units.

A typical monitoring network comprises single bucket fallout monitors (Figure 49). The main functions of dust monitoring in general are:

- quantification of the mining operation's contribution to dust deposition in the area;
- identification of possible problem areas;
- tracking of progress of control measures being implemented; and
- demonstration of compliance with accepted air quality standards.

1 Oblique view of dust blowing off the ERGO Daggafontein tailings impoundment (photograph with permission AngloGold Ashanti).

2 Typical single bucket fallout monitor (photograph courtesy of Harold Annegarn and Associates).

3 E-BAM sampling train for the real-time measurement of PM_{10} concentrations (photograph courtesy of Margot Saner and Associates).

Figure 49: Dust blown from a tailings impoundment. Typical equipment for measuring dustfall and particulates.

Dustfall measurement

Dust fallout sampling measures the fallout of windblown settleable dust. Single bucket fallout monitors can be deployed following the American Society for Testing and Materials (ASTM) standard method for collection and analysis of dustfall (Egami, Watson, Rogers, Ruby, Rood and Chow, 1989). This method employs a device consisting of a cylindrical container half-filled with de-ionised water exposed for one calendar month (30 days, ±3 days). The water is treated with an inorganic biocide to prevent alga growth. The bucket stand comprises a ring that is raised above the rim of the bucket to prevent contamination from perching birds. Once returned to the laboratory, the content of the bucket filtered and the residue dried before the insoluble dust is weighed.

PM_{10} measurement

PM_{10} is a mixture of various substances. These substances occur in the form of solid particles or as liquid drops. Some particles are emitted directly into the atmosphere. Other particles result from gasses that are transformed into particles through physical and chemical processes in the atmosphere. A variety of emission sources and meteorological conditions contribute to ambient PM_{10}.

PM_{10} standards are typically expressed as a weight of PM_{10} particles per volume of air in micrograms per cubic metre ($\mu g/m^3$). The standards do not consider the size distribution or the chemical make-up of the particles, although these are important factors in terms of control strategies and of the health risks associated with PM_{10}.

PM_{10} samples can be collected by means of using low or high volume selective size inlet samplers. The sampling schedules are continuous for either 1 hour or 24 hour averaging periods. Commercially available beta attenuation monitor (BAM) samplers and tapered element oscillating microbalance (TEOM) samplers are available for continuous PM_{10} monitoring. A BAM instrumentation train is typically required for time weighted gravimetric sampling of total particulates and metal compounds. Real-time sampling of total particulates requires the use of an E-BAM sampling train.

Measurement of ambient particulate concentrations at a tailings impoundment can be done by means of time weighted gravimetric and real-time sampling.

<u>Time weighted gravimetric</u> sampling requires the use of an air sampling train comprising a sampling pump (calibrated at a flow rate of 2 ℓ/minute), tygon tubing and an aerosol monitor cassette. If the sampling period is 24 hours the pump is left to run for 24 hours to capture total suspended solids generated on site. The samples are then sent to a reputable laboratory for gravimetric analysis in accordance with established methods to:

- establish the total weight of captured particulate matter; and
- analysis for metal contaminants by atomic absorption spectrophotometry.

<u>Real-time</u> sampling of ambient PM_{10} dust concentrations entails the use of an E-BAM monitor. This instrument can be located next to the sampling pump and left to run for a 24 hour period, following which it is stopped and returned to a laboratory where the collected data is transferred to a desktop computer for processing. Real-time sampling is used for comparative purposes, i.e. comparison to the time weighted sampling results, and to establish any trends in airborne dust concentrations throughout typical 24 hour periods such as variations between daytime and night-time concentrations and between working hours and after work hours.

Quantifying emissions

Models that predict dust deposition rates and ambient particulate matter concentrations are commonly used in mine planning. The models typically use predictive emission factor equations in conjunction with meteorological data, dispersion models, and mathematical plotting software to produce isopleths, i.e. visual presentation of dustfall and concentrations through contours. Emissions arise when the surface wind speed exceed the threshold friction velocity of the tailings.

The following parameters influence the rate of fugitive dust emissions:
- the extent of surface compaction;
- moisture content;
- ground cover;
- the shape of the tailings impoundment;
- particle size distribution of the tailings;
- wind speed; and
- precipitation.

Any factor that binds the erodible material, or otherwise reduces the availability of erodible material on the surface, decreases the erosion potential of the fugitive source. High moisture contents, whether due to precipitation or deliberate wetting, promote the aggregation of fines to the surfaces of larger particles, thus decreasing the potential for dust emissions. Natural crusting and cementation, surface compaction, and ground cover similarly reduce the potential for dust generation. The shape of a tailings impoundment influences the potential for dust emissions through the alteration of the airflow field. The particle size distribution of the material on the disposal site is important since it determines the rate of entrainment of material from the surface, the nature of dispersion of the dust plume, and the rate of deposition, which may be anticipated (Burger, 1994; Burger, Held and Snow, 1995).

Information regarding the nature of the source, the percentage of exposed surface area and the type of material are typically required. It was initially believed that wind entrains dust from the top surface of tailings impoundments with very little being entrained from the side surfaces. However, recent research conducted locally and internationally, has shown that the majority of the dust in entrained from the top one-third of the side slopes facing the prevailing wind direction(s). Such dust may, however, be deposited on the top surfaces of tailings and re-entrained under higher wind speeds (i.e. greater wind velocities are required for deflation at the tailings surface since the approach to surface wind speed ratio is lower). The conclusion reached is that the upper wind-ward slopes of tailings impoundments are subject to the highest wind erosion losses and therefore need careful attention within dust control plans. The implementation of dust controls on the surface of the tailings reduces the potential for re-entrainment if material is deposited on the surface.

The general quantification of the fugitive dust emissions is carried out in the following steps:
- determine the threshold friction velocity for the tailings;
- correct the wind speed values (u^*) for each frequency from the anemometer height (z) to a reference height of 10 m (u^*_{10});
- divide the exposed impoundment surface area into sub areas of constant frequency of disturbance and apply ratios of surface wind speed to approach wind speed;
- estimate the emissions on the basis of published US EPA emission factor equations; and
- model the dispersion of the particulates using the US EPA approved Industrial Source Complex Short Term (ISCST) Version 3 dispersion modelling software.

Determine friction velocity of tailings

The threshold friction velocity, defined as the minimum friction velocity required to initiate particle motion, is dependent on the size of the erodible particles and the effect of the wind shear stress on the surface. The threshold friction velocity decreases with a decrease in the particle diameter, for particles with diameters >60 µm. Particles with a diameter <60 µm result in increasingly high threshold friction velocities, due to the increasingly strong cohesion forces linking such particles to each other. The relationship between particle sizes ranging between 1 µm and 500 µm and threshold friction velocities (0,24 m/s to 3,5 m/s) is illustrated in Figure 50.

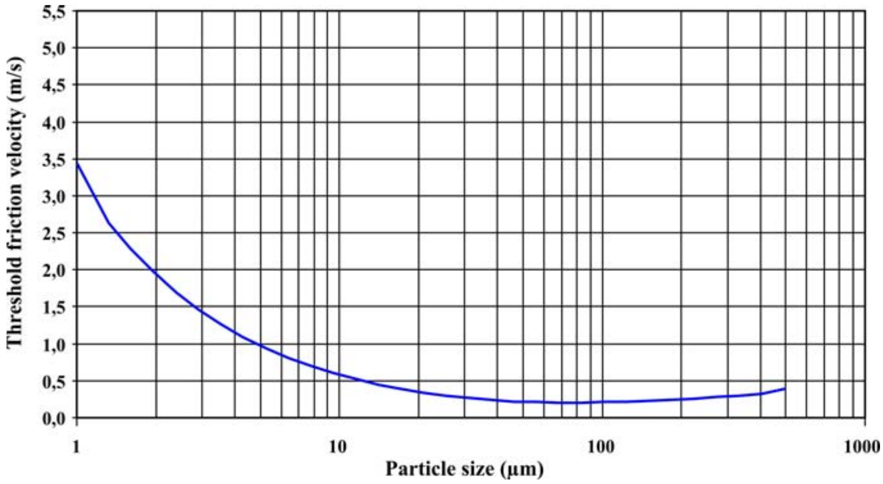


Figure 50: Relationship between particle size and threshold friction velocity using the calculation method proposed by Marticorena and Bergametti (1995).

Apply ratio of surface wind speeds to approach wind speeds

The wind speed variation over the residue deposit is based on the work of Cowherd, Muleski and Kinsey (1988). With the aid of physical modelling, the US EPA has shown that the frontal face of an elevated pile (i.e. windward side) is exposed to wind speeds of the same order as the approach wind speed at the top of the pile. The ratios of surface wind speed to approach wind speed, derived from wind tunnel studies for two representative pile shapes, are indicated in Figure 51 (p. 97), namely a conical pile and an oval pile with a flat top and 37° side slope. The contours of normalised surface wind speeds are indicated for the oval, flat top pile for various pile orientations to the prevailing direction of airflow. The higher the ratio, the greater the wind exposure potential (Cowherd et al. 1988).

Correct the wind speeds

Dust mobilisation occurs only for wind velocities higher than a threshold value, and is not linearly dependent on the wind friction and velocity. The typical wind speed profile in the surface boundary layer is found to follow a logarithmic distribution (US EPA, 1996):

$$u_{(z)} = \frac{u^*}{0,4} ln \frac{z}{z_0} \qquad (3)$$

where:

$u_{(z)}$ = wind speed (m/s)

u^* = friction velocity (m/s)

z = height above test surface (m)

z_0 = aerodynamic roughness height (m)

$0,4$ = von Karman's constant (dimensionless)

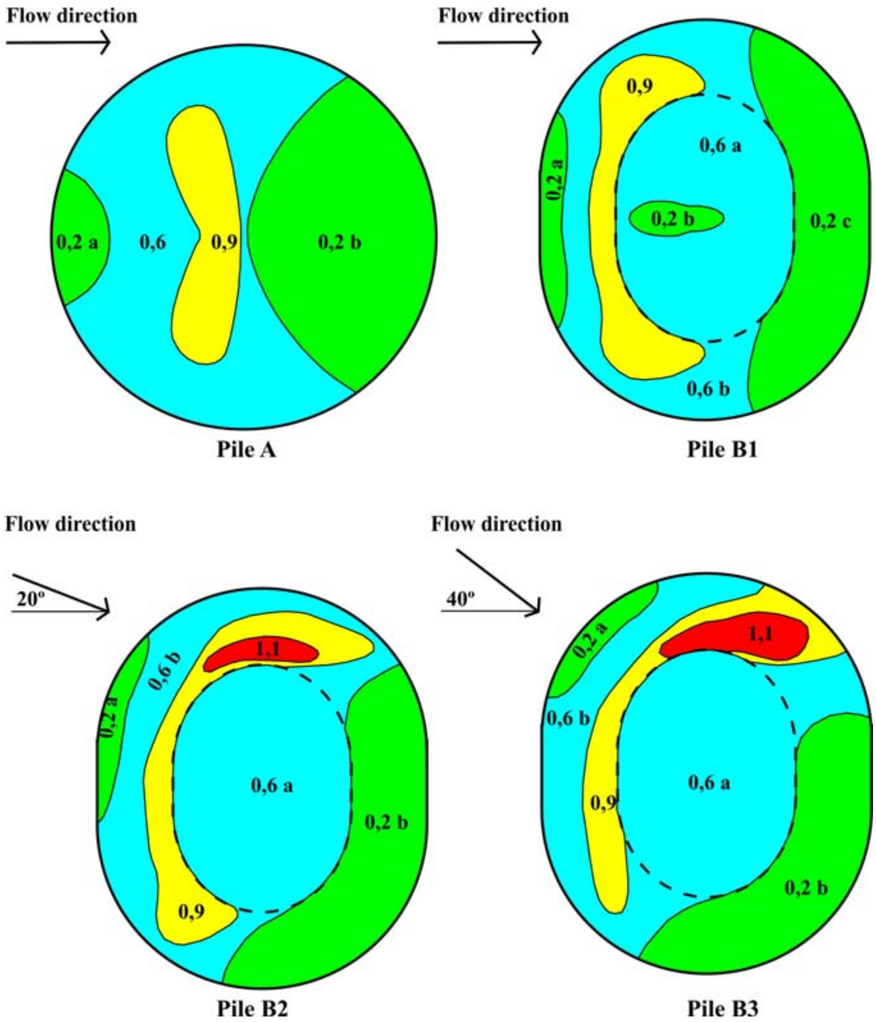


Figure 51: Contours of normalised surface wind speeds (US EPA, 1996).

Estimate emissions

The quantification of fugitive dust emissions from tailings impoundments makes use of emission factor equations published by the US EPA which relate emissions to parameters that characterise the source (US EPA, 1995). The parameters can be broadly grouped into three classes:

- measures of energy expended;
- properties of the material being disturbed; and
- climatic parameters.

An hourly emissions file must be created for each of the source groups. The ADDAS model is used to calculate an emission rate for every hour of the simulation period. This model is based on the dust emission model proposed by Marticorena and Bergametti (1995) and accounts for the variability in source erodibility through the parameterisation of the erosion threshold (based on the particle size distribution of the source) and the roughness height of the surface. Two important parameters, namely the threshold friction velocity of each particle size and the vertically integrated horizontal dust flux are used to quantify the vertical dust flux (i.e. the emission rate). The following equations are used:

$$E_{(i)} = G_{(i)} 10^{(0,134(\%clay)-6)} \tag{4}$$

for $$G_{(i)} = 0,261 \left[\frac{P_a}{g} \right] u^{*3} \left((1+R)(1+R^2) \right) \tag{5}$$

and $$R = \frac{u_*^t}{u^*} \tag{6}$$

where:

$E_{(i)}$ = emission rate (g/m²/s) for particle size class i
P_a = air density (g/m³)
g = gravitational acceleration (m/s²)
u_*^t = threshold friction velocity (m/s) for particle size i
u^* = friction velocity (m/s)

The following information on the impoundment configuration is required as input parameters into ADDAS:

- tailings material physical characteristics - the particle mass fraction or particle size distributions of material, material threshold friction velocity (m/s), particle density (g/cm³), bulk density of the material (kg/m³), the roughness height (m) and average moisture content (%), percent clay fraction – i.e. particles < 2 µm (%).
- dimensions of the impoundment – coordinates of the impoundment of south-western corner (LoX and LoY), horizontal clockwise angle (°), the height and the slope expressed as ratio between horizontal and vertical axis.
- receiving environment information – meteorological data, receptor locality and population density.

Modelling the dispersion of fugitive dust emissions

Dispersion models compute ambient concentrations as a function of source configurations, emission strengths and meteorological characteristics, thus providing a useful tool to ascertain the spatial and temporal patterns in the ground level concentrations arising from the emissions of various sources. Increasing reliance has been placed on ground level air pollution concentration estimates from models as the primary basis for environmental and health impact assessments, risk assessments and determining emission control requirements.

The ISCST3 Breeze version 3 model is an US EPA approved model. It is a steady state Gaussian Plume model typically used for near-field applications where the steady-state meteorology assumption is most likely to apply. The model can accommodate multiple point, area and volume sources. The model accounts for settling and dry deposition of particulates and has the ability to analyze concentrations in any type of terrain, and it can estimate hourly to annual pollutant concentrations. The model is recommended for both urban and rural use (World Bank Group, 1999:86). A disadvantage of the model is that spatial varying wind fields, due to topography or other factors cannot be included. A further limitation of the model arises from the models treatment of low wind speeds. Wind speeds below 1 m/s produce unrealistically high concentrations when using the Gaussian plume model, and therefore all wind speeds below 1 m/s are simulated using 1 m/s.

When simulating the patterns of dispersion using such dispersion modelling software the following input data types are required:

- receiving environment meteorological data including wind speed, wind direction, a measure of atmospheric turbulence, ambient air temperature and mixing height. Mixing height can be calculated from recorded ambient temperature and predicted solar radiation data.
- particle mass fraction (particle size distribution) same as required for the estimation of the emissions.

Concentrations for various averaging periods can be calculated. It has generally been found that the accuracy of off-the-shelf dispersion models improve with increased averaging periods. Reported model accuracies vary from application to application. Typically, complex topography with a high incidence of calm wind conditions, produce predictions within a factor of 2 to 10 of the observed concentrations. When applied in flat or gently rolling terrain, the US EPA (US EPA, 1996) considers the range of uncertainty to be – 50 % to 200 %. The accuracy improves with fairly strong wind speeds and during neutral atmospheric conditions.

Estimating ill health effects

It may well be necessary to consider the prediction and measurement of impacts incrementally (finite increase of value, i.e. impact solely due to source) as well as cumulatively (increase by addition, i.e. net impact including background information) in order to compare the outcomes with for argument some sort of guideline value. When assessing the impacts due to fugitive dust respirable particulates (PM_{10} concentrations) as well as dustfall or deposition rates (TSP) can be considered. Dust deposition may be gauged according to the criteria published by the South African Department of Environmental Affairs and Tourism (DEAT) (Table 9, p. 91).

PM_{10} is predicted or measured in $\mu g/m^3$ and typically compared to air quality guideline standards as a maximum 24-hour concentration or as an annual average concentration when determining the potential impact from an open surface. More important than the potential level as well as frequency of exceeding guideline standards, is the potential to impact on health. The WHO supports the idea of applying dose response relationships for suspended particulates with the linear relationship between concentrations and various types of health effects.

Two aspects need to be considered when evaluating the PM_{10} concentrations, namely:

- the potential to exceed an existing guideline standard; and
- the potential ill health effects due the increase in such concentrations.

It is obvious that the first approach will not necessarily provide an explicit indication of the impact on the receiving environment, whereas the latter does - i.e. impacting negatively on the ill health of people might well be. An important component in applying dose response functions is the presence of receptors (people) – information on the population density and the proximity to people is important to the impact prediction (Equations 7, 8 and 9).

Total population exposed = 25 µg/m^3 impact area (ha) x population density (persons/ha) (7)

Exposure = total population exposed x change in pollutant concentration (8)

No of hospital admissions due to respiratory ailments = exposure x dose-response function (9)

The WHO developed a procedure for the assessment of health impacts occurring due to airborne particulates. This was necessary since the threshold for the onset of health effects could not be detected. The approach adopted by the WHO is comparable to that for carcinogenic compounds, with linear relationships between PM_{10} or $PM_{2,5}$ concentrations and establishing various types of health effects being established. Such linear relationships are presented in Figure 52 for the change in various health endpoints such as bronchodilator use, cough and symptom exacerbation. A linear relationship of PM_{10} and $PM_{2,5}$ to various health effect indicators are assumed when determining acceptable levels of risk (WHO, 2000).

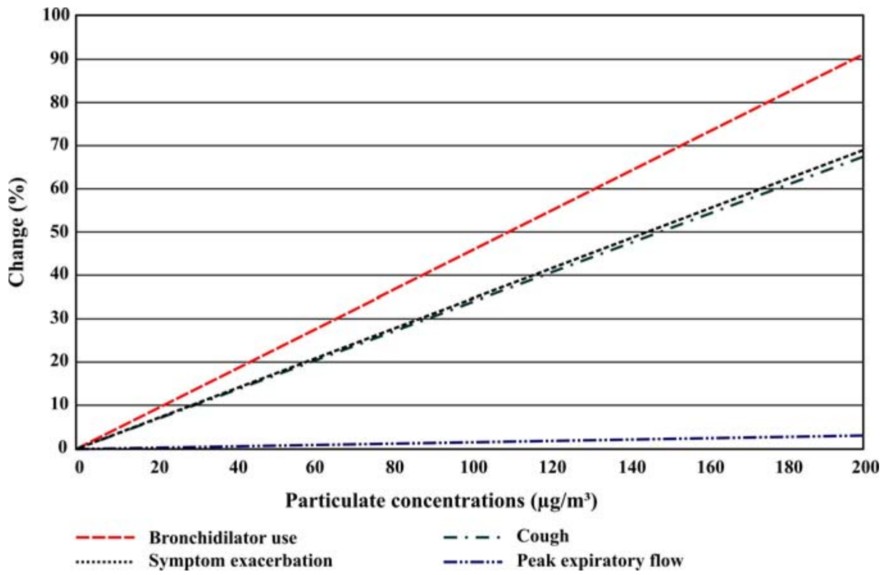


Figure 52: Percentage change in the occurrence of various health endpoints as a result of changes in ambient PM_{10} concentrations (WHO, 2000).

When determining 'acceptable' airborne particulate concentrations decision makers are faced with the following controversial decisions:

- selection of the curve to be used for deriving an acceptable ambient particulate concentration (i.e. decide from which health effect the population is to be protected);
- determine the population or sensitive groups to be protected from air pollution effects. For example, the use of the bronchodilator application curve would imply that asthmatics are a sensitive group to be protected by the chosen standard; and
- set a fixed value for the acceptable risk in a population so that a single value for a given exposure period may be defined.

Information limitations and general considerations

The graphs given in Figure 52 (p. 100) were not intended for use for PM_{10} concentrations below 20 µg/m^3, or above 200 µg/m3; or for $PM_{2,5}$ concentrations below 10 µg/m^3 or above 100 µg/m^3. This caution is required as mean 24-hour concentrations outside of these ranges were not used for the risk assessment and extrapolations beyond these ranges would therefore be invalid.

Questions that could be formulated as a result of the PM_{10} fraction of fugitive dust are:

- Are there any residential settlements within the air quality impact zone of influence?
- If so, what are the population densities?

Answering this in the affirmative will require further questions to be answered. If settlements occur within the predicted zone of influence, other aspects require further consideration such as control efficiencies of various cover considerations and the population density.

For example, the following tailings impoundment covers or means of stabilisation can be considered:

- using rip-rap (rock cladding);
- chemical stabilisation; or
- vegetative stabilisation.

Consideration of each of the above-mentioned covering methods will result in different control efficiencies of fugitive dust from the impoundment. A cover with a 100 % control efficiency will negate the impact altogether, whereas a cover design with say a 80 % control efficiency will reduce the zone of influence by the given percentage.

Are control efficiencies available for different cover alternatives and if so, how does the efficiency impact on the zone of influence? If it cannot be demonstrated that a certain control efficiency can be in fact be attained then the worst-case scenario must be assumed and hence the most conservative impact on the receiving environment must be predicted. What is the control efficiency which will be attained by the proposed cover on the impoundment? Does the control efficiency satisfactorily mitigate or reduce the impact? What is the population density? (maybe concepts such as high, medium or low density should be introduced or similarly rural, peri-urban and urban). If the population density is high (say > 250 people/ha) it may well be that the health risk will be unacceptable. This is the difficulty in pinpointing certain criteria.

2.11.5 Valuation of air quality impacts

Air quality is of vital concern in many locations. Prior to the construction of a tailings impoundment an impact assessment must be undertaken indicating the effect of the tailings impoundment on air quality. It is important that the characteristics of the tailings impoundment be known prior to the prediction of the potential effect on air quality. Even though an objective of constructing a tailings impoundment may be to limit impacts to human health, monitoring such effects are extremely difficult because of substantial uncertainties about the exposure of different populations groups to pollutants, their response to different levels of exposure, and the cumulative nature of damage (World Bank Group, 1999:16).

According to Scorgie, Kneen, Annegarn and Burger (2003) the contribution of tailings impoundments to total atmospheric emissions, ambient air pollution concentrations and related impacts on human health and wellbeing remains the subject of debate. More stringent national ambient air quality limits and the potential that exists for non-compliance with such limits necessitates the identification of cost-effective reduction opportunities which will result in the greatest reduction in human health risk.

Human health risks typically associated with PM_{10} emissions include decreased lung function, increased respiratory morbidity resulting in increased hospital admissions. It is proposed that a damage function approach will be applied to cost the increase in ill-health effects as a result of increased particulate concentrations. Following is the description of a systematic approach linking emissions from an impoundment to changes in environmental air quality. Air quality impacts are determined through:

- application of atmospheric dispersion modelling to quantify emissions;
- delineation and spatial representation of the air quality influence zone;
- determining potential exposure;
- predicting health risks by applying published dose-response relationships; and
- estimating the cost to treat ill-health effects.

Section 2.11.4 deals with the quantification and simulation of emissions. This section will discuss the estimation of health effects through applying dose-response functions.

Dose-response relationships and the estimation of health effects

Dose-response relationships measure the relationship between exposure to pollution and specific health outcomes. Dose-response functions translate changes in air quality into changes in health and provide an important link between exposures to ambient air pollutant concentrations and resultant health endpoints. Locally researched relationships are not available and it is therefore necessary to use international dose-response functions that are most applicable to South Africa. The dose-response functions used in this study are from sources which cite published epidemiological and economic literature and are given in Table 11 (p. 103). These factors are applied by multiplying the exposure (population x pollutant concentration) with the function to obtain an indication of impact. Impacts are expressed as the number of hospital admissions due to respiratory ill-health effects and cardiovascular related symptoms.

Table 11: Morbidity dose-response relationships typically used to quantify exposure per person to change in PM_{10} (µg/m^3).

Health effect	Function	Population sector	Source
Asthma attacks	$6{,}50x10^{-3}$	Asthmatics	Maddison (1997)
Cardiovascular hospital admission – daily exposure	$1{,}01x10^{-7}$	All persons	Dockery et al. (1989)
Chronic bronchitis – annual exposures	$1{,}61x10^{-3}$	Children <5 years	Dockery et al. (1989)
Chronic bronchitis – annual exposures	$4{,}90x10^{-5}$	Adults >20 years	Dockery et al. (1989)
Emergency room visits – annual change	$2{,}35x10^{-6}$	All persons	Ostro (1994)
Respiratory hospital admissions – daily exposures	$1{,}20x10^{-5}$	All persons	Ostro (1994)
Respiratory symptoms	$1{,}83x10^{-1}$	All persons	Ostro (1994)
Restricted activity days – annual average	$5{,}75x10^{-2}$	Adults	Ostro (1994)

The health impact can be estimated by the following relationship (Ostro, 1994:5; World Bank Group, 1999:59):

$$dH_i = b_i .POP_i .dA \qquad (10)$$

where:

dH_i = change in population risk for health effect *i*
b_i = slope from the dose response curve for health impact *i*
POP_i = population at risk of health effect *i*
dA = change in ambient air pollutant under consideration

A statistically significant relationship has been found between the incidence of hospital admissions due to respiratory disease and PM_{10} concentrations (Ostro, 1994:16). The results suggest a central range change in respiratory hospital admissions of 1,2 per 100 000 population for the change in PM_{10} concentration.

Costing of health effects

Cost associated with exposures to air pollution includes both direct and indirect costs (Scorgie et al., 2003:8). Direct costs are typically associated with health spending such as cost of hospital admissions and medication. Objective valuation approaches (OVA) are used to cost or valuate the impacts and is based on physical relationships (Section 2.9.2). Indirect costs typically include financial losses due to reduced productivity of economically active persons due to restricted activity.

Information used to calculate the costs related to respiratory hospital admissions were obtained from a study undertaken by Scorgie et al. (2003) for NEDLAC during 2002. The data for this study was made available by Medscheme and includes the ratio of inpatients to outpatients and both public as well as private costs to treat patients.

Although the data obtained from Medscheme in the NEDLAC report only allows for the estimation of costs related to respiratory hospital admissions, information in the report on the ratio of inpatients to outpatients permits the calculation of the number of outpatients likely to be treated. This ratio was given as 0,049. The report states that the public health treatment costs is approximately 70 % of that for private treatment and the average length of stay for a respiratory hospital admission are in the order of 8,8 days. Approximately 17,5 % of the population, based on national figures, was likely to receive treatment from the private health care sector and the remaining 82,5 % from public hospitals and clinics. At the time of the NEDLAC study the average public inpatient costs were estimated to be R16 618 compared to private inpatient costs of R23 740 per patient. Public outpatient costs are given as R1 354 compared to private outpatient costs of R1 933. In order to calculate the costs in terms of 2006 Rands, the costs used for the NEDLAC study were escalated by 40 % and is more or less equal to an annual increase of 10 % over the period. The escalated 2006 costs are R33 236 to treat inpatients privately, R23 265 for treat public sector inpatients, R2 707 to treat private outpatients, and R1 895 to treat outpatients in the public sector.

Applying Equation (10) and using the data provided above along with the published respiratory hospital admissions dose-response relationship (Table 11, p. 103), it is estimated that the health risk within the 25 µg/m^3 PM_{10} influence area are likely to be between R1500 and R79 000 depending on the populations density (Table 12). Population density classifications are derived from Statistics South Africa (2003) which uses enumeration area type classifications such as small holdings, urban settlement, recreational, industrial, and informal settlement for urban and rural areas.

Table 12: Costs due to respiratory hospital admissions and inferred respiratory treatments due PM_{10} exposures.

		Respiratory treatment costs (R/ha)				
Density classification	**People/ha**	**Private inpatient**	**Public inpatient**	**Private outpatient**	**Public outpatient**	**Total costs**
High	250	436	168	29 379	48 839	78 822
Medium	80	140	54	9 401	15 629	25 223
Low	25	44	17	2 938	4 884	7 882
Very low	5	9	3	588	977	1 576

2.11.6 Summary

The literature considers the possible impacts of fugitive dust as a result of tailings impoundments. Tailings impoundments can be one of the main sources of respirable particulates (PM_{10}) resulting from wind entrainment of particulates especially if they are not managed correctly. The upper windward slopes of tailings impoundments are most susceptible to wind erosion. This may be further affected by specific biophysical conditions of a site as well as the specific tailings characteristics, such as moisture content and particle size distribution.

Measures do exist to reduce or limit the amount of dust entering the atmosphere, with each having its own costs and benefits with regards to effectiveness of implementation.

The potential for fugitive dust to enter into the atmosphere and be transported to areas in which it can pose problems to health of animals, plants and humans is largely dependant on the initial height at which the particle enters the atmosphere, terminal settling velocity and the degree of atmospheric turbulence and particle size. Besides health impacts dust also has a nuisance factor and may result in the reduction in visibility and soiling.

Legislation requires measures are put in place during the planning phases of a project to address the potential impacts of such tailings impoundments. It is thus important that the characteristics of a tailings impoundment are known prior to its construction and that an impact assessment is conducted to establish what the potential air quality impacts are.

World Health Organization (WHO) standards identify dust concentrations of particulate matter and if instituted would significantly reduce rates of adverse health effects. However scientific evidence indicates that guidelines cannot be proposed that will lead to complete protection against adverse health effects and therefore the WHO is hesitant to propose absolute thresholds.

It is possible to measure and monitor total dust fallout, but varying degrees of accuracy are reflected by each model and requires detailed monitoring program requiring the measuring of particulates in the respirable range by employing single multi-stage low volume suspended dust sampling train units.

Dust is only mobilised once wind speed exceeds a certain level and can be quantified through the use of an emission factor equation published by the US EPA. The values for the equation are obtained through the use of models such as ADDAS which account for variability in source erodibility. Models such as the ISCST3 Breeze Version 3 model may be used to determine the spatial dispersion of emissions. A downfall with this model is that spatial varying wind fields, due to topographical change, cannot be included.

The air quality impact estimation and valuation process is relatively straightforward and requires that:

- dustfall and PM_{10} concentrations are determined by using predictive emission factor equations;
- the number of people exposed in the zone of influence is estimated;
- exposure is calculated by multiplying the number of people exposed with the particulate concentration; and
- health effect is determined by applying published dose-response functions to exposure.

The air quality zone of influence in hectares (ha) due to emissions from a tailings impoundment can be determined by:

- estimating the emissions through prediction;
- modelling the dispersion of the estimated emissions spatially; and
- plotting the air quality influence zone isopleths.

Different methods of rehabilitation such as using rip-rap (rock cladding) and using vegetative stabilisation will result in different control efficiencies of the fugitive dust from the impoundment. A cover type with a 100% control efficiency will negate the impact altogether, whereas a cover design with approximately 80% control efficiency will reduce the zone of influence by a certain percentage. One needs to be mindful of the fact that in developing a system that predict the potential impacts on human health that one should build in a factor of some sort to take account for the possibility of under prediction rather than over prediction, since the system should err on the side of conservatism for obvious safety reasons.

More stringent national ambient air quality limits and the potential that exists for non-compliance with such limits necessitates the need for the identification of cost effective emissions reduction mitigation measures.

2.12 Water

2.12.1 Introduction

The storage and disposal of mine tailings using impoundments can impact on surface and groundwater (Figure 53). Discharge from tailings impoundments could impact on surface water resources such as streams and rivers and groundwater resources such as aquifers.

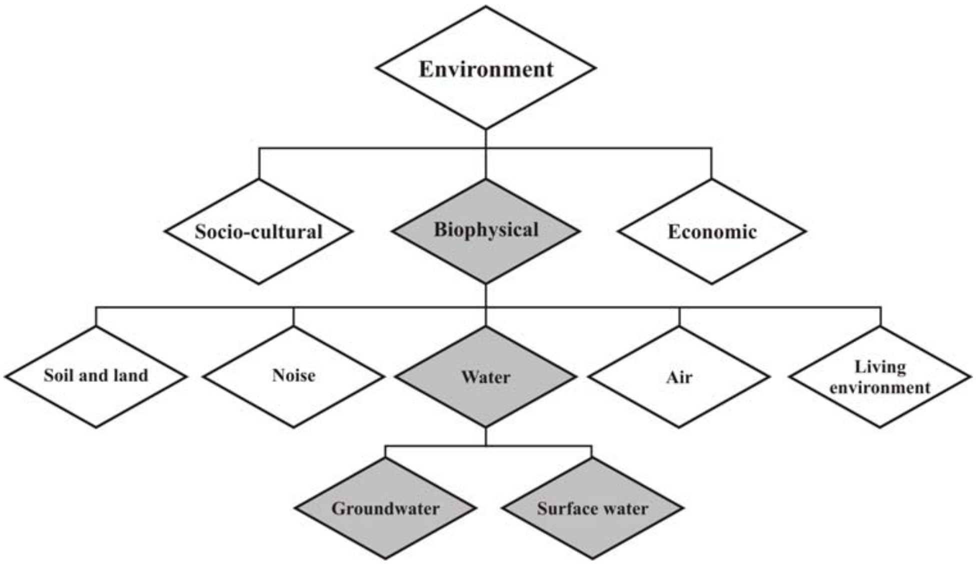


Figure 53: Simplified environmental aspects flow-diagram indicating the context of the water sub-account.

Erosion can cause a significant loss of mine tailings from impoundments and if the material is inadequately contained and managed will result in a release into the surrounding environment. Blight has found that erosion losses from mine tailings, which are the major cause of water degradation and air quality impacts, are more or less equally attributed to water and wind erosion (Blight and Amponsah-Da Costa, 1999, 1999a and 2001). The volume of acidic waters discharged from mines and mine residue deposits are significant. This discharge cannot be released before it is suitably treated as it poses a direct threat to drinking water, agriculture, vegetation, wildlife and waterways. Resultant seepage to ground and surface water can give rise to water pollution over large tracts of land. The impacts are difficult to predict and costly to manage and mitigate.

Discharging wastewater has certain negative impacts on downstream activities and more often than not users are not compensated for the loss in amenity. Examples of such impacts include (DWAF, 2006:28):

- damage to submerged property;
- public health effects;
- reduced value of water resources for recreational purposes;
- nuisance effects; and
- ecological damage.

Gold tailings and coal residue contain sulphide minerals, which upon weathering give rise to a range of potential pollutants (Rademeyer et al., 2007). Where there is insufficient neutralizing potential in the tailings, which is so for most gold and coal operations, acid mine drainage (AMD) occurs with its associated:

- low pH values;
- high salt loads such as sulphates; and
- high concentrations of metals.

Water coming in contact with the mining activities can mobilise pollutants and depends on:

- the type of and method of mining;
- geological context;
- the seams and ore bodies mined; and
- environmental conditions.

Typical standard practice water control measures include the construction of:

- tailings impoundment decant structures;
- solution trenches;
- catchment paddocks;
- under drainage systems; and
- return water dams.

Tailings impoundment decant structures

Tailings impoundments require a vertical freeboard (distance from the penstock outlet to the top of the wall) of at least 800 mm (DWAF, 1999). Although a freeboard of 800 mm is stipulated by DWAF's Regulation 704, it is likely that a vertical freeboard of at least 2 m will be required to satisfy dam safety requirements.

Solution trench

A solution trench constructed around the tailings impoundment perimeter conveys seepage water discharge from the under drain to the return water dam or a retention sump.

Catchment paddocks

A series of catchment paddocks are usually constructed adjacent to the solution trench around the full perimeter of the tailings dam. The paddocks consist of a catchment paddock wall linked to the starter and toe walls with cross walls at regular intervals. The paddocks are installed to catch contaminated storm water run-off from the outer face of the tailings dam and to avoid silt from gully erosion filling the solution trench.

Under drainage systems

Single or twin toe drains can be installed on the inside of the starter walls. The drain must be designed to meet the requirements of a particular impoundment but typically consist of a piped filter trench fed by a sand blanket drain. The size and specification requirements of the under drainage is linked to the required draw down of the phreatic surface within the dam over time.

Return water dam

The size of the return water dam must be large enough to contain the mean operating level plus the 1:50-year storm before spillage occurs. The freeboard (from spillway level to the top of the crest) must be a minimum of 800 mm. The upstream cut-off canals must be sized to divert the 1:50-year storm away from the tailings facilities. The return water dam must be at least 100 m from any river and outside the 1:100-year flood line (DWAF, 1999).

2.12.2 Decision-support system

The structure of the water module of the decision-support system developed for the Water Research Commission (WRC) by Rademeyer, Wates, Bezuidenhout, Jones, Rust, Lorentz, van Deventer, Pulles and Hattingh (2007) mirrors the traditional environmental risk assessment methodology insofar as it evaluates the impact of the particular tailings disposal facility, first as a source term, then in terms of pathways by which contaminants might migrate away from the source term, followed by assessment of impact at the receptor or downstream water user. This progression is shown in Figure 54 (p. 109). These questions are ordered in the risk assessment methodology sequence. A differentiation is also made on the basis of the water resource, i.e. ground water and surface water, and makes provision for the physical and hydrological interactions between the surface and ground water resource.

2.12.3 Tailings characteristics

Vick (1983) describes tailings as crushed rock particles that are deposited in slurry form and which includes finely ground mill or mineral processing wastes. Tailings is the waste product resulting from a physical or chemical treatment process to liberate and remove the minerals contained in the parent rock. Due to the variety of minerals that occur in different ores and parent rock types there are a large variety of tailings with different physical and chemical properties. For many mining projects the most significant source of water impact is the disposal of tailings.

Vick (1983) classifies the effluents originating in tailings impoundments in three main categories based on pH units:

- Neutral.
  This occurs when the process used in the plant does not significantly alter the pH. There may be some elements dissolved from the parent rock but only those soluble at neutral pH which could result in slightly higher levels of sulphides, chlorides, sodium and calcium.

- Alkaline.
  If the pH of the effluent is raised in the plant, similar chemical constituents can be found to those found at neutral pH. There could possibly be some cationic compounds, but cationic heavy metals are not usually mobilised in high concentrations.

- Acid.
  If present in the host rock, many metallic contaminants may be present in effluents subjected to a low pH in the plant and can include metals such as iron, lead, manganese, cadmium, selenium, copper, zinc and mercury. Such effluents may also contain higher concentrations of anions such as sulphates and/or chlorides. These acidic plant effluents cause the most trouble.

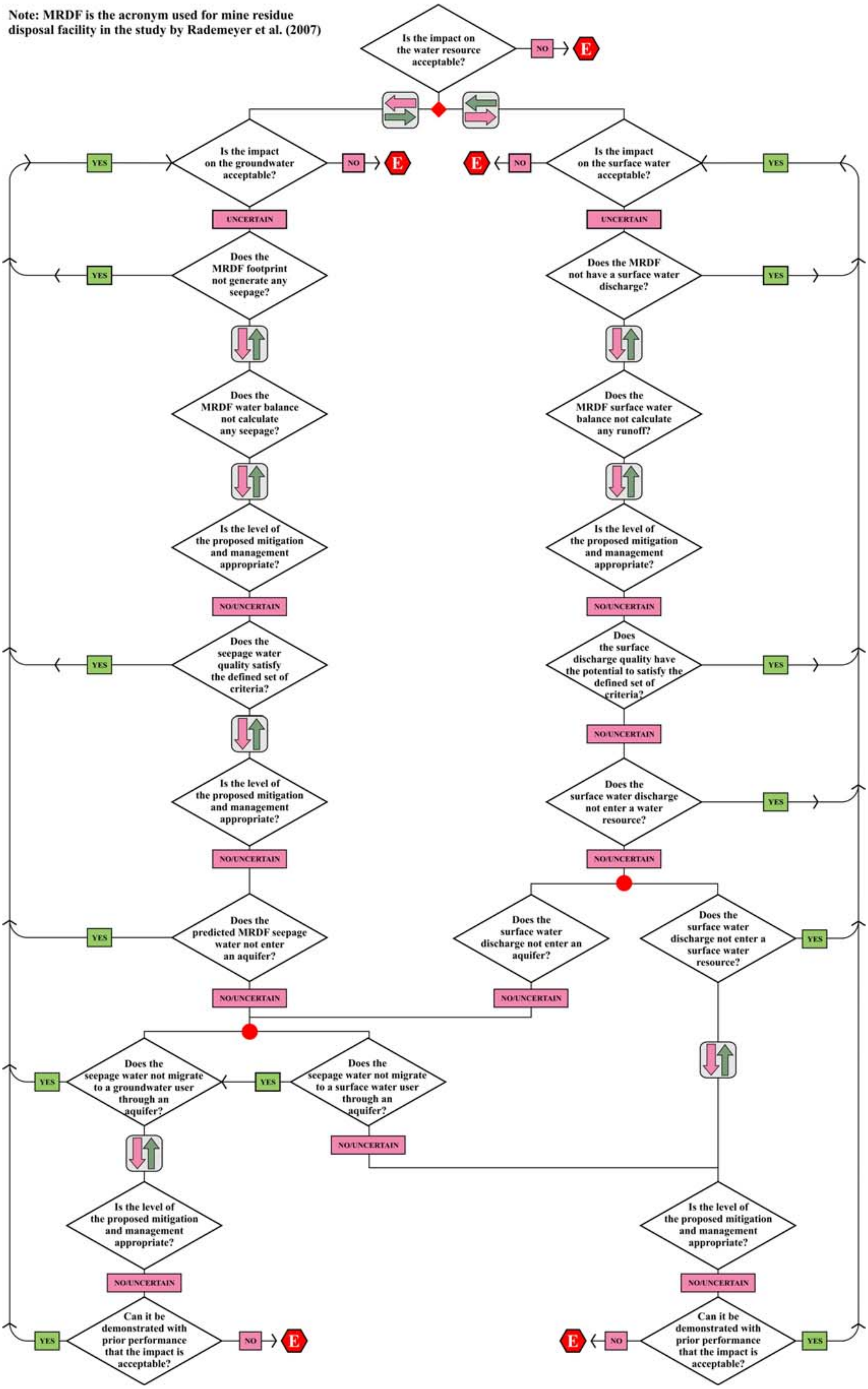


Figure 54: Water quantity and quality decision framework (Rademeyer et al., 2007).

Vick (1983:32) provides constituent levels for several acid and alkaline mill effluents (Table 13). There can be substantial variations from these values as a result of variation in the ore and milling technology. It does however illustrate the expected general differences in chemical constituent levels, particularly heavy metals, in the two main categories of effluents.

Table 13: Comparison of typical acid and alkaline mill effluents (Vick, 1983).

	Acid			Alkaline			
Constituent (mg/ℓ)	**Uranium Acid Leach**	**Gypsum Phosphoric Acid Plant**	**Copper Lead Zinc**	**Lead-Zinc floatation**	**Lead floatation**	**Trona**	**Tin**
pH	**2**	**2,6**	**6,4**	**10,1**	**8,1**	**10,9**	**11,0**
Aluminium	2 000	-	-	-	-	0,04	-
Arsenic	0,2	-	-	-	-	0,004	0,05
Cadmium	0,2	0,4	-	< 0,02	< 0,02	< 0,001	-
Calcium	500	-	-	-	-	-	-
Chloride	300	-	-	4	-	4 380	-
Copper	50	0,3	0,2	1,9	1,9	0,002	0,18
Cyanide		-	-	-	0,5	-	-
Fluoride	5	500	-	2,4	-	17	-
Iron	1 000	-	-	-	-	0,35	-
Lead	7	0,2	0,0	0,1	< 0,1	0,006	0,05
Manganese	500	-	0,6	0,5	1,1	0,02	0,84
Mercury	0,07	-	-	-	-	0,005	-
Molybdenum	100	-	-	-	-	-	-
Nitrate	500	-	-	-	-	-	-
Selenium	20	-	-	-	-	< 0,001	-
Sodium	200	-	-	-	-	-	-
Sulphate	30 000	-	-	-	-	1 530	-
Zinc	80	12,2	1,0	0,.2	0,4	-	3,4

Vick (1983) states that the deleterious effects of these effluents on the environment depend on both the toxicity of the elements contained in the tailings and the concentrations at which they occur. The chemical processes used to extract metals from ore are not the sole contributors to environmental impact of effluents. The most significant example of this is acid mine drainage (AMD), which is caused by the oxidation of sulphides such as pyrite (FeS_2) in the tailings.

According to Vick (1983) acid mine drainage from tailings facilities manifests after the closure of the facility once the water table inside the tailings drops. As the water drains away it allows free oxygen in the air to come into contact with the sulphide minerals. The main products of this oxidation process are sulphuric acid and metals and once the process is started, it can cause a dramatic reduction in the pH of the tailings effluent which in turn can cause the leaching out of metal cations, anions and sulphates that ordinarily would not have been released.

CM (1996) states that many residues are subjected to chemical and physical breakdown after they have been deposited. This can change their geotechnical and chemical properties which can affect the amount and quality of seepage from the tailings.

The levels of various constituents in tailings can be meaningfully judged in relation to levels that are harmful to people, plants, animals, and may have some sort of adverse effect to certain industrial processes. The South African Water Quality Guidelines Field Guide, Volume 8 of the South African Water Quality Guidelines series, is a compilation of all the different Target Water Quality Ranges (TWQR) for all the different water use sectors dealt with in volumes one to seven (DWAF, 1996):

- Domestic Water Use (Volume 1).
- Recreational Water Use (Volume 2).
- Industrial Water Use (Volume 3).
- Irrigation Water Use (Volume 4).
- Livestock Watering (Volume 5).
- Aquacultural Water Use (Volume 6).
- Aquatic Ecosystems (Volume 7).

The TWQR for a particular constituent and water use is defined as the range of concentrations or levels at which the presence of the constituent would have no known adverse or anticipated effects on the fitness of the water assuming long-term continuous use, and for safeguarding the health of aquatic ecosystems. For the aquatic ecosystems guidelines the TWQR is not a water quality criterion as it is for other water uses, but rather a management objective that has been derived from quantitative and qualitative criteria. Table 14 lists the TWQR provided in DWAF's water quality field guide. The same constituents listed in Table 13 have been included for illustrative purposes.

Table 14: South African Water Quality Guidelines (DWAF, 1996).

Constituent	Aquatic ecosystems	Domestic	Recreation	Industry	Agriculture
Aluminium (mg/ℓ)	≤ 0,005	0 - 0,15	NA[1] NA[2]	NA[3] NA[4] NA[5] NR[6]	0 - 5[7] 0 - 5[8] ≤ 0,03[9]
Arsenic (mg/ℓ)	≤ 0,01	0 - 0,01	NA[1] NA[2]	NA[3] NA[4] NA[5] NA[6]	0 - 1[7] 0 - 0,1[8] 0 - 0,05[9]
Cadmium (ug/ℓ)	≤ 0,15	0 - 5	NA[1] NA[2]	NA[3] NA[4] NA[5] NA[6]	0 - 10[7] 0 - 10[8] 0 - 0,2[9]
Calcium (mg/ℓ)	NA	0 - 32	NA[1] NA[2]	NA[3] NA[4] NA[5] NA[6]	0 - 1000[7] NA[8] NA[9]
Chloride (mg/ℓ)	NA	0 - 100	NA[1] NA[2]	0 - 20[3] 0 - 40[4] 0 - 100[5] 0 - 500[6]	0 - 1500[7] 0 - 1[8] 0 - 600[9]
Chromium (VI) (mg/ℓ)	≤ 0,007 ≤ 0,012 (Cr(III))	0 - 0,05	NA[1] NA[2]	NA[3] NA[4] NA[5] NA[6]	0 - 1[7] 0 - 0,1[8] ≤ 0,002[9]
COD (mg/ℓ)	NA	NA	NA[1] NA[2]	0 - 10[3] 0 - 15[4] 0 - 30[5] 0 - 75[6]	NA[7] NA[8] NR[9]
Copper	≤ 0,0003	0 - 1	NA[1] NA[2]	NA[3] NA[4] NA[5] NA[6]	0 - 0,5[7] 0 - 0,2[8] 0,005[9]

Constituent	Aquatic ecosystems	Domestic	Recreation	Industry	Agriculture
Cyanide (mg HCN/ℓ)	≤ 0,001	NA	NA[1] NA[2]	NA[3] NA[4] NA[5] NA[6]	NA[7] NA[8] ≤ 0,05[9]
Fluoride (mg/ℓ)	≤ 0,75	0 - 1	NA[1] NA[2]	NA[3] NA[4] NA[5] NA[6]	0 - 2[7] 0 - 2[8] NA[9]
Iron (mg/ℓ)	NA	0 - 0,1	NA[1] NA[2]	0 - 0,1 0 - 0,2 0 - 0,03 0 - 10,0	0 - 10[7] 0 - 5[8] 0,01[9]
Lead (mg/ℓ)	≤ 0,0002	0 - 0,01	NA[1] NA[2]	NA[3] NA[4] NA[5] NA[6]	0 - 0,1[7] 0 - 0,2[8] 0 - 0,02[9]
Manganese (mg/ℓ)	≤ 0,18	0 - 0,05	NA[1] NA[2]	0 - 0,05[3] 0 - 0,1[4] 0 - 0,2[5] 0 - 10,0[6]	0 - 10[7] 0 - 0,02[8] ≤ 0,1[9]
Mercury (ug/ℓ)	≤ 0,04	0 - 0,001	NA[1] NA[2]	NA[3] NA[4] NA[5] NA[6]	0 - 1,0[7] NA[8] 0 - 0,001[9]
Molybdenum (mg/ℓ)	NA	NA	NA[1] NA[2]	NA[3] NA[4] NA[5] NA[6]	0 - 0,01[7] 0 - 0,01[8] NA[9]
pH (pH units)	NA	6 - 9	6,5 -8,5[1] NA[2]	7,0 - 8,0[3] 6,5 - 8,0[4] 6,5 - 8,0[5] 5 - 10[6]	NA[7] 6,5 - 8,4[8] 6,5 - 9,0[9]
Selenium (mg/ℓ)	≤ 0,002	0 - 0,02	NA[1] NA[2]	NA[3] NA[4] NA[5] NA[6]	0 - 50[7] 0 - 0,02[8] 0 - 0,3[9]
Sodium (mg/ℓ)	NA	0 - 100	NA[1] NA[2]	NA[3] NA[4] NA[5] NA[6]	0 - 2000[7] ≤ 70[8] NA[9]
Sulphate (SO_4 mg/ℓ)	NA	0 - 200	NA[1] NA[2]	0 - 30[3] 0 - 80[4] 0 - 200[5] 0 - 500[6]	0 - 1000[7] NA[8] NA[9]
TDS (mg/ℓ)	NA	0 - 450	NA[1] NA[2]	0 - 100[3] 0 - 200[4] 0 - 450[5] 0 - 1600	0 - 1000[7] ≤ 40[8] NA[9]
Zinc	≤ 0,002	0 - 3	NA[1] NA[2]	NA[3] NA[4] NA[5] NA[6]	0 - 20[7] 0 - 1[8] ≤ 0,03[9]

NA – not available NR – not relevant
[1] Full contact [2] Intermediate contact [3] Category 1 [4] Category 2 [5] Category 3
[6] Category 4 [7] Livestock Watering [8] Irrigation [9] Aquaculture

2.12.4 Groundwater quality problem

According to Bear (1979) water quality is the limiting factor for the utilization of groundwater as a resource for human consumption. Both surface water and groundwater are subject to the polluting activities of man. Groundwater often seems to be less susceptible to pollution than surface water does. However, since water in aquifers moves that much slower than surface water, in the event of an aquifer becoming polluted, it is very difficult to clean up and restore it to its unpolluted state. Groundwater pollution may arise from different sources such as environmental, domestic, industrial, mining, and agricultural sources. The main mechanisms affecting the transport of a pollutant in an aquifer are:

- convection;
- mechanical dispersion;
- molecular dispersion;
- solid-solute interactions; and
- various chemical reactions and decay phenomena.

Hydrodynamic dispersion as described by Bear (1979) is the spreading of a contaminant into the uncontaminated water around it by a combination of mechanical dispersion and molecular diffusion at the microscopic level. This means that after a pollutant arrives in an aquifer it disperses in all directions but faster in the direction of groundwater flow. This dispersion leads to a gradual variation of pollutant concentration with distance away from the source.

2.12.5 Acid mine drainage

In mineral form sulphur may be present as sulphides such as pyrite (FeS_2), chalcopyrite (FeS.CuS), pyrrhotite (FeS) and/or sulphates such as gypsum ($CaSO_4.2H_2O$), barite ($BaSO_4$). Pyrite together with other sulphide minerals typically present in ore are liberated during the milling and metallurgical processes. Once the tailings is disposed the sulphides either oxidize to sulphate and/or dissolute. For example, oxidation of pyrite to sulphuric acid may be immediately followed, in situ, by acid neutralization by calcium calcite ($CaCO_3$) to form calcium sulphate ($CaSO_4$). Biological processes (micro-organisms) within the tailings may also cause reduction of sulphate to sulphide to form hydrogen sulphide. The reaction of hydrogen sulphide with dissolved metal ions may precipitate metallic sulphides which are chemically indistinguishable from naturally occurring sulphide minerals (Mills, 2006).

[1] Seepage from tailings impoundment into adjacent surface water body (photograph courtesy of Eben Rust).

[2] Aerial photograph of the Blesbokspruit (photograph courtesy of AngloGold Ashanti).

Figure 55: Typical impacts of mine waste water on the environment.

AMD takes place when sulphide minerals are exposed to water and oxygen and leached from the source. Mine residue is a major source for the generation of AMD which can lead to the pollution of surface and groundwater sources. Efflorescence may form in the presence of AMD reactions with other minerals and subsequent precipitation of secondary minerals. Efflorescence is composed of water soluble salts, iron hydroxides and sulphates, and several metals such as Co, Ni, Cu and Zn.

The following steps illustrate the typical chemical reactions to form AMD from pyrite.

In the first step the sulphur in the pyrite is oxidised to form hydrogen ions and sulphate which are the dissociation products of sulphuric acid in solution. Soluble Fe^{2+} is also free to react further:

$$2Fe_2S + 2H_2O + 7O_2 \rightarrow 4H^+ + 4SO_4^{2-} + 2Fe^{2+} \tag{11}$$

Oxidation of the ferrous ion to ferric ion occurs more slowly at neutral pH than at lower pH values:

$$4Fe^{2+} + O_2 + 4H^- \rightarrow 4Fe^{3+} + 2H_2O \tag{12}$$

At pH levels between 3,5 and 4,5, iron oxidation is catalyzed by a variety of filamentous bacterium. Below a pH of 3,5 the same reaction is catalyzed by the iron bacterium *Thiobacillus ferrooxidans*. If the ferric ion that is formed comes into contact with pyrite the following reaction can occur, dissolving the pyrite:

$$2FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+ \tag{13}$$

This reaction generates more acid. The dissolution of pyrite by ferric iron (Fe^{3+}), in conjunction with the oxidation of the ferrous ion constitutes a cycle of dissolution of pyrite. At ph above approximately 3 ferric iron precipitates as hydrated iron oxide as indicated in the following reaction releasing more acidity:

$$Fe^{3+} + 3H_2O \leftrightarrow Fe(OH)_3 + 3H^+ \tag{14}$$

$Fe(OH)_3$ precipitates and is identifiable as the deposit of amorphous, yellow, orange, or red deposit on stream bottoms.

The total reaction can be expressed as follows (Geldenhuys, Maree, De Beer and Hlabela, 2001):

$$2FeS_2 + 7½O_2 + 7H_2O \rightarrow 2Fe(OH)_3 + 4H_2SO_4 \tag{15}$$

The metal load and concentration of dissolved solids of leachate is dependent on the surrounding strata. In some cases the leachate will have very a low pH and a total concentration of total dissolved solids (TDS) exceeding 4000-5000 mg/ℓ. The concentration of sulphates can be in the order of thousands of mg/ℓ. The purpose of the National Water Act No. 36 of 1998 (NWA) is to ensure that the water resources of the nation are protected, used, developed, conserved and controlled in ways described in Section 2 of the Act. General regulations on water pollution control in the mining industry are contained in GN 704 of June 1999 (DWAF, 1999). General authorisations in terms of Section 39 of the NWA such as GN 1191 of October 1999 states that the water from mining activities must be treated to a pre-determined discharge quality in compliance with the South African water quality guidelines (Table 15, p. 115).

Table 15: South African Water Quality Guidelines of selected elements (DWAF, 1996).

Substance/parameter	Domestic use	Industrial use	Agricultural use[1]
Copper (mg/ℓ)	0 - 1	NA	0 - 0,2
Iron (mg/ℓ)	0 - 0,1	0 - 0,1	0 - 5
Nickel (mg/ℓ)	NA	NA	0 - 0,2
pH (ph units)	6 - 9	6,5 - 8	6,5 - 8,4
Sulphate (mg/ℓ)	0 - 200	0 - 30	NA
Zinc (mg/ℓ)	0 - 3,0	NA	0 - 1,0

[1] Using water for irrigation NA – not available

The typical mine water quality variables of concern include:

- pH, i.e. concentration of H^+;
- sulphate ions concentration; and
- the concentration of heavy metals in the AMD.

Common sources of sulphates at a tailings disposal facility include seepage from the impoundment, diffuse surface run-off, and spillage from return water dam (DWAF, 2006). A number of opportunities exist to reduce the sulphate load and either includes options to reduce the pollution at source or the treatment of effluent through desalination. Land management includes rehabilitating the impoundment, capturing diffuse run-off, and increasing the capacity of return water dam. Desalination processes such as reverse osmosis (RO) technology can either be undertaken to treat effluent at source or could be deployed in the resource. Water treated in this manner could be sold for domestic and industrial use, thereby off-setting some of the costs of treatment.

2.12.6 Liner systems

Liners for tailings impoundments can be necessary if the effluent poses an unacceptable risk. There are two main classes of liners namely semi-pervious linings and geomembranes (or flexible membrane liners). Semi-pervious linings include clay layers (imported or in situ) and bitumen or tar modifications. Natural clay liners can be affected by chemical interaction with the effluent. This can adversely affect the permeability of the liner. Geomembranes consist of plastic sheets welded or glued together at the seams. If geomembranes remain unflawed and undamaged, it can be assumed that they are impervious, but this is unlikely so it is common practice to assume the permeability of a flexible membrane liner to be between 0,01 and 0,1 m/annum.

2.12.7 Seepage

According to Chamber of Mines (CM, 1996) the seepage through a liner underneath the tailings impoundment under fully saturated conditions can be calculated by applying Darcy's law as follows:

$$v = k_1 \times \frac{p_0 - p_1}{d_1} = k_2 \times \frac{p_1 - p_2}{d_2} = k_3 \times \frac{p_2 - p_3}{d_3} \qquad (16)$$

where:

v = discharge velocity
p = the potential
d = the hydraulic head
k = the permeability

Taking p_3 as the potential at the regional water table and making it the datum with a value of zero, and expressing potential in terms of head one obtains

$$\frac{k_1}{d_1}\left[(d_0+d_1+d_2+d_3)-p_1\right]=\frac{k_2}{d_2}(p_1-p_2)=\frac{k_3}{d_3}p_2=v \qquad (17)$$

where the discharge velocity (v) is the seepage rate per unit area of the tailings impoundment and p_i is the total seepage potential (pressure head plus elevation) for each level as indicated in Figure 56 below.

Solving for p_1 yields:

$$p_1=\frac{k_1(d_0+d_1+d_2+d_3)}{d_1\left[\frac{k_2k_3}{k_3d_2-k_2d_3}+\frac{k_1}{d_1}\right]} \qquad (18)$$

From which the flow velocity (v) can be calculated.

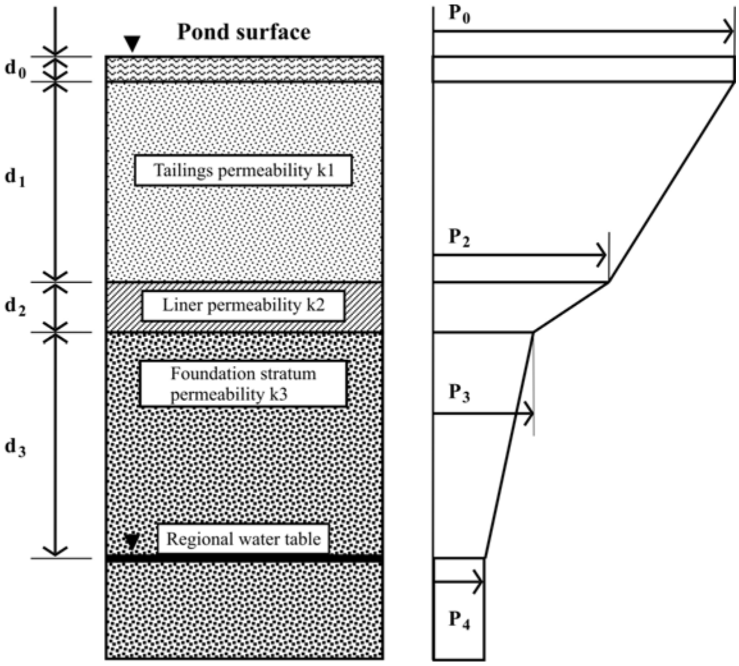


Figure 56: Schematic representation of information required to calculate seepage potential (CM, 1996:136).

2.12.8 Standard practice

Vick (1983:249) states that at the completion of the tailings operations stage, supply of effluent to the pond ceases. Gradually fluid stored in the tailings voids will drain by gravity and will be released to a lesser extent as a result of tailings consolidation. As the supply of seepage to the underlying aquifer dwindles, the groundwater mound will begin to decline. After a long period of time, typically in the order of 10 to 50 years or even longer, the tailings will be drained to their field capacity.

Infiltration of precipitation will continue over the long term, the amount depending on the:

- climate;
- permeability of the tailings; and
- type of the rehabilitation measures.

It is also unlikely that long-term infiltration will produce more recharge to the groundwater than occurred over the same area prior to impoundment construction. Ultimately then, the groundwater regime will eventually re-establish its original configuration in most cases (Vick, 1983:249).

Vick (1983:250) states that the physical factors that influence the quantity of seepage are:

- Permeability.
  Permeability is the physical factor that most influences groundwater contamination potential. The differences between the permeabilities of the tailings, the foundation, and the aquifer, as well as the variability of permeability within each material, produce a wide variety of responses in groundwater systems that have been observed at existing tailings disposal sites (Vick, 1983:246).
- Impoundment size.
  For unlined impoundments on foundations more pervious than the tailings, seepage loss can be considered directly proportional to the size of the impoundment area covered by water.
- Distribution of tailings within the disposal area.
- Engineered seepage barriers such as earthen or synthetic liners.

In a layout context, seepage can be minimised by reducing the area covered by the impoundment and increasing its height, assuming relative pervious foundation conditions. A compromise solution can be to construct a segmented impoundment to minimise the impoundment area covered by water at any given time (Vick, 1983:251).

The primary factors affecting groundwater contamination potential are:

- the toxicity and concentration of individual contaminants in the tailings effluent; and
- the permeability of the tailings, foundation and upper most aquifer.

By analogy to disposal methods, seepage control methods must be matched to the chemical characteristics of the seepage and the specific site conditions. But the recent flurry of concern for controlling seepage has come about so rapidly that the rush to implement elaborate and costly control measures may have outstripped an understanding of exactly what these measures are intended to achieve (Vick, 1983:301).

General principles related to seepage control emerge:

- Not all process plant effluents contain toxic constituents. Depending on ore type, milling process, and pH, contaminants may range from toxic heavy metals to such relatively innocuous materials as sulphates or suspended solids.

- For mill effluent that does contain toxic constituents, it is not necessarily the case that seepage of this effluent will result in pervasive groundwater contamination. Geochemical processes may retard or inhibit movement of some constituents.
- If toxic constituents do enter the groundwater regime, the ultimate effects on the groundwater environment must be determined before deciding on a seepage-control strategy intended to minimise these effects.

DWAF (2006) states that standard practice requires that operation, inspection, monitoring and maintenance according to a tailings impoundment management manual, which must comply with the specifications in the Department of Minerals and Energy (DME) (Mine Health and Safety Inspectorate) Guideline for the Compilation of a Mandatory Code of Practice on Mine Residue Deposits.

This should include:

- covering of side slopes with soil during the operation stage to assist in reducing any contact of rainfall runoff with the tailings;
- vegetation of side slopes to minimise erosion;
- collection of rainfall runoff into the dirty water storage facility (return water dam);
- after decommissioning, the top surface of the tailings impoundments should be shaped to suit drainage requirements and re-vegetated; and
- implementation of under drainage systems to collect seepage for re-use as process water.

Poor or non-compliance with the tailings impoundment management manual typically include:

- poor soil and vegetation cover; and
- no collection of dirty water runoff or seepage.

Decommissioning and closure

The Chamber of Mines (CM, 1996) states that the objective at decommissioning and closure of a tailings disposal facility is to ensure that the site continues to have minimal environmental impact and remains safe and aesthetically acceptable with a minimum of maintenance. The costs of proper closure should be factored into the costs of production right from the beginning of the life of the mine. Measures to ensure the optimal decommissioning and closure should be implemented throughout the life of the facility. This section indicates to what extent the facility complies with legal requirements and sets out further actions necessary for such compliance.

At closure the facility should be able to contain and withstand the effects of the maximum probable rainfall appropriate to the area. This could mean either containing all rainfall in a pond on top of the tailings impoundment, or transferring the rainfall to containment facilities where it could be evaporated, reused or treated.

Containing rainfall on top of the facility means that unless the pond is lined with an impervious liner, there will be constant seepage through the tailings which could cause pollution of groundwater or instability of slopes. If water is held on top of the facility it should be ensured that the water is able to evaporate at a rate which will balance the rate of precipitation by ensuring a maximum surface area to maximum depth ratio for all ponds. Ponds should not be constructed close to the sides of the facility to avoid slope failures (CM, 1996).

2.12.9 Groundwater and contaminant modelling

> "Polluted surface water may easily reach and pollute groundwater."
>
> Bear (1979)

Due to the interaction of surface and groundwater in a system, an action that affects the one, invariably affects the other in some way such as illustrated in Figure 54 (p. 109).

Characteristics of groundwater

Surface water is generally more susceptible to pollution than groundwater is. However, if pollution of groundwater does occur, depending on the nature of the formation in which the water occurs, the pollution can be very difficult, time-consuming or practically impossible to remedy. All of these also imply great cost for remediation (Bear, 1979).

Most sources of groundwater are of acceptable biological and physical quality. Groundwater is more likely than surface water to pick up minerals in solution. If groundwater does pick up minerals in solution, at an unacceptable concentration, it is usually very expensive to remove these minerals. The movement of groundwater is very slow, particularly in layers of very fine material such as clay. In these fine materials there are also other phenomena present. These are adsorption and ion-exchange at the surface of the solid matrix of the soil or rock. Species that have adsorbed can continue to be released into the groundwater for extended periods of time.

This process of ion-exchange and adsorption can also be very useful, causing the aquifer to act as a filter as unwanted species are removed from the water. In groundwater there is always a trend toward salinisation due to a continuous addition of solute by water entering the system from the surface. At equilibrium this will be balanced by the water leaving the system carrying solutes with it. The yield of an aquifer refers to the amount of water that can be abstracted from the aquifer, such that the total outputs balance the total input into the system (Bear, 1979).

Groundwater- surface water interaction

South Africa's water supply depends on surface water taken from rivers and dams as well as a large dependence on groundwater. Parsons (2004) repeatedly states that the management of water resources should not be separated into surface and groundwater as the two are intimately related and impacts on one will invariably have an impact on the other, even though it may not be immediately apparent.

Depending on the position of the water table in the phreatic aquifer underlying them, streams and rivers can either drain the aquifer or contribute water to it. A stream contributing water to an aquifer is called an influent stream and a stream draining an aquifer is called an effluent stream. A stream can be influent along one stretch of its length and effluent on another. From this it can be clearly seen that the pollution of an aquifer can have far-reaching effects as pollutants carried by the water released from a mine tailings impoundment can contaminate the water in an aquifer and be transported into other aquifers or into surface water and then even back into groundwater in another aquifer system.

The movement and concentration of the pollutants are subject to hydrodynamic dispersion and mixing and movement can be very slow through some aquifers, sometimes creating the impression that the pollution is of little consequence. Damming of surface flow causes a concentration of pollutants aggravated by evaporation and increases the possibility for groundwater contamination (Bear, 1979).

Evapotranspiration

Transpiration is the removal of water from the soil by plants where it is converted to gas and released to the atmosphere. Evaporation is the conversion of water from liquid phase to gas phase. Both processes are driven by energy from the sun. Evapotranspiration is the term used for the combined effect of the above two processes which remove water from an area partially covered by vegetation.

Flow in aquifers

According to Bear (1979), generally speaking, flow through a porous medium such as an aquifer occurs in three dimensions so that the specific discharge vector would have components in the x, y and z directions, all of which may be non-zero. However, due to the fact that most aquifers are much thinner than their length or breadth, it is both reasonable and accurate to neglect the vertical component and assume that flow is horizontal. Groundwater entering an aquifer carries dissolved substances obtained outside the aquifer and may be:

- salts dissolved from the matrix of adjacent aquifers;
- pollutants absorbed by rainwater; or
- pollutants derived from mine wastes.

The water leaving the aquifer carries with it these and any other substances accumulated whilst in the aquifer. The concentration of the substances in the water leaving the aquifer can usually be assumed to be the average concentration found in the aquifer (Bear, 1979).

Homogeneity and isotropy

For the purposes of this section homogeneity and isotropy refer to the permeability (k) of an aquifer. Saying that the aquifer material is isotropic, means that the permeability at a point is the same in every direction. Homogeneous means that the permeability is the same at all points throughout the material. These terms are applied to permeability (k) and to transmissivity (T) (Bear, 1979).

Natural replenishment from precipitation

If the ground surface is sufficiently pervious a phreatic aquifer can be replenished by precipitation. A confined aquifer would be recharged by inflow from adjacent phreatic aquifers. When looking at the recharge of an aquifer from precipitation alone, one can take the annual average of precipitation rather than taking into account each and every storm event. This is due to the buffer effect that an aquifer has due to the large volumes of water stored in it (Bear, 1979).

Infiltration of water from the ground surface to the water table is essentially unsaturated flow and is complex to model as it requires detailed information on the characteristics of the soil from surface to the water table.

There are many mathematical models which have been developed to model the replenishment of aquifers. On the whole these models use systems of equations to model the hydrologic cycle. They attempt to account for all inflows and outflows into and out of an aquifer. Most of the equations required for these models depend on the drainage properties of the soil (Bear, 1979).

Bear (1979), states that artificial recharge is the deliberate addition of water to an aquifer by human intervention. The quality, quantity location and time of replenishment are subject to human control. There are various methods of artificial recharge, but they are not relevant to this study.

2.12.10 Steady state flow

In 1856 Henry Darcy used an experimental apparatus consisting essentially of a vertical homogeneous sand filter to investigate the flow of water through a saturated porous medium. Darcy concluded that the rate of flow is directly proportional to the cross-sectional area, directly proportional to the difference in hydraulic head and inversely proportional to the length over which the head difference is measured. The resulting Darcy's Law can be written in various forms. However, the following are taken from Bear (1979):

$$Q = k.A.\frac{(h_2 - h_1)}{L} \tag{19}$$

Where:

Q = flow rate, i.e. volume of water per unit time
A = cross-sectional area (m^2)
(h_2-h_1) = difference in piezometric head across the length (L) of the flow path (m)
k = permeability of aquifer (m/d)
L = distance between head measurements (m)

$$q = k.J \tag{20}$$

Where:

q = Q/A is the specific discharge or the volume of water flowing per unit time through a unit cross-sectional area normal to the direction of flow (m^3/d per m^2).
J = $(h_2-h_1)/L$ is the hydraulic gradient. Some texts give J as i. (Craig, 2004)
k = the permeability of the aquifer. It is also referred to as the coefficient of proportionality, the permeability, or the coefficient of permeability of the porous medium.

Piezometric head describes the sum of the pressure energy and the potential energies per unit weight of water. For a phreatic aquifer, the height of the capillary fringe is usually much smaller than the saturated zone thickness of the aquifer that lies below the phreatic surface. This leads to the common assumption by most hydrologists that the water table is at the phreatic surface (Freeze and Cherry, 1979).

Assumptions:

- The flow is laminar.
- The aquifer is confined.
- The aquifer is homogeneous, isotropic and of uniform thickness.

The Dupuit – Forchheimer discharge formula

According to Bear (1979), in the case where there is steady, unconfined flow in an aquifer between two reservoirs with vertical faces, the water table will have a parabolic shape and the discharge per unit width will be described by the Dupuit – Forchheimer formula which is as follows:

$$Q = k.\frac{(h_0{}^2 - h_L^2)}{2.L} \tag{21}$$

Where:

Q = flow rate per unit width (m^2/d)
k = permeability of aquifer (m/d)
L = distance between h_0 and h_L measured along the flow path (m)
h_0 = upstream reservoir water level (m)
h_L = the downstream water level (m)

Modelling groundwater flow

From Segar, Basberg and Saether (1997), Darcy's law can be written as

$$v = -k.\frac{\partial h}{\partial l} \tag{22}$$

Where k is the permeability
Applying this equation to the three dimensions and assuming steady state conditions results in the continuity equation for steady state flow:

$$\frac{\partial}{\partial x}\left(-k_x\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(-k_y\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(-k_z\frac{\partial h}{\partial z}\right) = 0 \tag{23}$$

When the aquifer is isotropic and homogeneous, the value of k is the same in all directions which means it is independent of x, y and z. In this case Equation 23 can be simplified to the equation known as Laplace's equation shown below:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = 0 \tag{24}$$

This equation is only relevant for groundwater flowing through an isotropic, homogeneous medium under steady state conditions.

Karahan and Tamer (2003) propose the use of a spreadsheet simulation to solve equations for the case of transient flow in a confined aquifer. This method uses the plan view and models the head distribution in an aquifer due to discrete pumping wells and recharge wells. This method does not take into account recharge from rainfall or even attempt to consider the movement of contamination.

2.12.11 Unsaturated flow under steady state conditions

Fredlund and Rahardjo (1993) describe a flux (*q*) as the product of a flow rate (*v*) and a cross-sectional area (*A*). For steady state seepage of an incompressible fluid, the principle of conservation of mass implies that for an element of soil, the flux into the element must equal the flux out of the element. That is, the net flux must equal zero.

The flow of water through soil under unsaturated conditions is governed by Darcy's law just as for saturated conditions. The difference lies in the coefficient of permeability for water which is not constant for unsaturated flow. In unsaturated flow this coefficient is assumed to be a function of variables such as water content and suction. As opposed to saturated flow, unsaturated pore water pressures usually give a negative gauge value.

Unsaturated flow problems can be solved in one, two and three dimensions. One-dimensional problems are usually solved using finite difference methods with either the head or a flux as boundary condition. Two-dimensional problems are best solved using flow nets or finite element methods.

2.12.12 Pollution transport models

In addition to the groundwater flow equation, numerical pollution transport models use advection, dispersion, retardation and degradation to model pollution transport in groundwater. All these factors will be different for each different pollutant. These models do not include geochemical modelling methods that take account of speciation.

Some of the factors defining transport characteristics which may be included in these models are:

- Langmuir and Fruendlich sorption isotherms;
- biological degradation;
- retardation;
- mechanical dispersion; and
- diffusion.

Many computers software packages are available for the processing of modelling data in connection with pollution transport in groundwater used in hydrogeological investigations. Some of the computer programs available are:

- MOC.
  MOC is a USGS one and two dimensional finite-difference pollution transport model for steady state and transient saturated flow. It solves the groundwater flow equation for the saturated zone for advection, dispersion, dilution and mixing of water from different sources and it includes a number of chemical processes linked to the solution of the groundwater flow equation.
- MT3D.
  MT3D is a three dimensional solute transport model for the simulation of advection, dispersion and chemical reactions of contaminants in groundwater systems;
- MODFLOW.
  MODFLOW is a three dimensional groundwater and transport model developed by the USGS.

2.12.13 Treatment of discharges

The treatment of discharges may include capital and operating costs on the observed and expected water quality. Most primary treatment processes concentrate on the neutralisation of the acid mine drainage (AMD) and the partial removal of sulphates. Secondary treatments involve the removal of heavy metals and other components of the AMD to achieve wastewater limits and tertiary treatments are then used as polishing processes before the wastewater is released. The first step in treatment is to increase the pH of the AMD; this pH control measure determines to a great degree the efficiency of following treatments applied:

- Sulphates need to be removed from the effluents for the following reasons:
  - to prevent salination of surface water (discharge recommended at levels < 500 mg/ℓ);
  - to prevent scaling (this depends on the presence of Mg and Na in the water, where saturation levels are usually equal to 1500 mg SO_4); and
  - to prevent acid corrosion.

2.12.14 General treatment technologies

The processes shown in Figure 57 are the typical technologies applied in South Africa to treat mine water (van Niekerk, 2005).

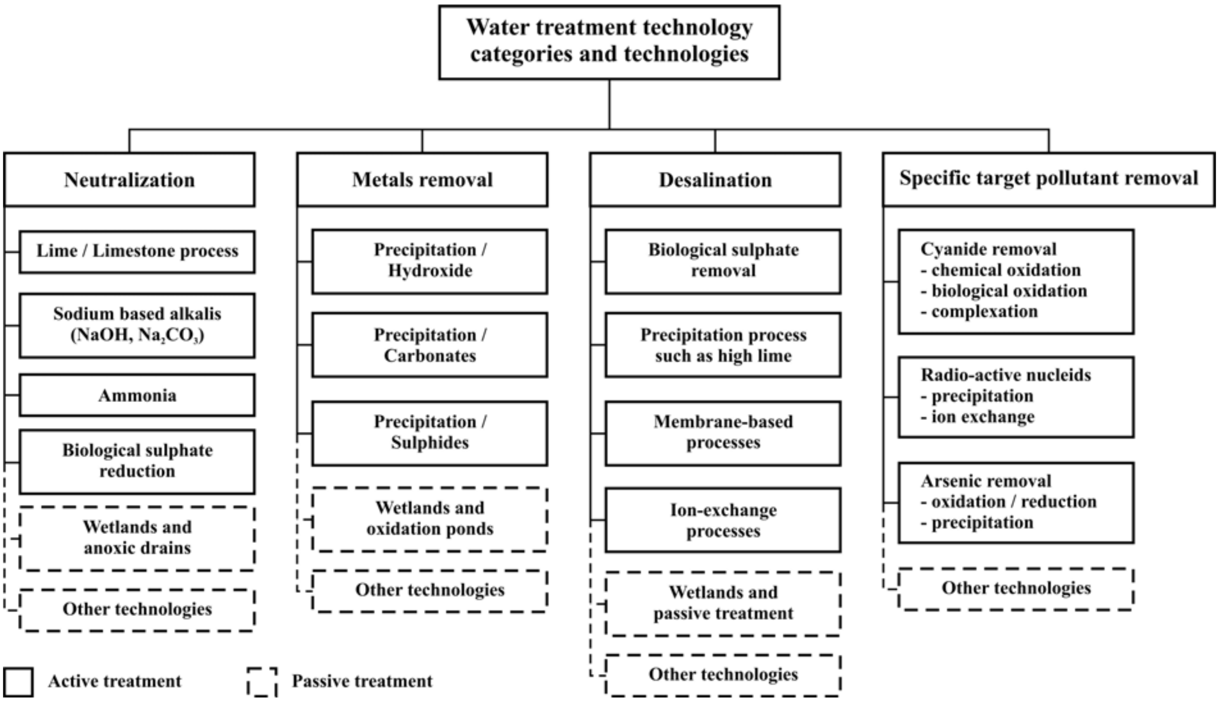


Figure 57: Generic range of mine water treatment technologies (van Niekerk, 2005).

The following key technologies are discussed:

- neutralisation;
- desalination; and
- passive treatment.

Neutralisation technologies

Neutralisation technologies have been enhanced from the conventional use of lime (CaO or $Ca(OH)_2$) to the use of limestone ($CaCO_3$) under the initiatives of the CSIR. Limestone, which occurs as a waste product in for example pulp or paper making industries or occurs in nature, is less expensive than lime.

Desalination technologies

Over the past decade, a wide selection of desalination treatment technologies have been developed, tested and applied to full scale installations and can be grouped under the following main categories:

- chemical precipitation;
- biological treatment processes; and
- membrane based treatment.

Chemical precipitation

Gypsum crystallisation process to decrease the calcium and sulphate concentrations to 1200 - 1400 mg/ℓ.

Biological treatment processes

The biological treatment processes are based on a two step process to remove sulphate.

$$SO_4^{2-} \rightarrow H_sS \rightarrow S^0(elemental) \qquad (25)$$

Three variations of this process in use in South Africa are:

- BioSure® process technology demonstrated on sewage sludge as carbon/energy source.
- Paques BV technology.
- CSIRosure technology demonstrated on a variety of carbon/energy sources.

Membrane based treatment

The application of membrane technology is very sensitive to the type of mine water and specifically the ionic profile of the water. In general, membrane-based treatment processes produce large volumes of sludge/brine which is not considered to be attractive at present because of the difficulty and cost to dispose of this.

Passive treatment technologies

Considerable research has been carried out on the use of passive treatment of mine waste water. The combination of active and passive systems has been widely researched to enhance the metals removal, acidity removal and sulphate reduction. However in South Africa, the application of such a process is restricted to small flow systems with low maintenance. A wider use of this operation is for polishing purposes of treated effluent before final discharge. Passive treatment systems utilise naturally available energy sources such as topographical gradient, microbial metabolic energy, photosynthesis and chemical energy and require regular but infrequent maintenance to operate successfully over their design live. Passive sulphate reduction technology rests on the biological reduction of sulphate to sulphide using an organic carbon source as the electron donor. The carbon source takes the form of a solid lignocellulose such as manure, sewage sludge and wood chips (Pulles, Coetser and Heath, 2005).

While there are different ways of constructing the chemical equation for the biological degradation of lignocellulose in the reduction of sulphate, the following one is sufficient:

$$(CH_2O)_{106}(NH_3)_{16}(H_3PO_4) + 53SO_4^{2-} = 53HS^- + 67HCO_3^- + 39CO_2(aq) + 39H_2O) + 16NH_4^+ + HPO_4^{2-} \quad (26)$$

2.12.15 Sulphate removal treatment technologies

The following treatment process technologies address the problems of acidification and salinisation in terms of sulphate:

- integrated limestone/lime;
- biological treatment; and
- membrane desalination.

Integrated limestone/lime process

The removal of magnesium, metals and sulphate (< 1200 mg/ℓ) has been achieved using this particular process. The use of limestone/lime (Figure 58) is the most cost effective technology for the neutralisation and the reduction of sulphate levels, due to the precipitation of magnesium and removal of associated sulphate by crystallisation of gypsum (Geldenhuys, Maree, De Beer and Hlabela, 2001).

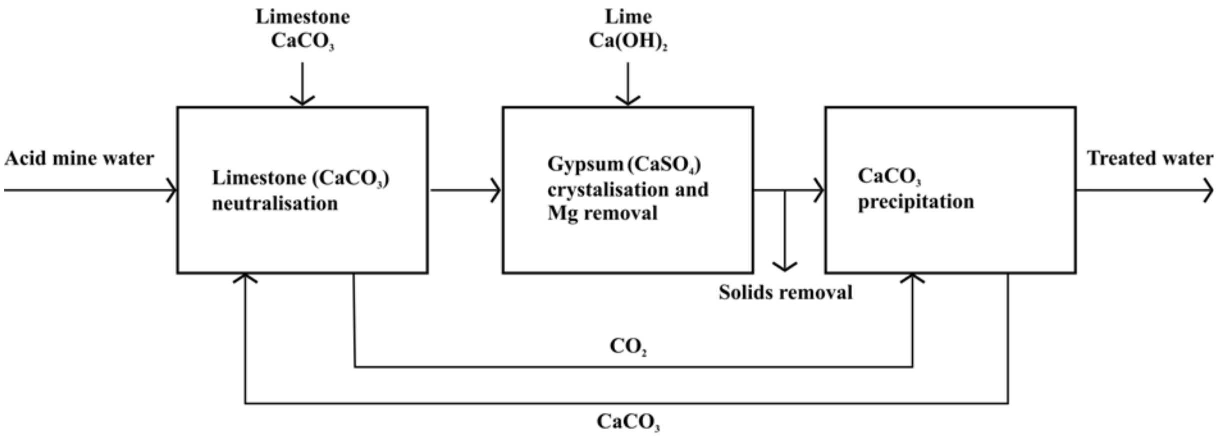


Figure 58: Simplified schematic of the integrated limestone/lime treatment process.

The process consists of the following stages:

Limestone ($CaCO_3$) neutralisation to raise the pH to 7 and CO_2 production.

$$CaCO_3 + H_2SO_4 \rightarrow CaSO_4 2H_2O + CO_2 + H_2O \quad (27)$$

Lime ($Ca(OH)_2$) treatment to pH values of 12 resulting in gypsum $CaSO_4$ crystallisation and the total removal of magnesium through $Mg(OH)_2$ precipitation.

$$MgSO_4 + Ca(OH)_2 \rightarrow Mg(OH)_2 + CaSO_4 \quad (28)$$

pH adjustment from 12 to 8,5 by bubbling the recovered CO_2 through the water which results in calcite ($CaCO_3$) crystallisation. The $CaCO_3$ formed during this process is recycled to the limestone neutralisation stage for re-use.

The integrated limestone/lime treatment process is used to neutralise acid water and partially remove sulphates to below saturation levels of gypsum, which is 1200 mg/ℓ. The process allows:

- for cost effective neutralisation using limestone and the removal of sulphate up to levels of 2000 mg/ℓ (as SO_4);
- that with additional lime treatment the sulphate can be further reduced to 1200 mg/ℓ when the gypsum crystallises and magnesium precipitates;
- for the reduction of scaling and corrosion during re-use of water in mines; and
- for the treated mine water to meet regulatory discharge quality requirements.

[1] Limestone make-up facility at the Landau Colliery navigation plant (courtesy of A. van Niekerk, Golder Associates Africa).

[2] Biological sulphate reduction chamber at the ERWAT Ancor WWCW implementing the BioSure® process.

Figure 59: Photographs of the limestone and BioSure® processes.

Biological treatment process

The Rhodes BioSure® process (Figure 60) is a patented cost-effective biological sulphate reduction process where high sulphate mine water is treated with primary sewage sludge. This process is used on a full scale to treat polluted mine water form the Grootvlei Gold Mine at ERWAT's Ancor wastewater treatment works on the East Rand. The primary sewage sludge acts as a carbon donor and when mixed with high sulphate mine water creates a conventionally-treatable bio-solid waste. Grootvlei Gold Mine pumps about 75 Mℓ/d mine water to be able to access its gold reserves. The groundwater results from closed neighbouring mines and if not pumped would otherwise fill the Grootvlei shafts. The site is adjacent to the vulnerable Blesbokpruit RAMSAR area necessitating the mine to come up with a solution to treat the water cost effectively before discharging it into the Blesbokspruit (Holtzhausen, 2006).

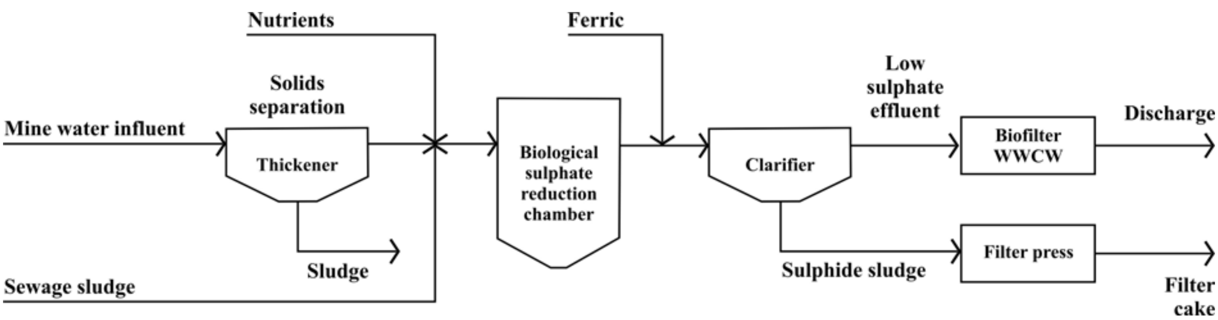


Figure 60: Simplified schematic of the BioSure® process.

After a testing period of two years, treating 2 Mℓ/d on a pilot basis, Grootvlei Gold Mine and Ancor decided to increase the process capacity to a full-scale plant capable of treating up 10 Mℓ/d. The project makes use of existing infrastructure at the Ancor wastewater treatment works site.

The pumped mine water is first treated at a high-density separation (HDS) plant to remove iron and condition the pH levels. The conditioned water is then pumped to the Ancor works where it is mixed with the primary sewage sludge in a mixing tank and then split to eight biological sulphate reducing bio-reactors. The reactors date from previous works and have been modified slightly to accommodate the new load. Modifications to the existing plant have been made to limit the escape of hazardous and odorous sulphurous gases.

The overflow, rich in sulphides is pumped back to the main pump station where it is treated with iron slurry, a by-product from the initial HDS. The mixture is then divided into reactor clarifiers for sulphide removal. The treated water from this process contains reduced sulphate levels and practically no sulphide.

The last stage is where the material is pumped to Ancor's bio-filters for removal of remaining COD and NH_3, for conventional sewage treatment before being released into the Blesbokspruit.

Membrane desalination process

Membrane desalination treatment is well established for many water and effluent applications. The technology requires some refinement and further development before it can be successfully applied to high sulphate containing mine water. The specific challenge has been to maximise water recovery and thereby reducing the brine/sludge volume production. The main stream membrane desalination process is fairly standardised for acid mine drainage and includes the unit treatment processes of:

- limestone/lime neutralisation;
- softening and excess gypsum crystallisation;
- micro/ultra filtration; and
- spiral reverse osmosis.

Different approaches are, however, implemented to further treat the first stage reverse osmosis (RO) brine stream as reflected in Figure 61 (p. Figure 61).

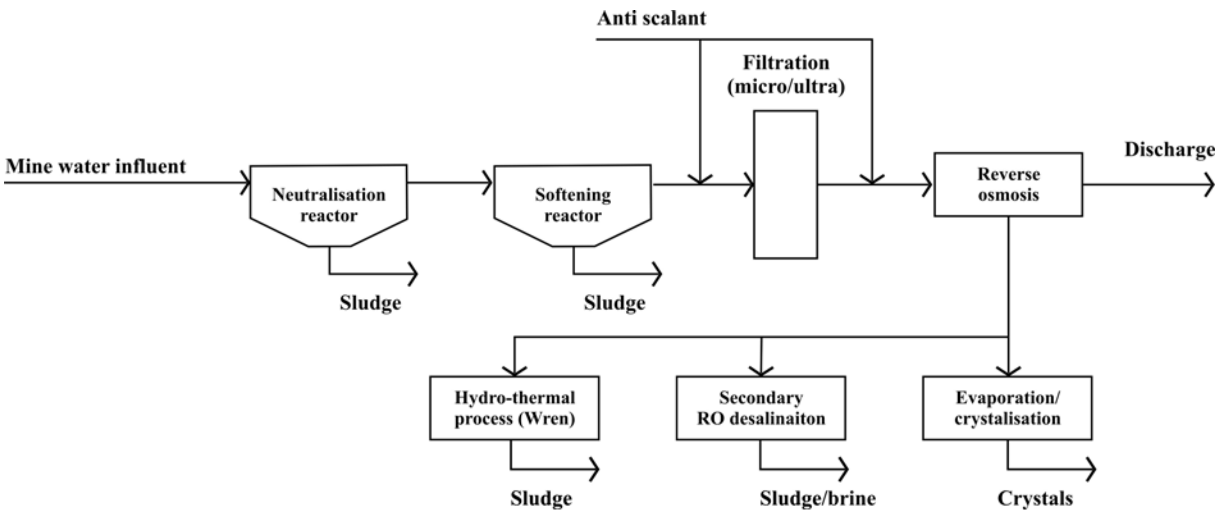


Figure 61: Simplified schematic of a desalination membrane-based process.

The different brine treatment options include:

- Precipitation of gypsum and anhydrite using a hydro-thermal process, originally developed by Wren. Gypsum and anhydrite have an inverse solubility dependence on temperature. The hydrothermal process is based on sequential high temperature (140 – 160 °C) and high pressure (5 - 6 bar) vessels to progressively precipitate the sulphate salts in the form of a pure gypsum and pure anhydrite salt. The water product of the hydro-thermal brined treatment is after cooling blended back into the main reverse osmosis (RO) permeate product stream.
- De-saturation and secondary RO treatment involves the chemical treatment of the RO brine stream to destroy the anti-scalant effect and to precipitate the super saturated salts such as gypsum and calcite. The de-saturated brine stream is then treated in a secondary micro/ultra filtration and spiral RO process to increase the recovery of water. The de-saturation process can be repeated on the secondary RO brine stream to increase the water recovery even further.
- Thermal evaporation and crystallising technology can also be applied to the RO brine stream. This employs conventional technologies and has been applied to many industrial and mining effluents. The residue is concentrated brine or moist salt crystals.

All three these brine treatment technologies have been successfully applied in Southern Africa and the achievable water recovery is as follows:

- hydrothermal brine treatment = > 98 % water recovery
- de-saturation and secondary RO treatment = > 95 % water recovery
- evaporation and crystallisation = > 90 % water recovery.

2.12.16 Economic feasibility of treatment processes

Neutralisation and sulphate removal from mine water to a level where the water quality is such that the water is suitable for mine process water or to be discharged into surface water body or sewage network can be achieved by using either the:

- limestone/lime process;
- biological treatment process; or
- membrane desalination process.

The typical treatment costs of the different technologies considered are listed in Table 16. According to the table the treatment costs for the limestone process is the cheapest at R100 – R460/t sulphate removed. Also, it is evident that the running costs can range between R100 and R2500/t sulphate removed depending on the technology chosen. The capital cost varies between R88 250 and R5 million per tonne sulphates which would be removed per day. The preferred technology will not only depend on the bottom line cost but will also depend on factors such as the volume and quality of influent water, the required level of sulphate removal, and locality.

Table 16: Comparing the costs of sulphate removal for different technologies.

Process	Plant capital cost (R/t sulphate removed per day)	Running cost (R/t sulphate removed)
Limestone[1] - $CaCO_3$	88 250	100 - 460
Slaked lime[1] - $Ca(OH)_2$	850 000 – 1 500 000	650 - 820
BioSure®[1]	4 600 000	3000
Biological process[1]	4 600 000	3000
Membrane based[2]	2 500 000 – 5 000 000	1200 – 2500

[1] CSIR – J. Maree

[2] Golder Associates – A. van Niekerk

2.12.17 Waste discharge charge system

The Department of Water Affairs and Forestry (DWAF) is developing a waste discharge charge system (WDCS) to promote waste reduction and water conservation.

This system forms part of an overall pricing strategy being established under the National Water Act No. 36 of 1998 (NWA) and is based on the polluter-pays principle which aims to:

- promote the sustainable development and efficient use of water resources;
- promote the internalisation of environmental costs by those responsible for the pollution;
- create financial incentives for dischargers to reduce waste and use water resources in a more optimal way; and
- recover the costs of mitigating the impacts of waste discharge on water quality.

The WDCS is a response to a pollution problem that is already imposing a cost on society. The WDCS endeavours to shift some of the cost back to dischargers according to the polluter pays principle. The common perception that environmental charges are a trade-off against the economy for the sake of environmental benefits is shown in the literature to be largely false. Accordingly, a pollution charge should not be viewed as an additional burden on the economy. The result of pollution charges is often that overall pollution costs are reduced while the economy as a whole is more efficient and less wasteful, and generally more attractive to investors.

Water resource management in South Africa links the acceptable level of impact to the concept of resource quality objectives (RQOs), which balance the need to protect water resources with the need to develop and use them. The setting of RQOs is catchment specific, based on the social, economic and political drivers for development and utilisation of a specific water resource. RQOs are to be set as part of the classification system for water resources, through a process of consensus seeking among water users and other stakeholders, in which the government is responsible for ensuring that environmental interests are represented.

It is also expected that the waste discharge charge system (WDCS) will apply to the following registered water uses, which disposing of mine residue reside under, in terms of Section 21 of the NWA:

- Section 21(f): discharging waste or water containing waste into a water resource.
- Section 21(g): disposing of waste in a manner which may detrimentally impact on a water resource.

Mine residue deposits are considered as non-point sources (NPS) in terms of the proposed policy. The charge will be based on an estimation of the load entering the water resource through the various diffuse pathways for the following:

- Disposal of effluent to land or to a facility (e.g. tailings impoundments, irrigated effluent, evaporation ponds, treatment wetlands).
- Disposal of waste to land or to a facility (e.g. landfill, waste-rock dumps, fly ash disposal, solid waste disposal).

Constituents

The WDCS includes, but is not limited to, the following variables:

- salinity such as electrical conductivity, chloride, sodium, sulphate (SO_4);
- nutrients: soluble phosphorus (PO_4), nitrate (NO_3), ammonium (NH_4);
- pH;
- heavy metals such as arsenic (As), cadmium (cd), chromium (Cr), copper (Cu), mercury (Hg) , lead (Pb), nickel (Ni), and zinc (Zn); and
- organics: chemical oxygen demand.

Charge categories

The WDCS can be conceptualised as two distinct components:

- Water use charges that provide a disincentive or deterrent to the discharge of waste, based on the use of the resource as a means of disposing waste (incentive charge).
- Water use charges to cover the quantifiable costs of infrastructure or other measures undertaken in the resource for the mitigation of waste discharge-related impacts to achieve resource quality objectives within a catchment area (mitigation charge).

The WDCS is therefore composed of two charges namely an incentive charge (IC) and mitigation charge (MC).

Incentive charge

The incentive charge (IC) seeks to change discharge behaviour by providing an incentive to reduce waste load at source. The charge rate is set at a level where sufficient dischargers are incentivised to reduce waste load at source, such that the cumulative waste load reduction within the resource (catchment) achieves the resource quality objectives. The charge does not recover any direct costs nor is it related to a particular service received and is thus considered an environmental tax. Owing to its tax nature, the charge will generate surplus revenue which could be used for a number of uses, through a process of implicit earmarking and budgetary allocation. The charge is based on monitored discharge load, given that the charge seeks to change actual discharge load, and where the waste load is reduced at source such will be reflected in a reduced charge.

Mitigation charge

The mitigation charge (MC) is intended to cover the costs of mitigation measures undertaken in the water resource and will be applied in cases where it is more economically efficient to reduce load within the resource than reducing discharge load at source. As such, the charge is a user charge to recover the costs of mitigation measures deployed in the resource.

There are four categories for this charge:

- mitigation through removal of load from the resource, including a regional mitigation scheme or infrastructure or a regional mitigation project;
- water resource system operation for the dilution, blending or purging of poor quality water.
- mitigation for treatment costs downstream; and
- treatment at source, in order to apply the most cost-effective treatment options to a limited number of dischargers in a catchment.

Calculating charge

Charges for mine residue deposits, i.e. non-point source (NPS), are calculated based on the load discharged to the resource. However, estimating discharge load is complicated. In some circumstances, good estimates of load entering the resource from specific NPS facilities are available (following extensive monitoring, regional modelling or detailed technical research). Under such circumstances, the available estimates will be used to calculate charges. However, estimations at that level of confidence are often not available. Under circumstances of information paucity, a desktop estimation of load entering the resource is required, based on the type and size of the facility, management practices, load disposed on to the facility and anticipated rainfall (DWAF, 2006:9).

Typical computation of waste discharge charges proposed by DWAF can be demonstrated by means of three scenarios (Table 17):

- Incentive charge.
  The objective of levying an incentive charge only will be to incentivise dischargers to reduce load at source. An incentive charge rate of R10 250/t SO_4 has been proposed.

- Incentive and mitigation charge.
  A total charge of R4 100/t SO_4/annum is proposed and is made up of a R2 600/t SO_4 mitigation charge and an incentive charge of R1 500/t SO_4. The mitigation charge is deployed for desalination while the incentive charge is levied to incentivise the reduction of discharge at source through land-management options.

- Mitigation charge
  DWAF proposes a total cost of R3 000/t SO_4 for the mitigation charge. Under this scenario, a combination of source load reduction options are chosen based on cost effectiveness, and these options are implemented collectively:
  - rehabilitation of impoundments;
  - upgrade capacity of return water facilities; and
  - desalination.

Table 17: Proposed waste discharge charge for sulphate removal.

Load	**Running Cost (R/t sulphate removed)**
Incentive charge	10 250
Incentive and mitigation charge	4 100
Mitigation charge	3000

2.12.18 Summary

In summary, water quality impacts from tailings impoundments are important when considering the environmental impact associated with mining, both in terms of consequences and cost. Drainage from mining operations is generally of poorer quality than ambient water quality. Deterioration may occur through salt mobilisation, excessive alkalinity, or more generally acidity.

Acid mine drainage (AMD) is one of the most serious forms of water quality deterioration and is also directly responsible for much of the salinity produced from sulphidic tailings impoundments. Acidity is generated through oxidation of sulphide to sulphate to form sulphuric acid. AMD is often also laden with metals, as sulphide minerals commonly contain metals which are released upon degradation, or the sulphuric acid released reacts with other minerals to release salinity and metals.

Polluted drainage affects both surface and groundwater resources and thus requires that specific mitigation measures are implemented. Although surface water resources are more easily polluted than groundwater resources in general, groundwater is very difficult (if not impossible) to clean and is also very expensive to remediate.

Mitigation generally focuses on either containment or treatment of pollution. Containment may include various options, such as lining to prevent seepage, or building containment dams to prevent uncontrolled transport of polluted surface water into the environment. Prevention strategies such as covering and vegetating wastes to prevent seepage recharge and oxidation of sulphide materials can also be implemented.

Various treatment strategies are currently implemented where required, to prevent build-up of polluted water and subsequent impacts on environmental or water resources. The treatment methods most commonly in use at present include limestone-lime treatment of sulphate waste water to neutralise acidity and precipitate metals, biological sulphate reduction to remove excess sulphate, and reverse osmosis to remove salinity from polluted waters. Various combinations of these technologies may be used in practice.

The Department of Water Affairs and Forestry (DWAF) are currently contemplating the implementation of a waste discharge charge system (WDDS) in an attempt to prevent water quality impacts from mining and other detrimental activities. The system relies on the use of incentive and mitigation charges. Incentive charges are intended to provide to industry with incentives to reduce pollution whereas mitigation charges are intended to recover costs incurred mitigating impacts.

These systems rely on quantification of pollution loads through various methodologies, most commonly through scientific studies of affected systems and numerical modelling of geochemical and hydrological processes.

2.13 Soil and landform

> "Many of the problems that society confronts are of such complexity that it takes the greatest dedication and zeal to assemble the necessary data, analyze and prescribe. Happily there are other problems, where a very small perception can produce astonishing results. If one accepts the simple proposition that nature is the arena of life and that the modicum of knowledge of her processes is indispensable for survival and rather more for existence, health and delight, it is amazing how many apparently difficult problems present ready solution."
>
> Ian Mc Harg (Mc Harg, 1969)

2.13.1 Introduction

Tailings impoundments are perhaps the largest man-made landforms on earth. Although the mining industry contributes significantly to the South African economy through the extraction of minerals it also produces large amounts of waste tailings that requires disposal. Before an impoundment can be closed, it must be demonstrated that the structure poses no further harm to the environment. For this reason, it is important that the configuration and impoundment design is carried out in such a manner that future environmental impacts are managed and damage prevented. This section deals with the possible loss of tailings due to surface erosion as a result of surface water runoff. Figure 62 illustrates where the soil and land account ties in with the overall environmental aspects framework.

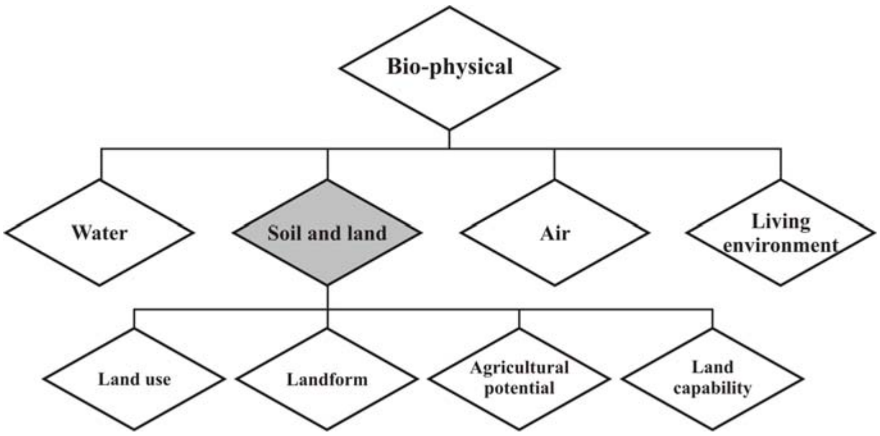


Figure 62: Simplified soil and land environmental aspects diagram.

Regulatory authorities will only issue a closure or exoneration certificate once it can be demonstrated that the tailings impoundment is safe, stable, and suitable for some sort of appropriate post-closure use. Most non-operational mine residue deposits in South Africa have not been officially closed. Geomorphic processes such as wind and rain will continue to reshape a tailings impoundment long after it has been abandoned (Figure 63, p. 135).

[1] DRD 2L24 tailings impoundment, a lunar-like landscape almost completely denude of vegetation.

[2] Pampas grass (*Cortaderia* sp.) growing within a silted-up paddock at the ERGO Daggafontein tailings impoundment.

Figure 63: State of a typical un-rehabilitated gold tailings impoundment.

The surface stability of a tailings impoundment affects both the off-site impact on the receiving environment as well as the integrity of the impoundment itself. The surface stability of the outer top surface and side slopes of tailings impoundments is one of the key considerations in assessing the impact of these facilities on the environment. The primary three key decision considerations comprise impacts under the tailings facility footprint, outside the footprint and on the impoundment (Figure 64). Key aspects are the impact of the impoundment on the sediment load within and outside the footprint. It is important to quantify the impact and demonstrate that the remedial measures ensure an acceptable long-term outcome.

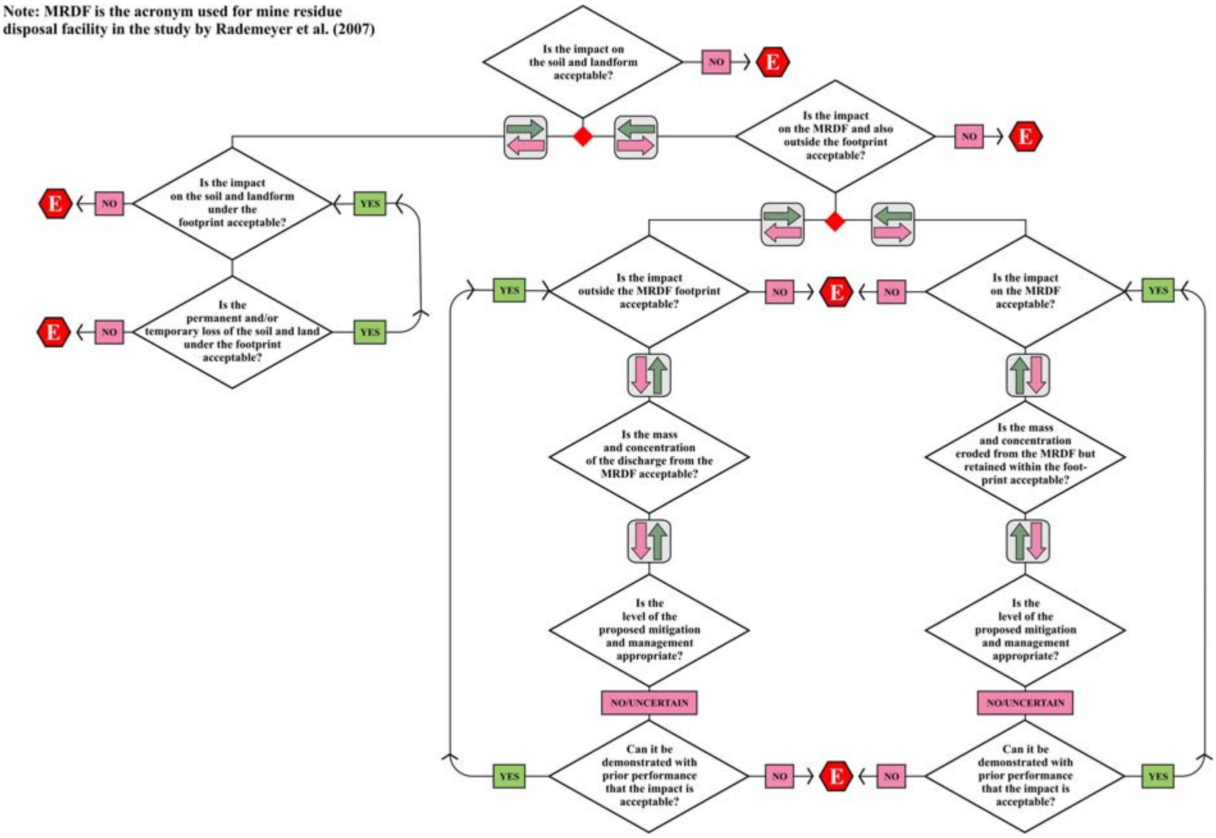


Figure 64: Surface stability decision framework (Rademeyer et al., 2007).

The Universal Soil Loss Equation (USLE) was originally developed to quantify soil erosion of agricultural land. The Revised Universal Soil Loss Equation (RUSLE) was adapted for mining conditions and its use on tailings impoundment side slopes is still being researched empirically. Although this is a limitation, the RUSLE is considered adequate to be used to guide decision-making and provide a preliminary indication of erosion resulting from surface water runoff (Rademeyer et al., 2007).

The close interrelationship between soil and landform (Figure 64) requires the study of the latter. Landform includes the slope factor and the assemblage of hill slope units. Agents of erosion typically include water, wind, glaciers and anthropogenic activities. Erosion includes a group of processes by which earth materials are entrained and transported across a given surface. Soil loss is that material actually removed from the particular hill slope or hill slope segment. The loss may be less than erosion due to on-site deposition. The sediment yield from a surface is the sum of the soil loss minus the deposition at the toe of the hill slope (Renard, Foster, Weesies, McCool and Yoder, 1996).

The purpose of this section is to present literature on tailings impoundment embankment slope erosion, discuss typical management measures, and describe:

- the importance of the subject;
- agents of erosion;
- parameters influencing erosion;
- erosion prediction equations; and
- the Revised Universal Soil Loss Equation (RUSLE).

2.13.2 Tailings impoundment slope erosion

Tailings impoundments permanently alter the topography of the area where they are constructed and will exist for many years. They are also likely to impact on the environment as they respond to natural forces which erode and level the surrounding landscape. This means that tailings impoundments have a long-term effect on the environment. The management of these structures must therefore continue until such time as the deposited tailings is assured to be permanently stable and environmentally innocuous (Vick, 1983).

Sometimes impoundments are designed with the steepest slopes possible consistent with slope stability for economic reasons forgetting that surfaces of steep slopes can erode excessively resulting in long-term costs to repair erosion which may exceed savings from such steep embankment slopes.

Losses of residue from gold mine residue deposit embankment slopes as much as 500 t/ha/annum have been measured resulting in maintenance problems and environmental impacts (Blight, 1991). Blight also states that vegetated tailings slopes can lose up to 200 t/ha/annum tailings as a result of erosion caused by surface runoff. Blight and Amponsah-Da Costa (2001) states that the loss of tailings by wind erosion may be as high as 1500 t/ha/annum or a depth of about 100 mm per annum.

Agents of erosion

When considering the erosion of slopes, both wind and water erosion must be considered (Blight and Amponsah-Da Costa, 1999 and 1999a). Wind is particularly a problem in arid regions where it is difficult to establish vegetation. Water is a problem in humid regions where it is easier to vegetate.

Baldwin, Shelton and Wall (1987) states that the rate of erosion by water is controlled by:

- Rainfall intensity and runoff
  The impact of raindrops on the surface can break down and disperse the aggregate material. Lighter material can be easily removed by raindrop splash and runoff water whereas greater raindrop energy and runoff is required to move the larger particles. Movement by rainfall is usually the greatest and most noticeable during short-duration high-intensity thunderstorms. Runoff can occur whenever there is excess water on a slope that cannot be absorbed into the soil or trapped on the surface. Compaction can also cause an increase in the amount of runoff.

- Soil erodibility
  Soil erodibility is an estimate of the ability of soils to resist erosion, based on the physical characteristics of each soil. Soils with faster infiltration rates and improved structure have a greater resistance to erosion. Decreased infiltration and increased runoff can be a result of compacted subsurface soil layers. Past erosion has an effect on the erodibility. Exposed subsurface soils on eroded sites tend to be more erodible than the original surface because of the decreased strength due to exposure.

- Slope gradient and length
  Generally the steeper the slope, the greater the amount of soil lost from erosion by water. Erosion increases as the slope length increases due to the greater accumulation of runoff and increased velocity of water which permits a greater degree of scouring.

- Vegetation
  Erosion potential is increased if there is very little or no vegetative cover. Cover protects the soil from raindrop impact and splash, slows down the movement of surface runoff and allows excess surface water to infiltrate.

According to Baldwin et al. (1987), the rate of erosion by wind is controlled by the following factors:

- Erodibility of soil
  Very fine particles can be suspended by the wind and then transported great distances. Fine and medium size particles can be lifted and deposited, while coarse particles can be blown along the surface. The abrasion that results can reduce soil particle size and further increase the erodibility.

- Soil surface roughness
  Rough surfaces offer more resistance to wind erosion than smooth ones.

- Climate
  The speed and duration of the wind have a direct relationship to the extent of soil erosion. Soil moisture is also a factor. Maintaining a wet surface will reduce wind erosion however; this may conflict with other management strategies for promoting consolidation of tailings.

- Bare distance
  The lack of windbreaks allows the wind to put particles into motion for greater distances thus increasing the abrasion and erosion.

- Vegetative cover
  The lack of permanent vegetative cover results in extensive erosion by wind. Loose, dry, bare soil is the most susceptible.

Parameters affecting erosion

Blight (1989) and CM (1996) identify the most important parameters affecting erosion of the slopes of gold tailings impoundments in South Africa as:

- shear strength of the slope surface determined by the type of cover;
- the length of the slope and hence the quantity of water collected by the slope in a storm of given intensity; and
- the slope angle which largely controls the velocity with which water runs down the slope.

The forces of erosion are resisted by the strength of the material composing the slope surface. If it is loose and not compacted, it will erode easily. If it is compacted or armoured by being covered with a layer of large particles, it will better resist erosion. Blight and Amponsah-Da Costa (1999) showed that an 'erosion rate surface' exists in a slope angle-slope length-erosion loss space as shown in Figure 65.

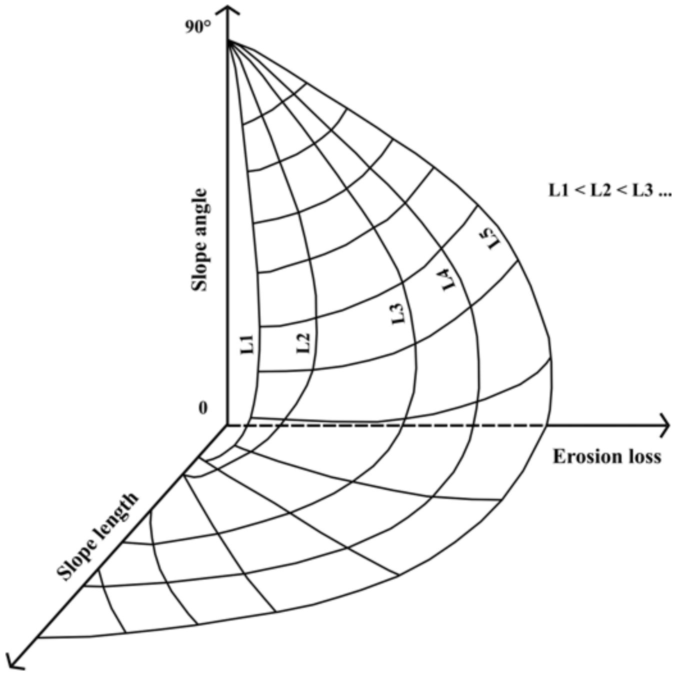


Figure 65: The erosion rate surface showing the effects of slope length and slope angle on rates of erosion from the outer slopes of tailings impoundments (Blight and Amponsah-Da Costa, 1999).

The surface shows that erosion rates increase with slope length but are low both at very flat and very steep slope angles. Maximum erosion loss occurs at intermediate slopes which is the range of slopes usually used for tailings impoundments.

Erosion resistant slopes

A structure is considered to have failed when it releases more tailings than a specified limiting value. This limiting value may be set by regulators or determined from an assessment of acceptable environmental impact. To determine the acceptability it is required to know how structures degrade, over what time, and the resulting rate of tailings release. To prevent problems it is important to consider the long term stability from the onset of planning a tailings impoundment.

Objectives for a tailings impoundment design and closure planning must include the following:

- Environmental protection
  Tailings solids must be contained to avoid their distribution, at intolerable rates, into the environment by surface and sub-surface erosive forces.

- Aesthetics and land use
  The impoundment configuration and cover should be rehabilitated to lessen the aesthetic impact of the tailings deposit and permit an appropriate long term post-closure land use.

- Disruptive forces
  These can be short term, such as floods and fires which apply forces to the impoundment in excess of what it was designed for, or long term, which include the slow but continual action of forces which bring about deterioration in the form of water and wind erosion, weathering and chemical change of tailings.

According to CM (1996) the design of the outer walls of mine residue deposits is dependent on the operational factors as well as considerations relating to ultimate closure or rehabilitation of the residue deposit. If space is not a problem, slopes as flat as 15˚ to 20˚ (approximately 1:4 to 1:3) must be designed for. This will reduce erosion by water runoff (provided the slope length is broken by berms) and will simplify application of a cover to the slope and reduce maintenance after closure. Where space is not available, both the slope of the deposit and the rate at which it is to be built may become crucial factors.

The method of placement mainly determines the angle at which a residue slope is placed while the stability considerations determine the overall angle of the slope. Erosion losses reach a maximum for slope angles of between 25˚ and 35˚. While vegetative cover on a slope inhibits wind erosion, it does less to prevent erosion by water. However, raindrop impact is reduced by vegetative cover and the roots of vegetation assist by reinforcing the surface. The conclusions regarding slope length and angle are shown schematically in Figure 66.

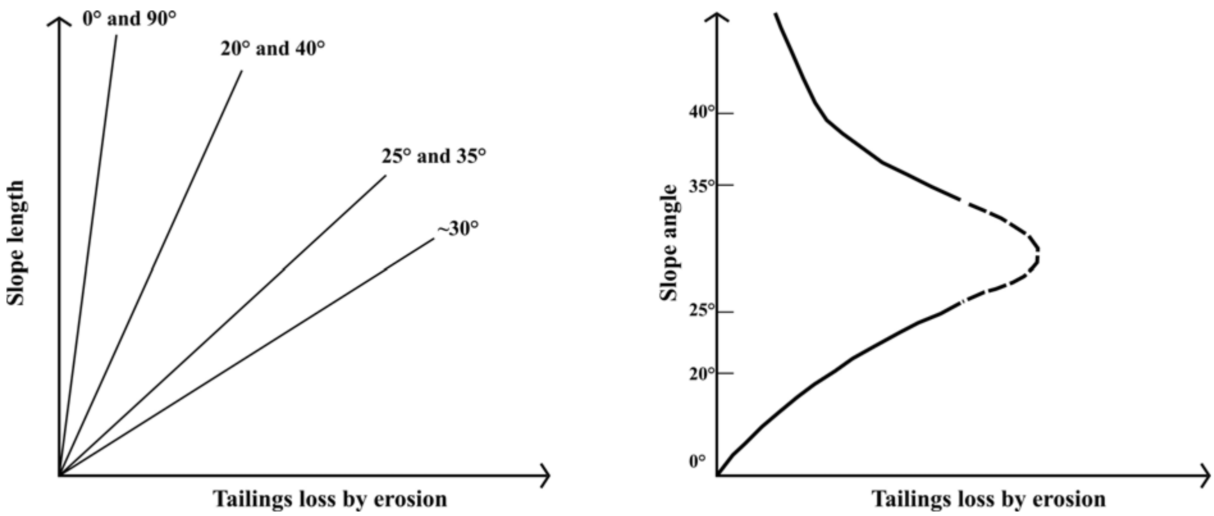


Figure 66: Effect of slope length and slope angle on rates of erosion from the outer slopes of tailings impoundments (CM, 1996).

2.13.3 Estimating soil loss

The revised universal soil erosion (RUSLE) equation and approach is used as the basis to discuss the evaluation of soil loss in this section. In practice the equation is mostly used for estimating soil loss for undisturbed lands experiencing overland flow, from lands undergoing disturbance, and from newly or established reclaimed lands. The RUSLE may also be used as a part of the procedures to prepare permit applications and to assess reclamation success in support of bond release (Renard et al., 1996).

The equation is:

$$A = R.K.LS.C.P \tag{29}$$

Where:
A = average annual soil loss in tonnes per acre per year (t/ha/annum)
R = rainfall/runoff erosivity (MJ.mm/ha/h/annum)
K = soil erodibility (t.h/MJ/mm)
LS = hill slope length and steepness (dimensionless)
C = cover-management (dimensionless)
P = support practice (dimensionless)

Factors

The six factors used in the RUSLE are summarised:

- Rainfall / runoff erosivity (R)
  Analyses of data indicates that when factors other that rainfall erosivity are held constant, the soil loss is directly proportional to a rainfall factor composed of total storm kinetic energy (E) times the maximum 30 min intensity (I_{30}) (Renard et al., 1996).

  E may be calculated from the following equation:

  $$E = R.[\,11{,}8975 + 3{,}7922\,log(\,I\,)] \tag{30}$$

  Where:
  E = kinetic energy in $J.m^{-2}$
  R = rainfall (mm)
  I = rainfall intensity in mm/h

  Collected data showed that the rainfall factor used to estimate average annual soil loss must include the cumulative effects of both moderate-sized storms and occasional severe ones. The numerical value used for R in the RUSLE must quantify the effect of raindrop impact and reflect the amount and rate of runoff likely to be associated with the rain. Rainfall energy on its own is not a good indicator of erosive potential.

- Erodibility (K)
  The material erodibility can be viewed as the change in the material as per unit of applied external force or energy. The erodibility factor signifies the resistance of soil or surface material to erosion, how movable the sediment is and the amount and rate of runoff. This factor is based solely on soil properties. Fine textured soils that have a high clayey content have low K value because the particles are resistant to disconnection. Coarse textured soils, even though they are

easily disconnected, also have low *K* values because of high infiltration which results in low runoff. The permeability of the soil also affects the *K*-factor because with an increase in infiltration, runoff decreases and so the erosive potential of the water is decreased.

- Slope length and steepness (*LS*)

  The slope length is the horizontal distance from the toe to the point where either the slope gradient decreases enough that deposition occurs or where the slope ends. Erosion increases as slope length (*L*) increases. The slope steepness factor (S) reflects the influence of slope gradient on erosion. As the slope length increases, the soil loss per unit area increases due to the progressive accumulation of runoff and as the slope gradient increases, the velocity and erosivity of runoff increases.

  In general slopes that are both steep and long tend to produce the greatest erosion because they generate runoff that is high in both velocity and volume (Figure 67). It has been found that this is only true for slopes up to 50 ° because at steeper angles the exposure of the slope face to rainfall grows rapidly smaller (Marsh, 1997:231). The slope steepness factor (*S*) and length factor (*L*) have been combined into an equivalent factor (*LS*) as they are highly related. Some research has examined natural soils to determine possible steady state equilibrium slope length and angle relationships. However there is very little evidence of these relationships for long term stability of tailings. It may be that the definition of acceptable long term loads is a more reliable method of assessing acceptability of long term impact and that new definitions should be developed to incorporate tailings.

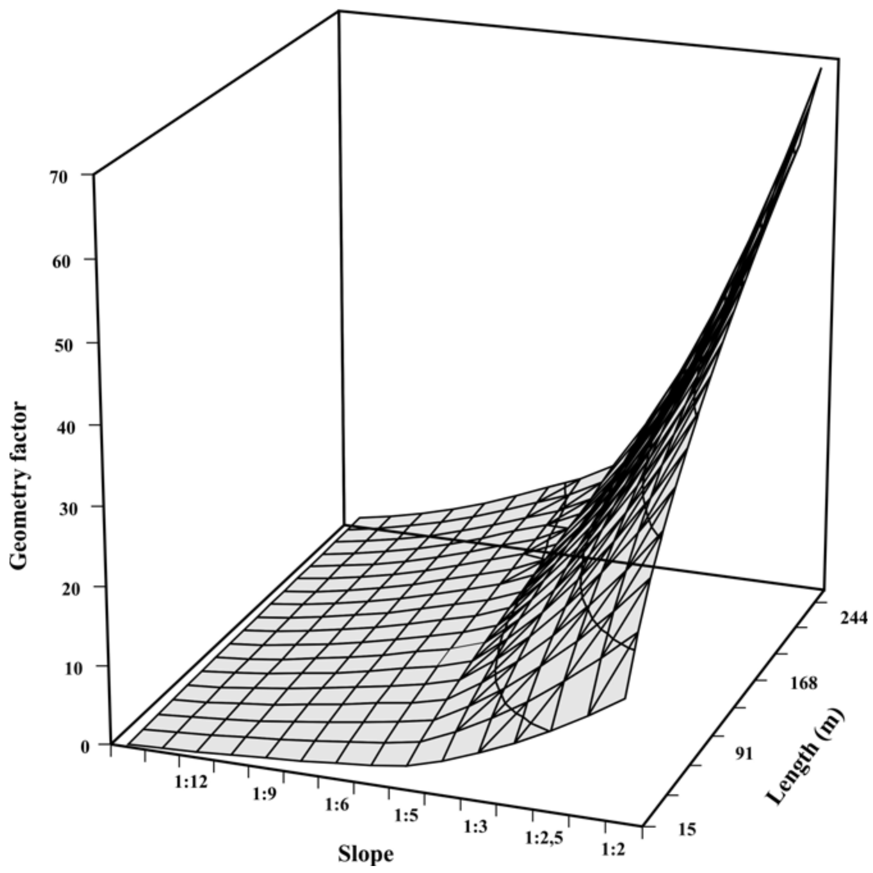


Figure 67: Slope geometry factor based on steepness and length.

- Cover management (*C*)
  The cover management factor (*C*) represents the effects of vegetation, management and erosion control practices on the soil loss. The factor can range between 1 and 0,003 and is difficult to estimate and vary during the year. Cover protection can comprise vegetative or physical techniques and has the most significant influence in erosion protection of all the factors affecting erosion, given a fixed slope. Vegetative cover protection consist of managed vegetation cover or constructed vegetation supporting cover systems, while physical covers include engineered covers such as rock cladding and armouring (Rademeyer et al., 2007).

- Support practice (*P*)
  The support practice factor (*P*) is the ratio of soil loss with a specific support practice to the corresponding loss with straight-row upslope and down slope tillage. It accounts for control practices that reduce the erosion potential of the runoff by their influence on drainage pattern, runoff concentration, runoff velocity and hydraulic forces exerted by runoff on soil.

Limitations of RUSLE

The revised universal soil loss equation (RUSLE) is a product of research with the aim of formulating a technology to quantify losses due to erosion. The RUSLE consist of six factors and although research has been conducted on its use in the mining environment, it is uncertain to what extent the RUSLE can be used on tailings impoundments. Tailings impoundments differ from agricultural farmlands in terms of material characteristics, slope steepness (steeper slopes), and slope length (shorter slopes).

The limitations of the RUSLE are similar to those of the USLE (Evans and Loch, 1996) which are:
- the RUSLE provides soil loss estimates rather than absolute soil loss data;
- the soil loss estimates are long-term average rates rather than precipitation-event-specific estimates;
- there are slope length and angle limits for *LS*-factor component of the RUSLE equation; and
- the use of the RUSLE in geographic areas beyond its certification should be used with caution.

Blight considered the universal soil loss equation (USLE) approach to soil erosion prediction and concluded that it does not extrapolate well to the much steeper slopes of mine residue deposits. Because agricultural fields invariably have flat slopes, it is generally not possible to extrapolate the results of studies on agricultural erosion to the very steep slopes of mine residue deposits (Blight, 1989). The USLE and RUSLE combine the effects of slope length and angle in the term *LS*, whereas slope angle and length each have independent effects on erosion rates.

2.13.4 Practices for reducing surface erosion

It is important to prevent or minimise erosion because repairing damage is costly and the surrounding environment should be protected from pollution by wind and water borne fugitive tailings (Blight and Amponsah-Da Costa, 1999 and 1999a).

According to the Guidelines for Environmental Protection (CM, 1996), to control and reduce damage to the slopes of a tailings impoundment caused by erosion:

- Slope lengths should be reduced by the introduction of berms or step-back (Figure 68, p. 143). Experience has shown that the vertical distance between berms or step-back should not exceed 9 m, although 5 to 6 m would be even better.
- Impoundment crests and the edges of berms should be graded away from the edge to prevent water flowing over the edge. Water must then be drained from the surfaces of berms by means of penstocks and pipes or armoured surface drains. Water may be held on the berms to evaporate but this water must be prevented from accumulating in low spots on the berms and overtopping the berm edge. This may result in disastrous erosion of the slope.
- Slopes should be vegetated as soon as possible. This will reduce wind and water erosion.
- Material will therefore be lost from the slopes of the tailings impoundments provision should be made to catch the lost material at the toe of the impoundment by silt catchment paddocks or silt traps. These must be designed so that they can be easily de-silted and a minimum freeboard of 0,5 m is maintained.

Slope lengths should be broken by berms even when the slope is relatively flat. Severe erosion can occur even on a flat slope if the slope length is too long. Water accumulates down the lengths of a slope and the worst erosion therefore occurs at the bottom of the slope.

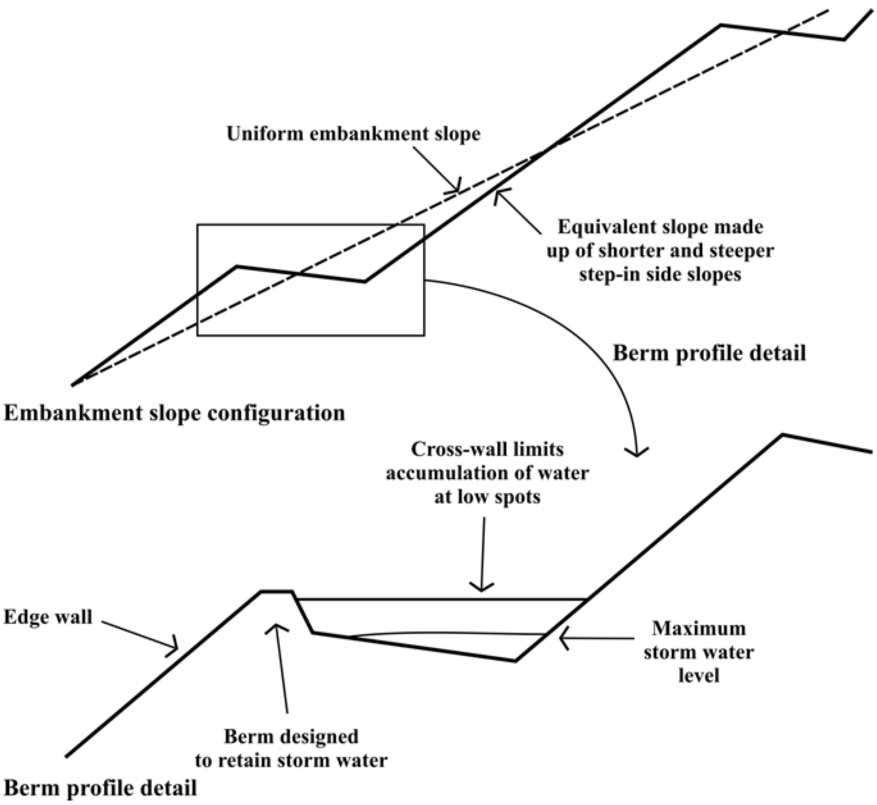


Figure 68: Tailings impoundment embankment side slope and berm details (CM, 1996).

Obstructions that roughen a slope surface help reduce erosion losses by dissipating the energy of water or wind moving over the slope. It is recommended to leave the soil surface in a roughened state, using mulch or a temporary cover crop, contouring, terracing and establishing sustainable vegetation as effective erosion control measures.

Water erosion of the top surface can be prevented by crest walls that subdivide the surface of the impoundment into paddocks (Blight, 1991). Crest walls also prevent precipitation on top of the impoundment from falling down the outer slopes and increasing the potential for slope erosion.

Specific surface management practices are known to reduce erosion. However there is still very little quantitative information on the success of these practices. The following typical practices are in use with varying success:

Reshaping

The main object of reshaping embankments is to produce slopes whose angles, lengths, and shapes are stable, suitable for the proposed final land use, and not prone to an unacceptable rate of erosion. This should be integrated with the final cover and surface water control system which must be capable of conveying runoff without risk of erosion and sedimentation. Storm water control measures are required to ensure minimum damage to slopes and other structures during heavy rain storms.

Erosion control through terracing

A means of controlling surface flow is to construct graded terraces (benches) at intervals down the slope. The effect of these is to divide a long slope into a series of short ones with the catchments area commencing at each terrace. This prevents the runoff from reaching a depth of flow or velocity, which could cause erosion. Graded terraces have an advantage of providing erosion protection as well as drainage of runoff to selected points. However, to achieve this function they must be constructed within close tolerances of shape, capacity, and gradient. The gradient is selected according to soil type, channel shape and vegetation cover, to maintain the flow below an erosive velocity. The use of benches is standard practice for most new tailings impoundments.

Covers

Rock cladding

As an alternative means of reducing erosion, the slopes of an impoundment can be clad with rock. The rock cladding is usually pervious and water running down a rock clad slope will tend to run at the interface between the rock and the underlying tailings. This water will cause erosion unless a geofabric or a filter layer is provided at the rock-tailings interface.

Armouring

Using armouring (gravel materials mixed with fines to reduce the permeability) can overcome the shortcomings of rock cladding and may be a cheaper alternative to protect slopes against erosion, depending on earthwork cost versus geotextile cost.

Vegetation

Establishing a vegetative cover can be an option. Depending on the nature of the tailings it is usually required to reseed bare patches. The choice of seed mix should also be investigated to ensure the correct species are used. Additional cover of seed is necessary to ensure proper germination. Very often nutrient deficiencies are the major factor which influences poor vegetation cover and it is so simple to rectify the problem. The correct type of fertiliser application could be determined by means of sampling and assaying. In some cases it might be necessary to re-apply ameliorates such as lime or compost. More resistant types of vegetation should be identified and established on tailings impoundments with unfavourable vegetation growth medium properties. In severe conditions where slopes are excessively steep slopes and dry climatic conditions prevail it might be necessary to change the normal vegetation establishment practices.

2.13.5 Integrated soil and landform planning

Decision making involved with impoundment landscape planning and design require the involvement of many stakeholders such as planners, designers, landscape architects, engineers, scientists and others integrating the aesthetic, functional, economic, political and philosophical dimensions. The detailed nature of environmental planning and design requires joint working between planning professionals, the public, landowners and land users.

Integrating environmental planning with design, of which principles are discussed in Section 2.7.6, is best demonstrated by means of an example. The example illustrates the design of a tailings impoundment based on landform design principles and guidelines. The result envisages a sustainable landform which is the outcome of an iterative planning process. These principles and guidelines are hypothetically applied to a typical site in the Rustenburg region (Figure 69) that is suitable for depositing tailings from a platinum mine and strives to achieve the following objective:

> "To design a tailings impoundment (landform) that will support a suitable surface cover which will support a diversity of habitats with the aim of establishing a sustainable and regenerative landscape for the long-term benefit of the natural and social environment."

Photograph courtesy of Mader van den Berg.

Figure 69: Panorama photograph of a proposed tailings impoundment site in the Rustenburg platinum mining belt.

To achieve the preferred land use, several ecological principles and guidelines are derived from natural landforms and systems that feature similarities with tailings impoundments. These principles and guidelines inform the technical design response which is a function of geometric configuration and surface cover. Innovative design responses are required to fulfil the goal of a sustainable and regenerative landform design. Three main aspects that need to be considered in order to establish a sustainable and regenerative landform are:

- surface stability;
- habitat creation; and
- aesthetics.

Surface stability

Surface stability refers to the erosive potential of the material on the surface that is exposed to the environmental conditions. Some of the main factors that affect surface stability are:

- surface cover;
- slope configuration;
- climate; and
- surface management practices.

Surface cover

Surface cover refers to the material layer on the surface of a tailings impoundment as well as the vegetation cover that may be established in the rehabilitation stage. The outer slopes of a tailings impoundment mostly consist of the coarser fraction of the tailings which are exposed to the climate and are most prone to erosion. Studies have shown that unprotected slopes of gold tailings in South Africa can erode at a rate up to 500 t/ha/annum (CM, 1996:69). This is mainly due to the low cohesion forces that exist between the tailings particles and the impacts of wind and water erosion. Figure 70 indicates, if tailings was compared to natural soils, the water velocity thresholds for comparable particle size. Water velocities of 0,5 m/s and higher will dislodge the material.

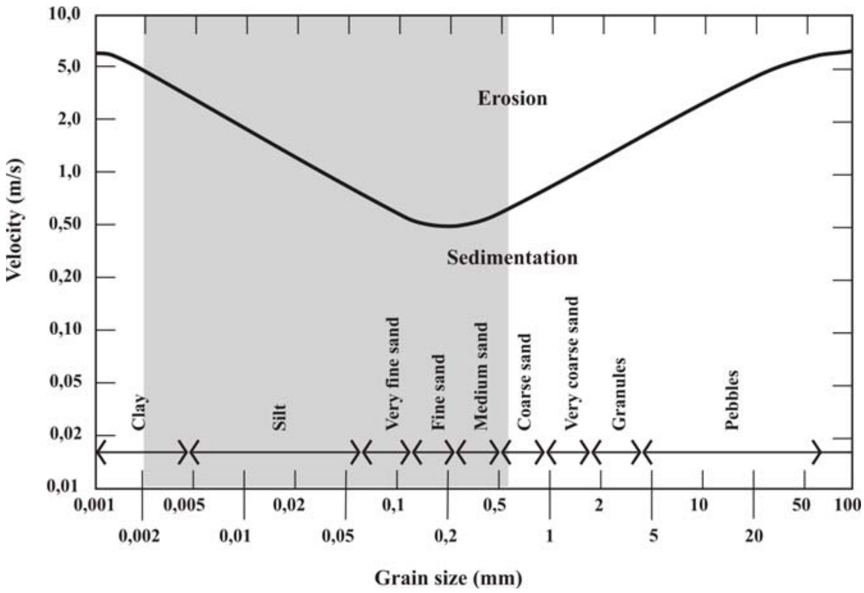


Figure 70: Water erosion thresholds for natural soil particles with the shaded section indicating the area where it is expected that tailings anthropogenic soils would fit (Marsh, 1997:231).

During rehabilitation the material layer may consist of the following or a combination thereof:

- tailings in situ (no cover);
- topsoil;
- rock cover; and
- armouring consisting of a rock and soil mixture.

The vegetation cover on tailings impoundment could consist of:

- no vegetation (no cover);
- grass cover; and
- diverse vegetation with a diversity of species.

Slope configuration

Slope lengths and gradients affect surface erosion. Studies have indicated that a steeper slope gradient and long slope lengths increase water erosion considerably (Blight, 1989). The introduction of benches in the slope configuration of tailings impoundments partly impedes high erosion rates, but a reduction in slope gradient and the application of appropriate surface covers will further increase erosion control. Marsh (1991 and 1997) describes slope configuration in its most basic forms; straight, concave, convex and S-profile (Figure 71, p. 147).

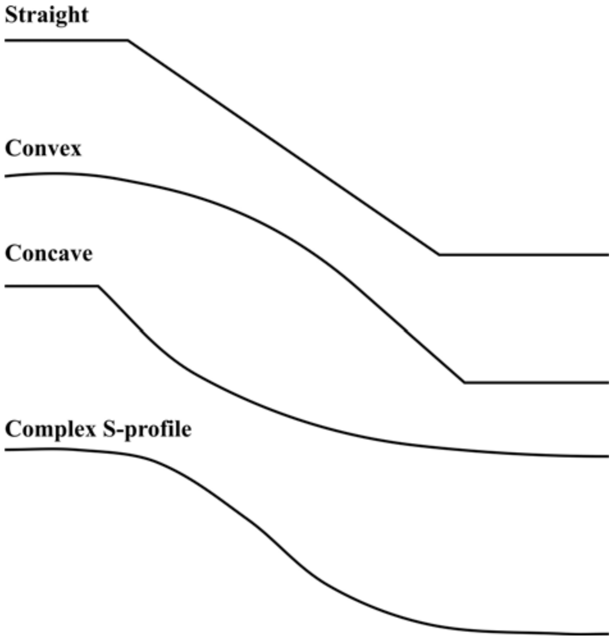


Figure 71: Basic slope profiles.

Smooth S-profile slopes usually indicate long-term stability and a state of equilibrium among slope forces, i.e. erosion and deposition. It is expected that the forces of erosion and deposition will act upon natural slopes until an angle is reached which, for a given soil type, is in equilibrium with the effects of catchment area, runoff volume and vegetation cover. This results in a slope which becomes progressively flatter towards the bottom so that flow velocity is maintained at a roughly constant, non-erosive value.

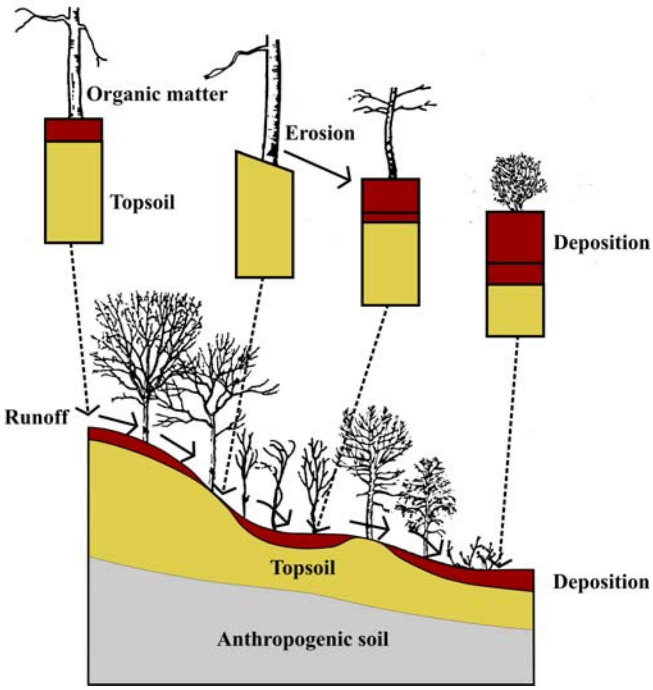
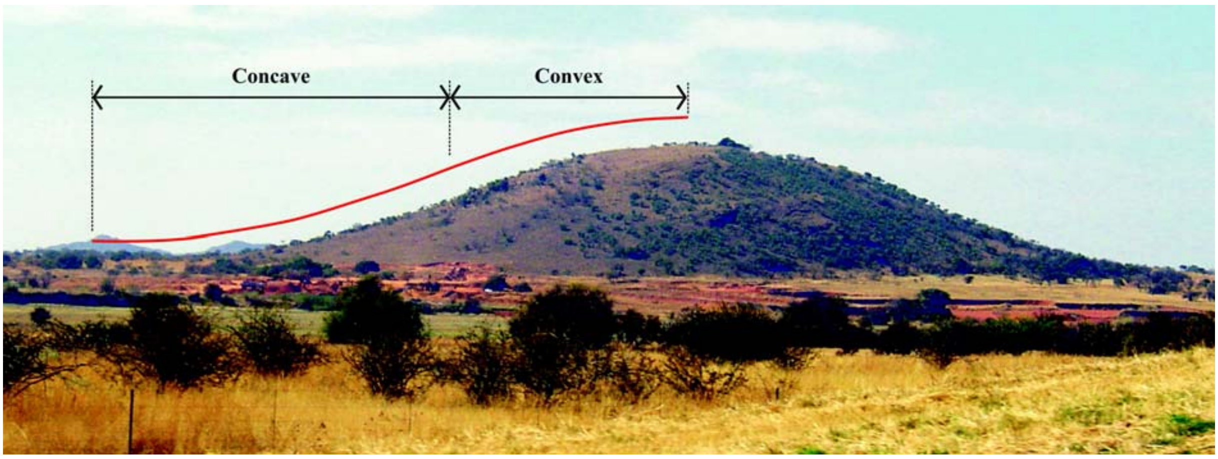


Figure 72: Effects of erosion and deposition (Marsh, 1997:102).

Figure 72 (p. 148) illustrates the dynamics between erosion and deposition of natural mineral soils. Geomorphologic principles are responsible for the shaping of a landform. Clear contrasts exist between natural landforms (Figure 73) and man-made tailings impoundment landforms (Figure 74) regarding the slope configuration and the vegetation cover. The design and operation of tailings impoundments need to take cognisance of these land forming principles to convert to a sustainable landform once rehabilitation is implemented.



Photograph courtesy of Mader van den Berg.

Figure 73: Slopes profile of a natural landform.

Figure 74: Typical side slope profile of an upstream constructed ring-dyke gold tailings impoundment.

In order to implement these land forming principles successfully, geometric alterations are necessary to the conventional tailings impoundment design. Geometric alterations to tailings impoundments should occur within the parameters of geotechnical stability which is greatly dependent on the character of the tailings material. In order to propose viable geometric alterations one has to do a thorough assessment of the opportunities and constraints of the possible surface cover (Section 2.13.2).

The following factors must be considered to decide which covers are most suitable:

- particle size distribution;
- material texture (Figure 75, p. 150);
- material composition; and
- chemical properties.

The combination of physical and chemical properties provides the surface cover with a specific character with unique attributes that respond to environmental conditions in a predictable fashion. Environmental conditions are a function of the climate and the dynamics of energy in the region where the tailings impoundment is situated (see below).

The character influences the following factors:

- angle of repose;
- erosive potential;
- geotechnical stability;
- water infiltration rate and absorption capacity; and
- potential to sustain vegetation.

The character of platinum tailings can be described according to the soil texture triangle that is used to classify soil (Figure 75). On the soil texture triangle, platinum tailings particle size will fall in the sandy-loam soil section. When analysed, tailings typically consist of 10% - 40% silt fraction, 60% - 90% sand fraction and a negligible clay fraction (CM, 1996:19). Natural soils with similar characteristics are colluvium deposits found at the toe of slopes formed by slides and runoff. These soils generally drain very well and have a gentle slope angle due to the relatively high erosion potential.

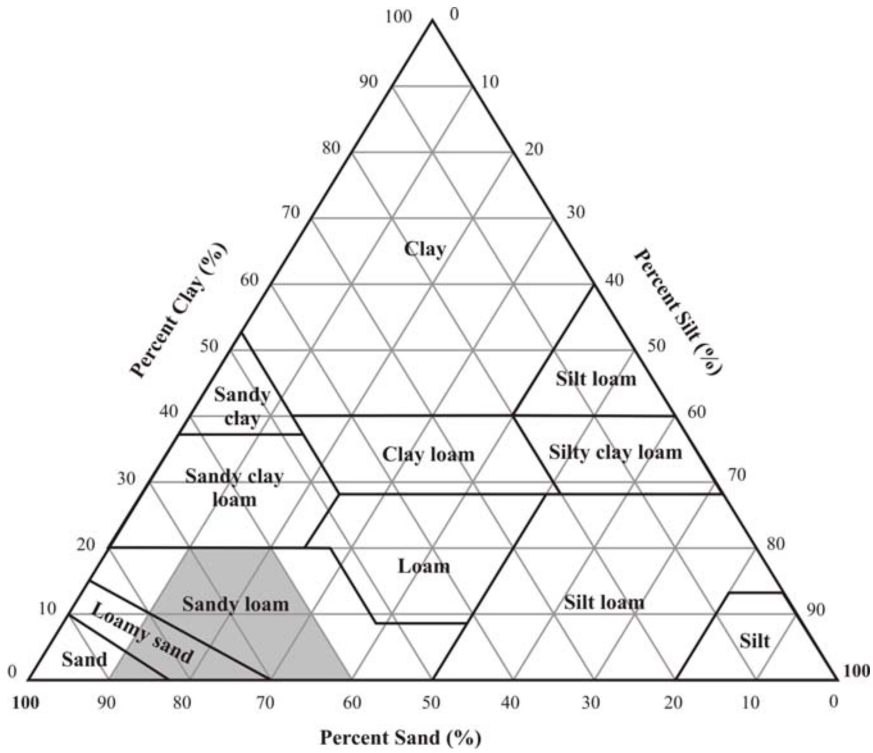


Figure 75: Shaded section indicates area where it is expected that tailings anthropogenic soils would fit if the soil texture triangle for natural soils is applied (Marsh, 1997:96).

By comparing the characteristics of the tailings with similar soils one can at least get some sort of first order understanding of what the tailings anthropogenic soil's response to environmental conditions might be. It is evident that the current deposition angle of 33° will continue to erode until a stable angle is reached which is in equilibrium with the relevant region's eroding conditions. The current approach to this problem is either the continuous re-placement of material eroded off the side slopes and contained in the paddocks or unsuccessful attempts to vegetate the surface in order to stabilise the surface. Both these practices are proven to be unsustainable in the long term.

Climate

Climate describes the environmental conditions of the site where the tailings impoundment is proposed. The climate has an effect on the surface stability of the tailings impoundment in that it has the potential to weather/erode the surface material to a state of equilibrium.

Surface management

Surface management refers to the human practices that alter the surface conditions. Such practices are needed to maintain surface stability of a tailings impoundment during operation and rehabilitation. The surface management that is required to achieve a sustainable and regenerative landform would typically include; shaping of the side slopes, amelioration of the surface with alternative surface coverings and vegetating of the tailings impoundment. These rehabilitation practices can be costly and it is therefore important that the foregoing principles should be included in the early design stages of a tailings impoundment to achieve an end land use that does not require major shaping and amelioration expenses.

Habitat creation

Habitat creation can only be successfully accomplished after a comprehensive analysis of the surrounding landscape and its landforms. This includes the specialist field of ecology to resolve the multi-faceted problems.

To create habitat for fauna it is necessary to provide appropriate food sources and suitable environments for reproduction. Faunal habitat is often dependent on floral distribution and therefore the focus is on creating suitable habitats for vegetation. Figure 76 provides a simplified analysis of the western slope of an adjacent landform. It indicates the vegetation communities that occur on different sections of the slope and an in depth study will also disclose knowledge of the growth medium, nutrients, water availability and micro climate.

Figure 76: Local types of vegetation communities can be of uses when selecting suitable plant species for rehabilitation purposes (van den Berg, 2004).

The growth medium is a function of the surface covering, featuring characteristics of moisture retention and nutrient availability. Tailings is generally a poor growth medium and requires extensive amelioration to sustain a healthy vegetation cover. Isabel Weiersbye from the School of Animal, Plant and Enviroscience at the University of the Witwatersrand, South Africa, is the programme leader of an initiative to test the performance of woody and semi-woody plant species in the containment of pollution from gold tailings impoundments.

According to Weiersbye grasses alone produce too little organic litter, nitrogen and potassium which are necessary to keep the whole ecosystem functioning and to ensure a healthy vegetation cover. It can however be achieved with woody species and experiments on the Harmony's Freegold tailings impoundment in Welkom are currently underway (Knoll, 2004:25).

Micro climate refers to the surface climate resulting from a combination of macro climatic and surface conditions and is influenced by factors such as:

- slope aspect;
- depth of suitable growing medium; and
- slope gradient.

Northern and western slope aspects in the Rustenburg region feature similar vegetation distributions and densities. The southern and eastern slopes are considered cooler and wetter slopes due to the smaller inclination angle of the sun's rays, thus less evaporation and energy absorption. Slope aspect will greatly influence the design response when one has to select between the different surface covers.

One approach to providing a suitable growth medium is to cap a tailings impoundment with a consistent depth of topsoil over the whole impoundment. This approach is insensitive to the demands of different vegetation species and to the slope aspect. The capping of a tailings impoundment with a suitable growth medium is very expensive but strategic placement of thicker layers of topsoil will considerably increase the spectrum of species that can be established on the tailings impoundment and aid subsequent rehabilitation success.

Slope gradient influences water infiltration and retention in the surface layer. A porous surface layer with a high organic material content will be able to effectively absorb available water on steeper slopes, thus reducing surface water run-off and possible erosion. It is important to coordinate the placement of different surface covers and depths of covers on varying slope gradients in order to maximise rehabilitation success. Figure 72 (p. 148) illustrates the dynamics in nature and the principles that need to be included in tailings impoundment design.

Slope gradient is usually a determining factor when considering human "habitats". Slope gradient place certain restrictions on development and should be understood during the design of the tailings impoundment in order to increase the range of future land uses on the impoundment. Figure 77 provides information regarding the maximum slope gradient for various land uses. The conclusion that can be drawn from the figure is that lower slope gradients have the capacity to facilitate a wider range of land uses.

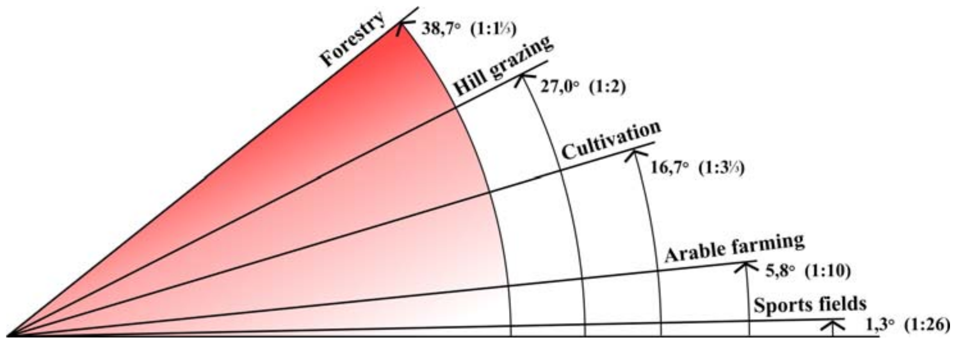


Figure 77: Typical land uses as a function of slope steepness.

Aesthetics

Three surface covers are photo realistically simulated in Figure 78 and indicate the difference in visual perception with regards to altering the surface cover. The scenario with the diversity of vegetation species can easily be mistaken for a natural landform and it is assumed that alterations to the overall geometry of the tailings impoundment will further contribute to the camouflaging effect (Rademeyer and van den Berg, 2005).

Rock cover

Grassed

Diverse vegetative cover

Figure 78: Visual simulations for different tailings impoundment surface covers.

The visual perception of tailings impoundments is addressed in detail in Section 2.10. The visual perception study aims to determine critical threshold distances of detection and recognition of a tailings impoundment with different geometric alterations and surface covers. The effectiveness of mitigation is measured against the capability to "camouflage" the tailings impoundment with its environment and to reduce visual impacts.

Five factors influencing camouflage are:

- silhouette;
- shape;
- surface;
- shadow; and
- size.

2.13.6 Summary

The South African mining industry is required to control erosion when constructing tailings impoundments. Wind and water are the two major agents of erosion with wind being more predominant in dry climatic regions and water in more predominant in wet regions. Although water and wind erosion differ, the type of protection from both is similar and the application of covers to prevent water erosion may prevent wind erosion as well. An impoundment must be safe, stable and suitable for some sort of post-closure use before a closure certificate can be issued. The tailings must also be contained within the area demarcated for the purpose and access is also usually restricted onto the facility for safety reasons.

From a landscape architectural point of view, when designing a tailings impoundment, some of the main aspects to take into consideration are:

- erosion;
- habitat creation;
- aesthetics;
- economic considerations; and
- long-term stability of the tailings deposit.

The erosion of tailings impoundment embankments resulting from surface water runoff is affected by:

- slope length;
- slope steepness; and
- surface roughness (cover).

A two-branched correlation exists between the slope angles of gold tailings impoundments and the rate of erosion with very flat very steep slopes erode less than slopes of intermediate angle. It is for this reason that Blight and Amponsah-Da Costa (1999 and 1999a) developed the three-dimensional "erosion sail' diagram with axes of slope length, slope angle and erosion loss (Figure 65, p. 138).

The quantities of soil eroded off embankment side slopes can be significant and requires careful forethought in the design and management of especially tailings impoundment embankments.

Deciding on an ideal tailings embankment slope configuration is complex. It may be useful to consider how natural slopes are formed and apply the same principles to tailings embankment slopes. Unfortunately the argument is not that simple as only equivalent soil slopes can be considered and also because of the time scale. Natural soil slopes tend to flatten over time.

To improve on the current depositional models in use key factors should be considered in the design of new impoundments. The remobilization of particles (tailings) should be controlled to acceptable limits. Embankment slope design must take cognizance of physical stability characteristics as well as long-term surface stability aspects. The design must allow for suitable habitats to be established on the tailings impoundment which will be in unison with the surrounding landscape and natural environment. The final landform should be visually pleasing, merging with the surrounding natural landforms.

While economic considerations and implications play an important role in the final design outcome it is suggested that the test for an acceptable impoundment design lies in the demonstration of long-term surface stability.

2.14 Concluding remarks

Legislation is becoming more stringent and regulatory authorities are stricter in the implementation thereof. Also, a growing understanding of sustainable development requires a more positive post-closure state of tailings impoundments with aspects such as post-closure land use and residual impacts being important.

Using an impoundment for a post-closure land use has certain constraints such as:

- the difficulty to decide on an embankment slope;
- interpreting tailings characteristics in terms of landform constraints; and
- the ability to establish vegetative covers.

Tailings impoundments must be designed to ensure that the environmental consequences are adequately considered in the planning, implementation and management stages. A paradigm shift is required to achieve this.

There is a need for a rational system to integrate environmental impacts and engineering aspects in order to resolve problems that relate to the configuration of tailings impoundments. It is postulated that tailings impoundment can be designed and constructed taking account of both the environmental costs and benefits and engineering costs to produce an optimal sustainable end land use.

Environmental aspects that must be built into the overall model are:

- visual aspects;
- air quality aspects;
- water aspects.

A visual impact methodology that is objective and contains defensible measurements is required to assess the impact of tailings impoundments on the receiving environment. Visibility and the distance from the scheme are two fundamental factors that influence the quantitative assessment of visual impacts. These factors are required to calculate the zone of visual influence (ZVI) and delineate the extent of the visual impact. A geographic information system (GIS) can be used to generate a two-dimensional map which spatially represents the zone of visual influence of a scheme within the landscape.

Similarly air quality and water pollution are important environmental aspects. It is important that the potential influence on the air and water quality must be quantified and included in the overall system. Air quality influence can be quantified using existing models which calculate the emissions and model the dispersion thereof spatially. However, it is necessary to calibrate some of the tailings specific parameters the iterative prediction of emissions and comparison with monitored results.

A simple analytical mass flux model that calculates the change of sulphates and which assumes steady state flow conditions will be adequate for inclusion in the overall model. Such a model can readily be developed for the purpose of this research.

CHAPTER THREE: EXPERIMENTAL WORK AND MODELLING

"There is nothing that is a more certain sign of insanity than to do the same thing over and over and expect the results to be different."

Albert Einstein (Arden, 2003:51)

"Success is going from failure to failure with no less enthusiasm."

Winston Churchill (Arden, 2003:122)

3.1 Introduction

The purpose of the research is to develop a model that can be used to rationally inform decision making with regard to the sustainable configuration of tailings impoundments. The emphasis is on the post-closure long-term land use of such and to determine the sustainability of various impoundment configurations.

Simplistically the post-closure land use of a facility is controlled by:

- access to the facility which in turn is dependent on the side slope profile;
- the land use as a function of slope; and
- the land use as a function of final cover.

The premise is that by integrating environmental impacts and engineering costs a holistic view of change in impoundment configuration can be accomplished. The engineering model calculates the costs incurred over the life of the facility, i.e. during the design, construction, deposition, decommissioning, closure and post-closure stages and is described in Section 3.7.

There is an apparent drive in industry to flatten the overall impoundment embankment side slopes from say a 1:1,5 to a 1:3 slope during final rehabilitation in order to close the facility. The principle is illustrated in Figure 79, Figure 80 and Table 18 (p. 157). Flattening the overall side slope from 1:1,5 to 1:3 results in step-in side slopes that will vary between 1:1 and 1:2,5 respectively. The flattening of the overall embankments side slope also impacts on the physical extent of the footprint and in certain instances the larger footprint can result in the covering and subsequent decommissioning of existing engineered stormwater runoff and sediment control measures.

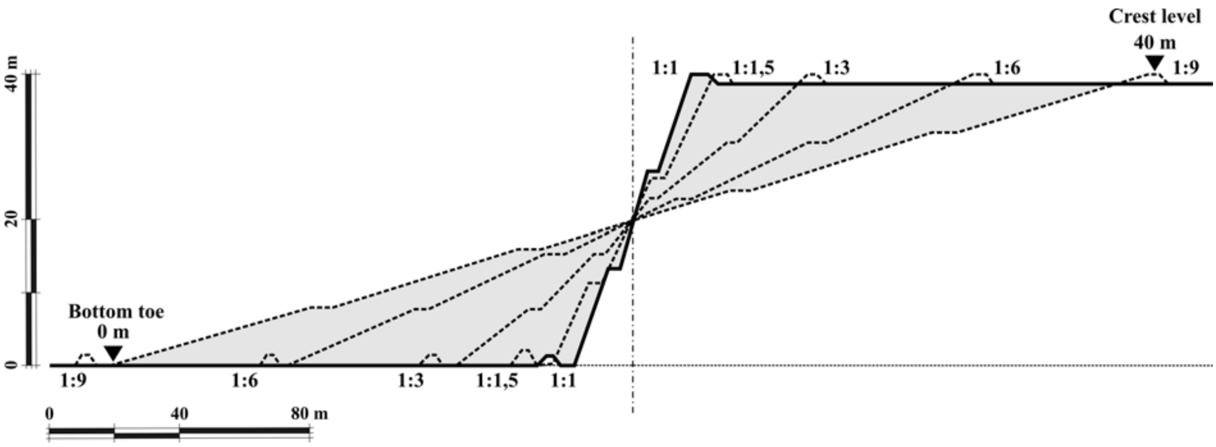
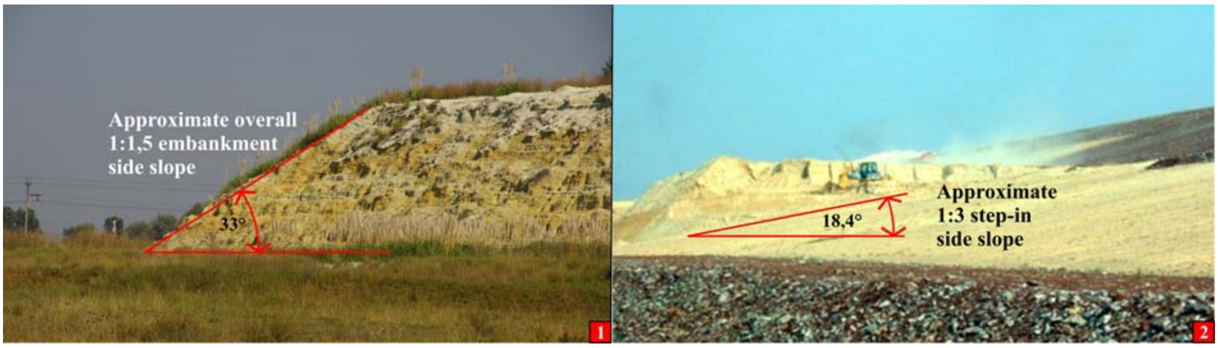


Figure 79: Schematic illustrating the flattening of the embankment slope of a tailings impoundment.

It is not so much the overall embankment slope as the step-in slope that is important. Although what may be considered to be an acceptable overall embankment slope of 1:3 is achieved the resulting step-in slope is much steeper (1:2,5) and may in certain instances result in excessive erosion or be inaccessible. Table 18 provides typical slope configuration information when flattening the embankment slope by means of mechanical methods and keeping the impoundment height constant.

Table 18: Typical embankment slope configuration when flattening side slopes.

Overall slope ratio	**(V1:?H)**	**1,5**	**3**	**6**	**9**
Overall slope angle	**(°)**	33,7	18,4	9,5	6,3
Intermediate slope ratio	**(1V:?H)**	1	2,5	5,5	8,5
Intermediate slope angle	**(°)**	45	21,8	10,3	6,7



[1] Photograph of a tailings impoundment with an overall embankment side slope of 1:1,5 (33°).

[2] Photograph of the ERGO Daggafontein impoundment embankment being flattened mechanically.

Figure 80: Photographs of impoundment embankment comparing the overall slopes.

The overall environmental aspects framework identifies and contextualises the most important environmental aspects. It is described in Section 2.8. Decision models are used to predict the environmental impacts and estimate the engineering costs in order to determine the overall sphere of influence and are described in detail later on in this section. The ERGO Daggafontein impoundment is used as a case study site for spatial contextualisation and information on this impoundment is provided in Section 3.3.

When changing an impoundment configuration the following typical questions arise:

- should industry continue disposing tailings at steep side slopes – i.e. say overall side slope of between 1:2,5 to 1:3 and do nothing. In many case the slopes are even steeper (1:1,5);
- deposit tailings at a steep overall side slope – i.e. overall side slope of between 1:1,5 to 1:2,5 and suitably cover the facility in order to mitigate some of the environmental impacts;
- pro-actively deposit the impoundment at flattened side slopes from the start ending with an intended and designed overall flatter side slope;
- when flattening the side slopes is it possible to determine what flat enough is or what the ideal side slope is? Is an overall embankment slope of 1:3, 1:6 or 1:9 ideal?
- continue to deposit at say 1:2,5 and then mechanically flatten to 1:3, 1:6 and 1:9 side slopes and do nothing or cover the impoundment surface with rock, or an engineered armoured cover in order to create a suitable growing-medium to sustain vegetation.

3.1.1 Test impoundment site

In order to answer the above the ERGO Daggafontein impoundment site is used to model the various upstream deposited ring-dyke tailings impoundment configurations. General limitations are:

- The ERGO impounded tailings was cycloned and not spigotted – hence a modelled dry density of the placed product of 1,8 t/m^3 and not 1,45 t/m^3. Also a safe rate of rise was fixed at 2,5 m/annum.
- The production is constant at 990 000 t/annum over 16 years with a total storage requirements of 105,6 Mm^3.
- The final height must ideally remain constant – see Table 19 which provides the results using the engineering cost model.
- The overall embankment side slope angles are 1:1,5, 1:3, 1:6 and 1:9. Also, one should be able to specify step-ins and end with and impoundment with say and overall side slop of 1:3 but with steeper step-in side slopes with varying slope angles. Our understanding is that the side slope configuration (i.e. the step-in side slope, length and cover) determines the surface runoff and hence resultant erodibility of the material.

[1] Oblique photograph looking south-west. Photograph with the courtesy of AngloGold Ashanti.

[2] Oblique photograph at the southern corner also referred to as 'Windy Corner'. Photograph with the courtesy of AngloGold Ashanti.

Figure 81: Views of the ERGO Daggafontein tailings impoundment.

3.1.2 Spatial overlay of environmental aspects considered in this study

Figure 82 illustrates the concept of total sphere of influence by overlaying of the different environmental aspect zones of influence for a specific impoundment configuration.

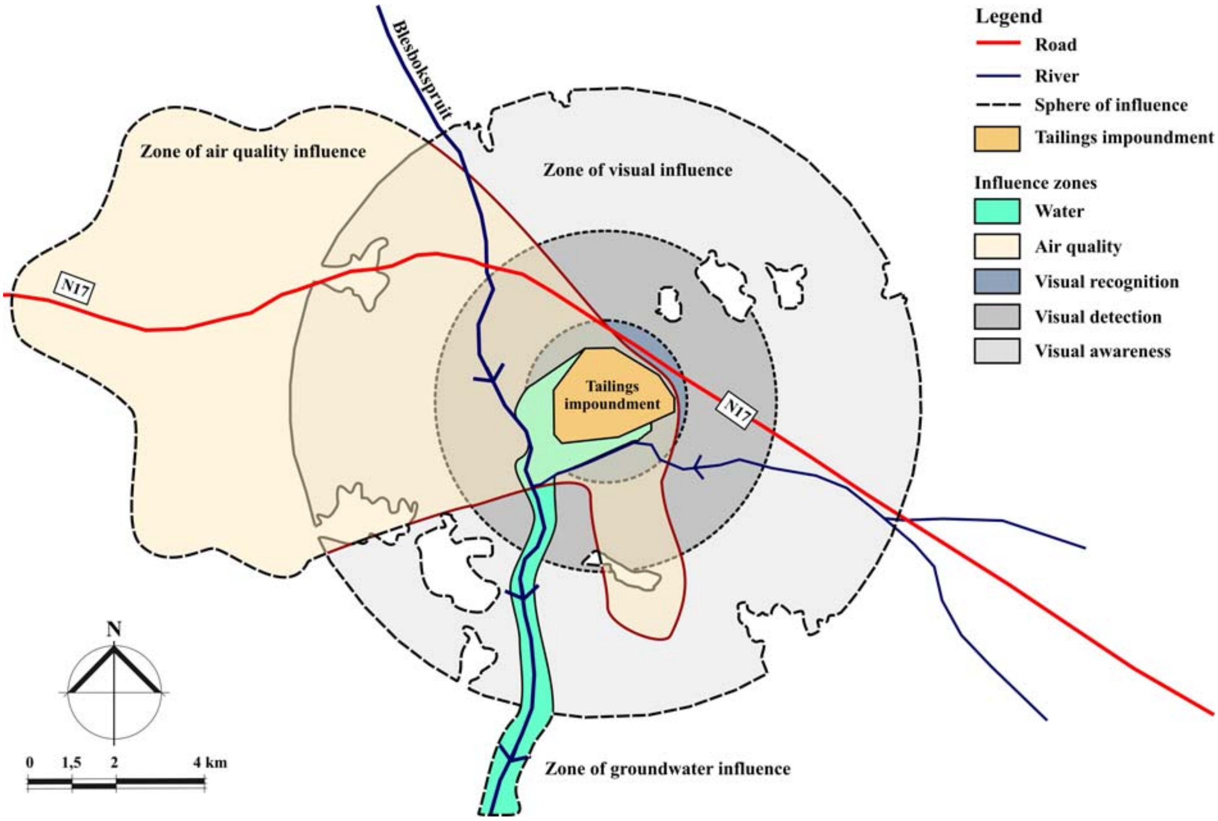


Figure 82: Total environmental sphere of influence anticipated as an outcome of this study.

Figure 82 indicates the total sphere of influence for a particular impoundment configuration. The total cost for this specific configuration could be the sum of the:

- engineering costs to construct, operate, and close such a facility;
- permanent or temporary take of land by the impoundment footprint;
- value of property sterilised for future use;
- direct costs as a result of the impact on health (inhalable particulates causing ill-health effects);
- costs to treat polluted groundwater or having to purchase replacement water;
- mitigation costs; and
- long-term post-closure maintenance costs.

3.2 Configurations modelled

Configuration is the term used to describe the combination of geometry and cover, whereas geometry is a function of height, side slope and volume. Side slope is a function of slope length and gradient. Slope gradient is usually the determining factor when considering various land use options and can restrict development and should be carefully considered during the design of the tailings impoundment in order to increase the range of future land use options. Figure 83 provides maximum slope gradients for various land uses. A wider range of land uses can be accommodated by lower slope gradients.

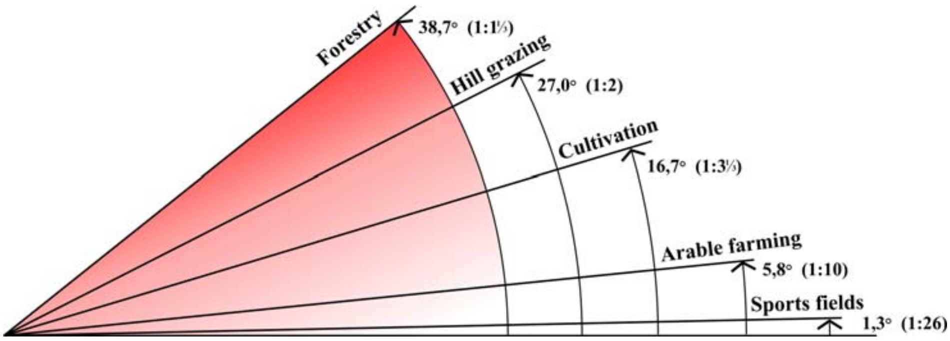


Figure 83: Typical land uses as a function of maximum slope gradients.

3.2.1 Geometry

Table 19 indicates the different overall slope profiles modelled in this study. Although the overall embankment slopes are indicated and used in the modelling of the respective environmental aspects, the engineering cost model optimises the slope length and angle for each step-in. The engineering model also allows for the bench width to be included in the calculations. This is important as the overall impoundment embankment is a combination of the step-ins and although the modelling of the key environmental aspects are undertaken for an overall embankment slope configuration only. Future refinement of the environmental models should allow for the inclusion of such detail.

Table 19: Embankment slope configurations modelled. Production and height are kept constant.

		Configurations			
		S1	**S2**	**S3**	**S4**
Overall slope ratio	**1V:?H**	**1,5**	**3**	**6**	**9**
Production	tpm	990 000	990 000	990 000	990 000
Dry density of placed product	t/m^3	1,8	1,8	1,8	1,8
Life of facility	years	16	16	16	16
Step-in width	m	4	4	4	4
Geometric volume	m^3	105 600 000	105 600 000	105 600 000	105 600 000
Impoundment height	m	37,28	37,28	37,28	37,28
Rate of rise at closure	m/annum	2,5	2,7	3,2	3,9
Step-in side slope angle	°	45	21,8	10,3	6,7
Top surface area	m^2	2 640 000	2 444 444	2 062 500	1 692 308
Footprint length	m	2 204	2 271	2 399	2 516
Footprint width	m	1 377	1 419	1 499	1 572
Footprint surface area	m^2	3 035 257	3 223 056	3 596 259	3 955 614

Table 19 provides the slope configurations used in the engineering cost model to calculate life-cycle costs. The same configurations are used when modelling the environmental impacts for the various environmental aspects in this study. A comparison of the engineering costs and the environmental impacts will be made for the status quo (i.e. depositing at steep embankment slopes and during the closure stage flatten the embankment mechanically to the final configuration) and the pro-active deposition of flatter slopes during the operation stage.

3.2.2 Covers

During rehabilitation the final impoundment material layer can consist of the following:

- tailings in situ (no cover);
- soil (imported soil suitable to sustain plant growth);
- rock cladding; and
- armouring (cover consisting of a 60 % rock and 40 % topsoil mixture).

The vegetation cover on tailings impoundment could consist of:

- nothing;
- grass cover; and
- diversity of vegetation species.

Tailings cover is the in situ tailings material and is representative of many tailings impoundments where no rehabilitation has taken place.

A rock cladding or riprap cover is often applied in order to reduce the surface erodibility potential. The rock is usually sourced from rock dumps in close proximity. The colour of rock can vary considerably. In this study, photographs were taken from a nearby rock dump and used as reference for further photo manipulation.

Re-vegetation of the tailings impoundment with grass is common practice and for this reason the ERGO Daggafontein site is considered typical of the other impoundments that have been grassed.

Establishment of diversity of vegetation on an impoundment could be regarded as the ultimate in rehabilitation. Even though this may not yet be a common approach, it is important to demonstrate the relevance and possible success of this approach.

The overall 1:1,5 through 1:3 (vertical to horizontal) slope configuration is the status quo scenario for most impoundments. The 1:6 through 1:9 slope configurations were selected as flatter side slopes are occasionally applied to enhance vegetation establishment. There is also common perception that flatter side slope configurations may reduce the overall visual impact.

3.2.3 Defining the scenarios modelled in the study

The purpose of this section is to model different tailings impoundment embankment scenarios using a set of tools which comprise:

- a visual (visual perception) model;
- a air (dust) model;
- a water (sulphate flux) model; and
- an engineering cost model.

The ERGO Daggafontein tailings impoundment site is used to provide context to the modelling and demonstration of the approach. Also, for the purpose of this research the modelling is undertaken for a very large impoundment with a tailings production of 990 000 tpm with a life of facility taken as 16 years and a tailings placed dry density of 1,80 t/m^3. The amount of tailings placed over the life of the impoundment and the final height of the impoundment is kept constant. Other parameters are included in Table 19, p. 160. Table 20 to Table 23 provide descriptive codes used for the various aspects modelled. For continuity and ease of reference it is necessary to use the codes throughout the study.

Table 20: Engineering scenarios modelled.

	Modelled Engineering Configurations			
	Slope 1	**Slope 2**	**Slope 3**	**Slope 4**
Engineering costs of placing material at the following side slopes with no further flattening				
Covers	**1:1,5**	**1:3**	**1:6**	**1:9**
Tailings in situ (no cover)	ES1	ES2	ES3	ES4
Rock cladding (300 mm)	ES5	ES6	ES7	ES8
Grassed armouring	ES9	ES10	ES11	ES12
Diverse vegetation	ES13	ES14	ES15	ES16
Engineering costs to construct at steep (i.e. 1:1,5 overall) side slope and flattening such to 1:3, 1:6 and 1:9				
Covers	-	**1:3**	**1:6**	**1:9**
Tailings in situ (no cover)	-	ES17	ES18	ES19
Rock cladding (300 mm)	-	ES20	E21	E22
Grassed armouring	-	ES23	ES24	ES25
Diverse vegetation	-	ES26	ES27	ES28

Table 21: Visual perception configuration scenario modelling codes and buffer distances.

	Overall side slope	**Buffer distances for levels of visual perception**			
Covers	**1:3**	**Recognition**	**Detection**	**Awareness**	**10 000 m limit of ZVI**
Tailings in situ (no cover)	VS1	R-1645	D-5490	A-2865	-
Rock cladding (300 mm)	VS3	R-1890	D-4085	A-4025	-
Grassed armouring	VS5	R-975	D-2745	A-3530	O-2750
Diverse vegetation	VS7	R-180	D-855	A-3655	O-5300
Covers	**1:6**				-
Tailings in situ (no cover)	VS2	R-4145	D-4695	A-1160	-
Rock cladding (300 mm)	VS4	R-1890	D-5245	A-2865	-
Grassed armouring	VS6	R-1645	D-2625	A-2430	O-3300
Diverse vegetation	VS8	R-180	D-855	A-3165	O-5800

Table 22: Air quality modelling scenarios and area of influence codes for the isopleths.

	Overall side slope	Air quality isopleths	
Covers	**1:1,5**	**PM$_{10}$ (µg/m^3)**	**TSP (mg/m^2)**
Tailings in situ (no cover) 0% efficiency	AS1	AS1_10day	AS1_DDday
Rock cladding (300 mm) 100% efficiency	AS5[1]	no emissions	no emissions
Grassed armouring 50% efficiency	AS9	AS9_10day	AS9_DDday
Diverse vegetation 80% efficiency	AS13	AS13_10day	AS13_DDday
Covers	**1:3**		
Tailings in situ (no cover) 0% efficiency	AS2	AS2_10day	AS2_DDday
Rock cladding (300 mm) 100% efficiency	AS6[1]	no emissions	no emissions
Grassed armouring 50% efficiency	AS10	AS10_10day	AS10_DDday
Diverse vegetation 80% efficiency	AS14	AS11_10day	AS12_DDday
Covers	**1:6**		
Tailings in situ (no cover) 0% efficiency	AS3	AS3_10day	AS3_DDday
Rock cladding (300 mm) 100% efficiency	AS7[1]	no emissions	no emissions
Grassed armouring 50% efficiency	AS11	AS11_10day	AS11_DDday
Diverse vegetation 80% efficiency	AS15	AS15_10day	AS15_DDday
Covers	**1:9**		
Tailings in situ (no cover) 0% efficiency	AS4	AS4_10day	AS4_DDday
Rock cladding (300 mm) 100% efficiency	AS8[1]	no emissions	no emissions
Grassed armouring 50% efficiency	AS12	AS12_10day	AS12_DDday
Diverse vegetation 80% efficiency	AS16	AS16_10day	AS16_DDday

[1] AS5 through AS8 is included in the table although not modelled during the study. The 100% control efficiency implies that there will be no emissions from the impoundment.

Table 23: Groundwater quantity and quality modelling scenarios.

	Side slope configuration			
Covers	**1:1,5**	**1:3**	**1:6**	**1:9**
Tailings in situ (no cover)	WS1	WS2	WS3	WS4
Rock cladding (300 mm)	WS5	WS6	WS7	WS8
Grassed armouring	WS9	WS10	WS11	WS12
Diverse vegetation	WS13	WS14	WS15	WS16

3.3 Study site

East Rand Gold and Uranium Company Limited (ERGO) was established in 1977 to reclaim and retreat gold residue deposits on the East Rand, in Gauteng, South Africa. In 1985, following an agreement with East Daggafontein Mines Limited, a 1 Mtpm carbon-in-leach (CIL) plant was completed for this purpose. The plant recovered approximately 3700 kg of gold per annum, depositing the tailings at the ERGO Daggafontein site at an average rate of 1,37 Mtpm. Active deposition of reworked tailings onto the impoundment ceased during December 2001 after about 200 Mt had been deposited during the 15 years.

The ERGO tailings facility is located in the Ekurhuleni Metropolitan Municipality, Gauteng Province, South Africa. Springs lies approximately 5 km West and Nigel approximately 15 km North East of the impoundment (Figure 84). It covers a total area of approximately 600 ha, whereas the footprint of the impoundment covers 435 ha – one of the largest of its kind in the world.

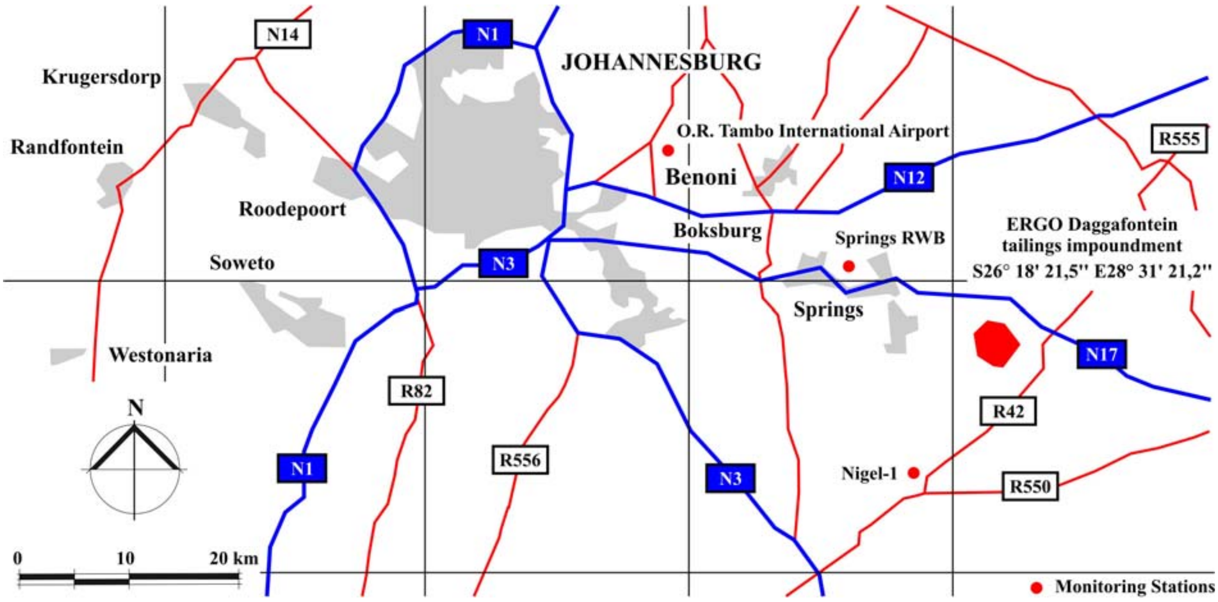


Figure 84: Regional locality map of the ERGO Daggafontein tailings impoundment.

The reclamation of old mine residue deposits predominantly take place by means of hydraulic monitoring methods. High pressure water jets are directed onto the face of the deposit, breaking up the material and turning it into slurry. The slurry flows to a pump station located at a low point on the site, which is then pumped to a process plant for treatment and subsequent disposal on an impoundment.

The ERGO Daggafontein tailings impoundment was designed as a free-standing upstream deposited ring-dyke impoundment with the outer perimeter wall built from coarse cycloned underflow impounding the fine tailings overflow. The lowest point of the tailings impoundment is at the south-western corner at about 1578 m.a.s.l. with a maximum height of about 68 m (Figure 86).

Aerial photograph downloaded from GoogleEarth.com.

Figure 85: ERGO Daggafontein tailings impoundment aerial photograph.

The impoundment is currently in various stages of rehabilitation for a wilderness end land use (Wates, Sabbagha, Geldenhuys, and Steenkamp, 2001) through:

- the mechanically flattening of the embankment step-in side slopes varying between 18° and 20° with 13 m vertical steps and 7 m wide benches – this results in an overall side slope of less than 18°;
- the placing of an armouring consisting of a 40 % topsoil and 60 % rock mixture;
- providing lateral drainage in order to route stormwater collected on the benches to concrete stormwater chutes spaced at 200 m intervals; and
- planting grass on the embankment slopes.

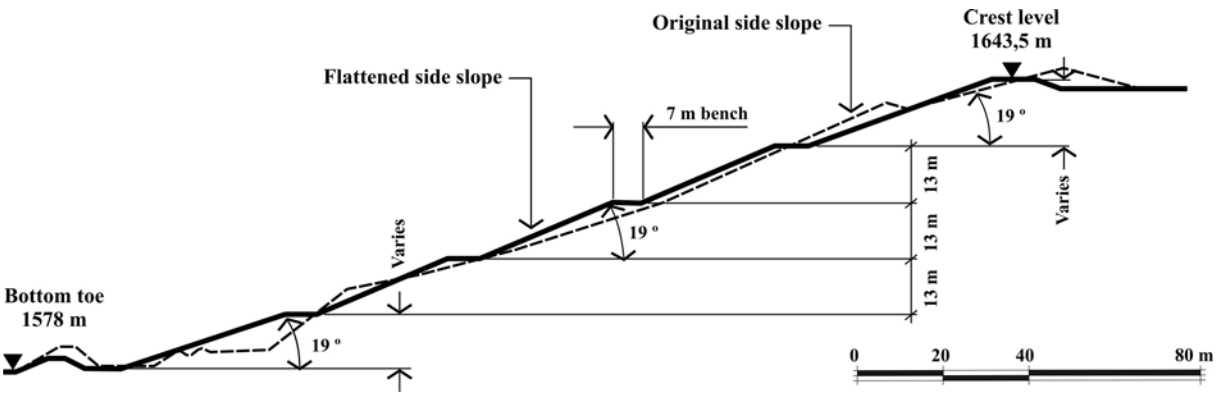


Figure 86: Typical section through ERGO Daggafontein tailings impoundment embankment.

The area has a rural character and the impoundment lies within the highveld grassland broad vegetation type. The regional terrain morphology varies between slightly irregular to moderately undulating plains, that is to say a rolling topography (Figure 87). The surrounding land is mainly used for agriculture such as grazing, and the cultivation of sunflowers, maize and beans (Figure 88). The Endicott and Viskuil agricultural holdings are located about 5 km to the East of the site. The biological productivity, i.e. primary productivity expressed as the harvestable yield in tonnes per hectare for a complete growing season, is estimated at 6,25 t/ha (van Riet et al., 1997:28).

Figure 87: The ERGO Daggafontein tailings impoundment lies within an area with a rural character and rolling topography.

The Blesbokspruit wetland is located to the West of the impoundment. A tributary lies South of the impoundment and joins the Blesbokspruit at the northern boundary of the Maryvale Bird Sanctuary. The site slopes gently in a westerly direction towards the Blesbokspruit.

Figure 88: The land surrounding the ERGO Daggafontein tailings impoundment is extensively used for grazing and the cultivation of cash crops such as maize, sunflowers and soya beans.

3.3.1 Climate

The South African Weather Services maintains two automatic weather stations within the Ekurhuleni Metropolitan Municipality, one situated at the O.R. Tambo International Airport (erstwhile Johannesburg International Airport) and a second at Springs. Data, unless otherwise indicated, were used from the weather station at O.R. Tambo International Airport (26° 8' S and 28° 14' E) for the period 1961 to 1990.

Rainfall

Rainfall is highly seasonal over most parts of South Africa and precipitation over the interior, including Eastern Gauteng, follows an annual cycle. The impoundment falls within a summer rainfall area with an average annual precipitation of 713 mm (Figure 89). However, during the period monitored the annual rainfall has been as high as 1019 mm (1987) and as low as 443 mm (1984).

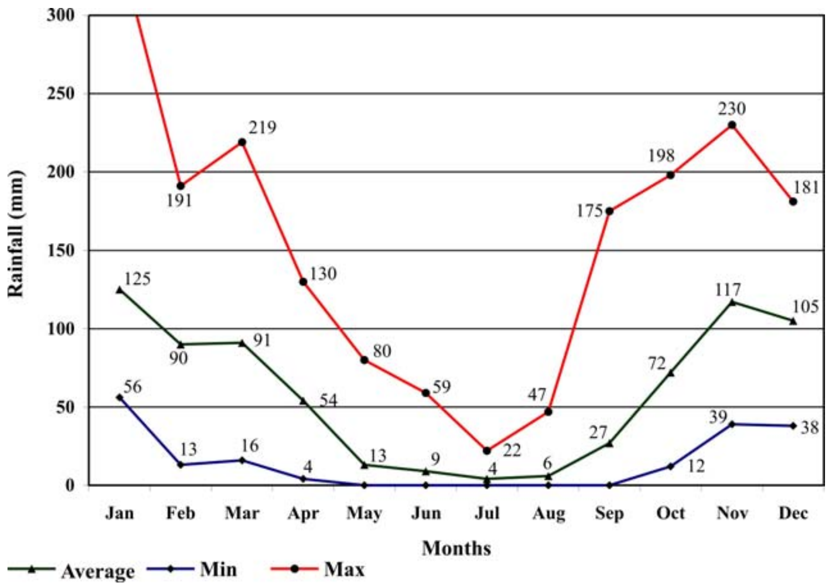


Figure 89: Graph indicating annual average, minimum and maximum rainfall figures.

Rainfall figures for the O.R. Tambo International Airport monitoring station is given in Table 24. Rainfall in the region is almost exclusively due to showers and thunderstorms that fall mainly during summer in the period between October and March. Summer months receive about 70 % of the rainfall and winter months are normally dry. The maximum rainfall occurs during December and January. The average monthly rainfall for the months April to September ranges between 3 mm and 34 mm. An average number of 90 to 95 rain days are experienced per year.

Table 24: Long-term average monthly rainfall for O.R. Tambo International Airport (Schulze, 1986).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Ave rainfall (mm)	188	55	92	49	70	31	30	25	42	89	65	102	838
Average number of rain days	14,4	11,0	11,0	8,5	3,6	2,0	1,2	2,0	3,5	9,6	14,3	14,0	95,5

Temperature

The temperature for Eastern Gauteng varies greatly from summer to winter (Figure 90). The average daily maximum temperature is 25,6°C in January and 16,0°C in June, while the average daily minimum temperature ranges from 14,7°C in January to 4,1°C in June.

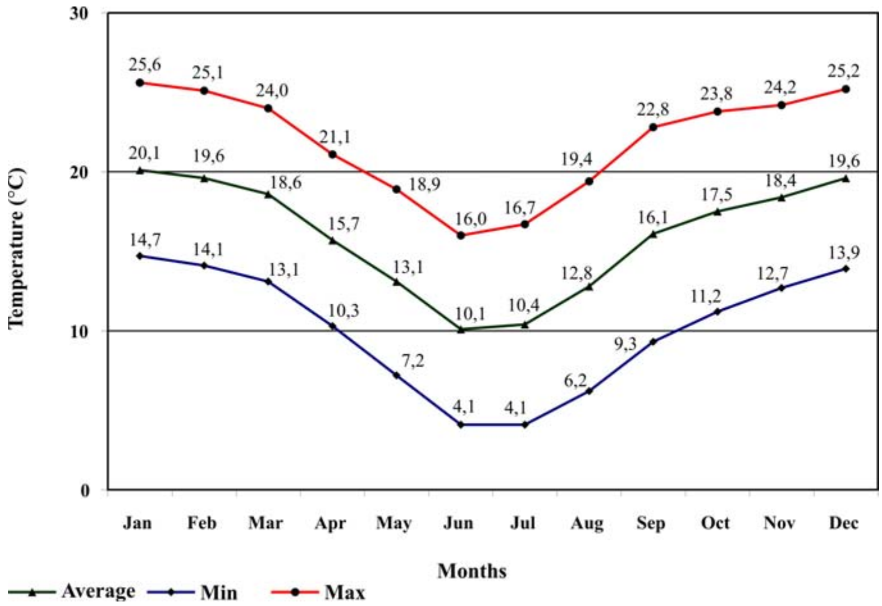


Figure 90: Graph indicating average, minimum and maximum temperature figures.

Long-term average maximum, mean and minimum temperatures for O.R. Tambo International Airport (1951-1984) are given in Figure 90 (Schulze, 1986). Annual mean temperatures for are given as 15,9°C. The average daily maximum temperatures range from 25,3°C in January to 16,0°C in June, with daily minimum ranging from 14,3°C in January to 4,0°C in June and July.

Table 25: Minimum, maximum and mean temperature (°C) for O.R. Tambo International Airport for the period 1951-1984 (Schulze, 1986).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Maximum	25,3	24,9	23,9	21,2	18,6	16,0	16,5	19,2	22,7	23,9	24,1	25,0
Minimum	14,3	14,1	12,9	10,2	7,0	4,0	4,2	6,0	9,2	11,3	12,7	13,8
Mean	19,8	19,5	18,4	15,7	12,8	10,0	10,4	12,6	15,9	17,6	18,4	19,4

At Springs the average daily maximum temperature is about 27 °C in midsummer and 17 °C in midwinter. Temperature extremes of 38 °C and 26°C may occur during summer and winter, respectively. Sunshine duration in summer is about 60%, whereas insolation duration of 80% is typical of winter months.

Mixing depth and atmospheric stability

The atmospheric boundary layer constitutes the first few hundred metres of the atmosphere. This layer is directly affected by the earth's surface, either through the retardation of flow due to the frictional drag of the earth's surface, or as result of the heat and moisture exchanges that take place at the surface. During the daytime, the atmospheric boundary layer is characterised by thermal turbulence due to the heating of the earth's surface and the extension of the mixing layer to the lowest elevated inversion. Radiative flux divergence during the night usually results in the establishment of ground based inversions and the erosion of the mixing layer.

Atmospheric stability is frequently categorised into one of six stability classes. These are briefly described in Table 26. Hourly standard deviation of wind direction, wind speed and predicted solar radiation are used to determine hourly-average stability classes.

Table 26: Atmospheric stability classes.

Designation	Stability Class	Atmospheric condition
A	Very unstable	Calm wind, clear skies, hot daytime conditions
B	Moderately unstable	Clear skies, daytime conditions
C	Unstable	Moderate wind, slightly overcast daytime conditions
D	Neutral	High winds or cloudy days and nights
E	Stable	Moderate wind, slightly overcast night-time conditions
F	Very stable	Low winds, clear skies, cold night-time conditions

The atmospheric boundary layer is normally unstable during the day as a result of the turbulence due to the sun's heating effect on the earth's surface. The thickness of this mixing layer depends predominantly on the extent of solar radiation, growing gradually from sunrise to reach a maximum at about 5-6 hours after sunrise. This situation is more pronounced during the winter months due to strong night-time inversions and slower developing mixing layer. During the night a stable layer, with limited vertical mixing, exists. During windy and/or cloudy conditions, the atmosphere is normally neutral.

For elevated releases, the highest ground level concentrations would occur during unstable, daytime conditions. The wind speed resulting in the highest ground level concentration depends on the plume buoyancy. If the plume is considerably buoyant (high exit gas velocity and temperature) together with a low wind, the plume will reach the ground relatively far downwind. With stronger wind speeds, on the other hand, the plume may reach the ground closer, but due to increased ventilation, it would be more diluted. A wind speed between these extremes would therefore be responsible for the highest ground level concentrations. In contrast, the highest concentrations for ground level, or near-ground level releases would occur during weak wind speeds and stable (night-time) atmospheric conditions.

Wind speed and direction

One of the main interests in wind data is to determine the potential for wind blown dust from the impoundment. The wind erosion potential is a function of the wind velocity. The vertical dispersion of pollutants is largely a function of the wind field. The wind speed determines both the distance of downwind transport and the rate of dilution of pollutants. The generation of mechanical turbulence is a function wind speed and surface roughness.

Wind roses comprise 16 spokes which represent the directions from which winds blow during the period. The colours reflect the different categories of wind speeds. The grey area, for example, represents winds of 1 m/s to 3 m/s. The dotted circles provide information regarding the frequency of occurrence of wind speed and direction categories. Each dotted circle within the wind roses in Figure 91 represents 5 % frequency of occurrence whereas the figure given in the centre of the circle describes the frequency with which calms occur, i.e. periods during which the wind speed is below 1 m/s.

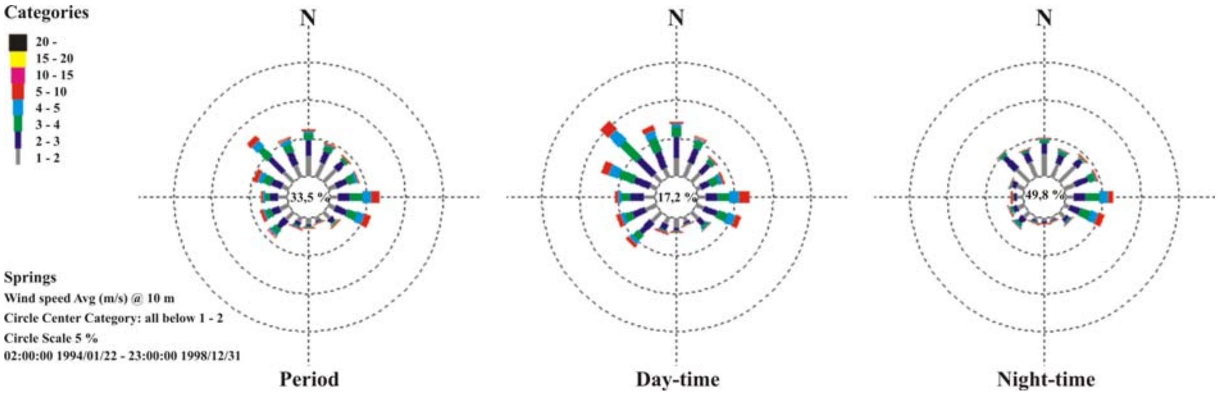


Figure 91: Period-average, day-time and night-time wind roses depicting the wind profile in Springs for the period January 1998 to December 2002.

The wind regime largely reflects the synoptic scale circulation. The flow field is dominated by north-westerly and easterly winds, with northerly winds prevailing due to the anticyclones that dominate the region throughout much of the year. Infrequent winds are noted to occur from the southern sector. Thermo-topographical impacts on the flow regime give rise to distinct diurnal trends in the wind field. During the day-time, the predominant wind flow is from the northwest with frequent wind also from the southwest and East. Strong winds (> 5 m/s) occur from the northwest and East and east-southeast. During the night-time the decrease in winds from the westerly sector are evident with the prevailing winds from the East and east-southeast. A decrease in the wind velocity is also apparent with wind mainly between 1 m/s to 3 m/s for most of the night. This is typical of night-time airflow when calm periods and low wind speeds are generally more prevalent.

Evaporation

In Eastern Gauteng evaporation is greater than precipitation, which gives a net loss throughout the year. Even in the wet season (November to April) when rainfall is higher, evaporation still exceeds precipitation. The evaporation figure 1165 mm is the average evaporation for the months November to April obtained from 1959 –1987.

3.3.2 Geology

Regional geology

The oldest rocks which outcrop within the region are sediments of the Witwatersrand Supergroup which form pronounced ridges in the Germiston region. Gold-bearing reefs within the Witwatersrand sediments have been mined over a significant portion of the East Rand (Figure 13, p. 19). Some of the reclaimed mine residue of these deposits have been disposed of at the ERGO Daggafontein tailings impoundment.

The Witwatersrand sediments are overlain by andesitic lava of the Ventersdorp Supergroup, which outcrops over the western portion of the study area. This formation is unconformably overlain by the Transvaal Sequence which is represented by the Black Reef Quartzite and Malmani Dolomite which outcrop along the southern and eastern margins of the study area.

Surface outcrops across the project area consist predominantly of Karoo age sediments of the Dwyka and Vryheid Formations which have been unconformably deposited on the older strata. This sedimentary sequence contains several coal seams which have been mined in the Springs area.

Strata generally dip at a variable angle in a South or south-westerly direction towards the centre of the East Rand basin.

The regional geology has been modified by the intrusion of both Karoo and Pilanesberg-age dykes. Extensive dolerite sills are also encountered during mining in the Springs area.

Site geology

The following provides a brief description of the geological sub-strata underlying the ERGO Daggafontein tailings impoundment site. The nature of the geology (Figure 92, p. 172) is considered important for the following reasons:

- the proximity to aquifers determine the susceptibility of groundwater to contamination; and
- the lithology and structure of formations influence the direction and rate at which contaminants migrate from the source.

The geology of the ERGO Daggafontein tailings impoundment site is varied with most of the site underlain by Karoo sediments consisting mainly of sandstone. These sediments are underlain by chert-rich tillite of the Dwyka Formation which weathers to wad and outcrops over the south-west corner of the site.

Karoo sediments are underlain by recrystallised Monte Christo dolomite of the Transvaal Supergroup which outcrops over the South and south-west of the site. The sediments in this area have been modified by the intrusion of Karoo age dolerite and Pilanesberg age syenite dykes cross-cutting the Transvaal strata.

Rocks of the Proterozoic Witwatersrand Super Group sub-crop at a depth of more than 400 m at the site, with the western edge of the Main Reef workings occurring at a depth of approximately 600 m. The oldest rocks mapped at the site are the Proterozoic-aged Monte Christo Formation (Transvaal Super Group), characterized by minor dolomite and interbedded chert.

Surface outcrops of the Jurassic-aged Vryheid Formation (Karoo Super Group), which overlie the Monte Christo Formation across part of the site, consist of gently dipping to horizontal mudstone, shale, siltstone, poor quality coal (occasional), and sandstone interbeds, the mudstone weathering to clay of low plasiticity. The underlying and Carboniferous-aged tillite of the Dwyka Formation (Karoo Super Group) comprises hard, sub-angular to angular chert fragments within a mudstone matrix.

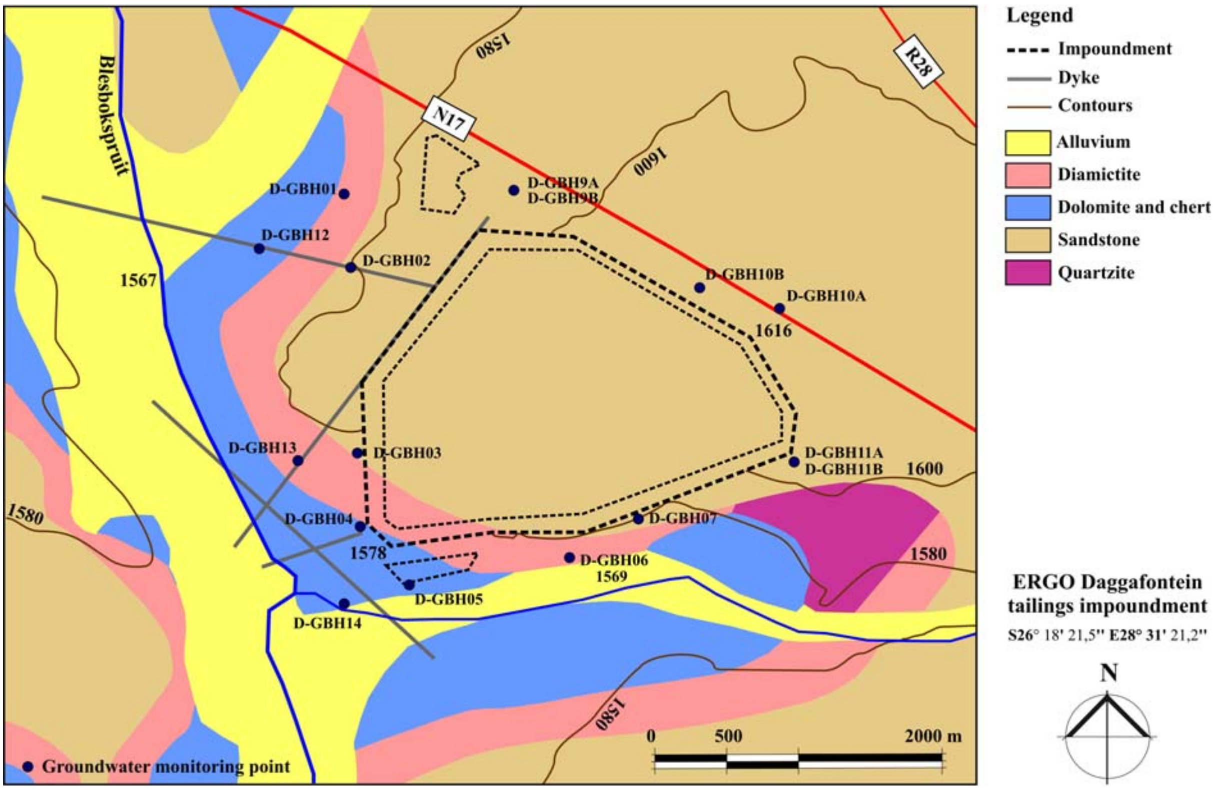


Figure 92: ERGO Daggafontein tailings impoundment site geology and structures.

3.3.3 Soil, land and landform

The regional topography is flat to gently sloping with isolated higher areas. The nature of the topography causes man-made landforms to be prominent features in the natural landscape and therefore quite visible. The ERGO Daggafontein tailings impoundment site slopes in a westerly direction towards the Blesbokspruit. An un-named tributary of the Blesbokspruit lies South of the impoundment and flows from East to West. The slope changes toward the south-west, over the western half of the site and toward the South of the eastern side of the site. A small valley runs from North to South to the West of the impoundment.

The toe of the tailings impoundment at the south-western corner is also at the lowest point with an elevation of about 1578 m.a.s.l. The highest point of the tailings impoundment toe is at about 1616 m.a.s.l. This local high dictates the site drainage. Stormwater and seepage from the tailings impoundment site either drains in a southerly direction or in a north-easterly direction away from this high. Drainage of seepage from the toe drain gravitates to either the collector dam at the south-western corner of the tailings impoundment or to the return water dam at the north-western corner of the tailings impoundment.

The soils covering the site can be described as predominantly pedogenic and colluvial soils with variable thickness. Pedogenic ferricrete deposits consist of well-cemented fine to coarse ferricrete gravels set in a sandy clay matrix, varying in thickness between 0,3 and 6,1 m. The colluvial soils consist of brown clayey sands and silts, which are occasionally ferruginised. These soils are highly variable in thickness, but cover most of the site to depths of between 0,2 to 0,4 m. Falling head permeability tests conducted on the soils in even 100 mm trial pits around the perimeter of the tailings impoundment during January 1984 displayed low permeabilities of between 6 – 10 m/s, which can be attributed to their elevated clay content.

Soil classification

For the purpose of conducting an initial soil-land evaluation and assessment of the site, it is necessary to study the key issues relating to the soil-landform. The main objectives of this study are to identify and classify the soil-landform resources at an appropriate level. From a soil classification perspective the soils found on the ERGO Daggafontein site can be classified into five main categories namely:

- Undisturbed natural soils. These soils are classified according to the standard South African soil classification system and can be mapped to give an indication of agricultural or crop production potential.
- Disturbed natural soils. The classification of disturbed soils in the South African soil classification system is restricted to one soil form namely the Witbank soil form. Although adequate for the physically disturbed soils on the site this form is not adequate for the chemically impacted soils. New categories incorporating the nature characteristics of the chemical degradation will have to be established. As such there is currently an effort underway by members of a working group to establish such categories.
- Tailings material that will undergo some alteration due to mixing with soil or the establishment of vegetation. The classification of tailings material suffers the same shortcomings as the chemically disturbed soils mentioned above. Dedicated categories are foreseen for the classification of such material. At present the body of information on suitability of tailings material to support new uses is very restricted and this aspect requires significant future research as well as structured compilation of existing knowledge.
- Tailings impoundment armouring (rock and soil mix used as cover) can currently be accommodated under the Witbank form but will be incorporated in an expanded classification of anthropogenic soils in the envisaged future classification system.
- Tailings material that will undergo some form of alteration excluding further dedicated human activity. This category presents the material that will not be exposed and as such does not require classification from a soils perspective.

In terms of chemical characteristics the closest soils to the tailings material is Fluvisols with sulphuric soil horizons. These soils are very restricted in their global distribution and are formed from the drainage of previously water-saturated soils and subsequent oxidation of high levels of sulphide minerals is the soil matrix.

Land capability and agricultural potential

The criteria, regarding soil depth and slope, are summarised from the Chamber of Mines Rehabilitation Guidelines (CM, 1981) and for the purposes of this study, the following land capability classes apply:

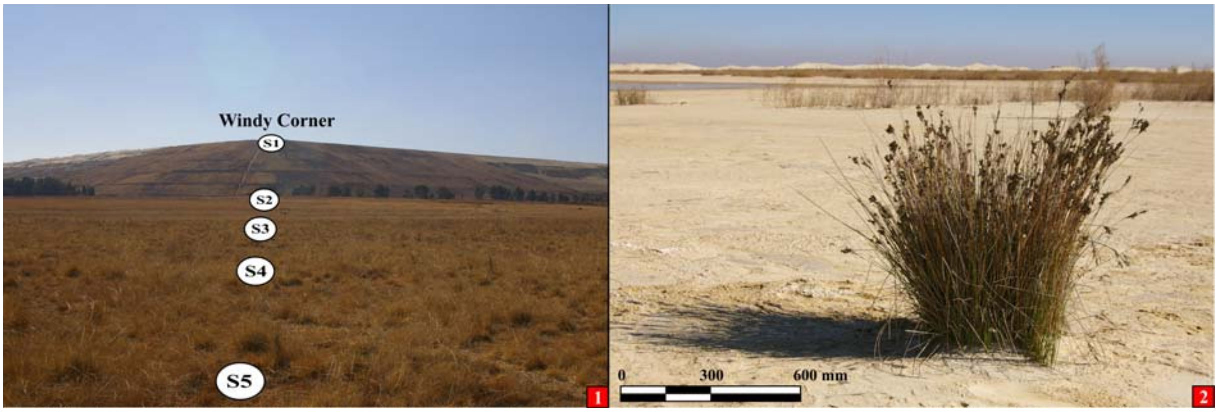
- Arable land: soil depth will not be less than 0,6 m and the slope will not exceed 7 % (1:14).
- Grazing land: soil depth will be at least 0,25 m an the slope will not exceed 30 % (1:3).
- Wilderness land: soil depth is less than 0,25 m but more than 0,15 m.
- Wetland: no criteria given.

The area covered by the tailings impoundment footprint can for all practical purposed be considered to be permanently lost. The land capability of the ERGO Daggafontein impoundment prior to deposition was mainly used for grazing with about 30 % cultivated. The arable section was used for growing cash crops such as maize, sunflowers and beans.

The agricultural potential of the ERGO Daggafontein tailings impoundment site is directly related to the quality of the soils in terms of physical and chemical characteristics. The undisturbed soils will have the highest potential (depending on depth and chemistry) and the disturbed soils will decrease in potential which is proportional to the extent to which they have been disturbed. The in situ tailings material is considered to be of zero agricultural potential mainly due to its characteristics as well as a general lack of information on possible crop types and yields.

Soil sampling and analysis

Seven surface soil samples were collected from the tailings impoundment as well as the surrounding area (Table 27 and Figure 94) and were analysed for a number of parameters (Table 28 and Table 29).



[1] Looking in a north-eastern direction towards Windy Corner of the ERGO Daggafontein tailings impoundment indicating the surface soil sampling points.

[2] Close-up photograph of a sedge (*Juncus* sp) growing on the ERGO Daggafontein tailings impoundment basin.

Figure 93: Surface soil sampling points.

The tailings samples exhibit typical mine tailings character in that it has a high salt content (low resistance) in the form of sulphates and low levels of the plant nutrients Ca, Mg, and K (T1). T2 sample has high levels of these plant nutrients and in sufficient quantities to support the growing of *Juncus sp*. at this point (Figure 93, photo 2).

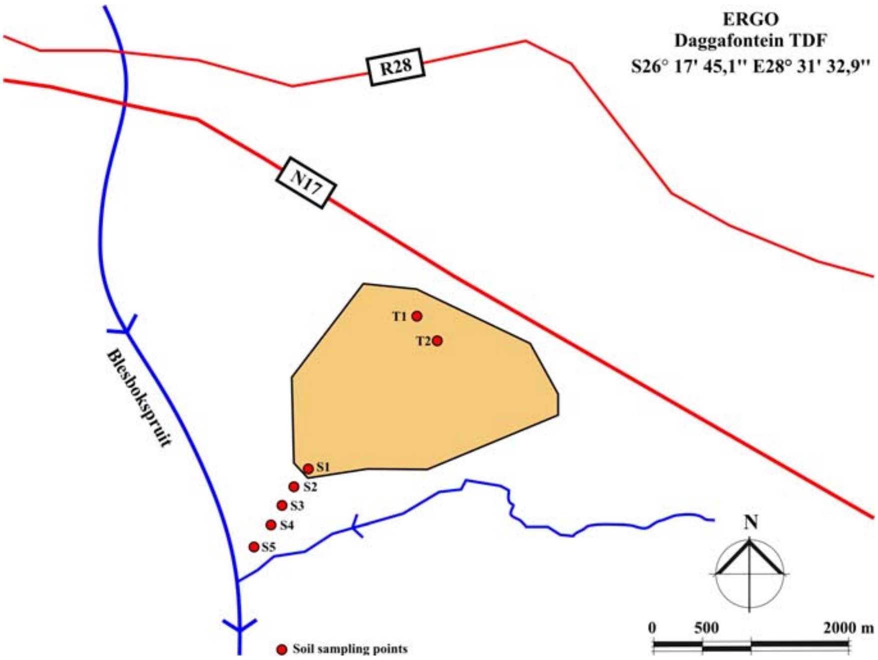


Figure 94: ERGO Daggafontein soil sampling points.

Table 27: Surface soil sampling point co-ordinates.

	Grid	**Lat. and Long. (hddd°mm'ss,s'')**
	Datum	**WGS 84**
Ref	**Description**	**Position**
S1	**Soil 1 Windy Corner**	S26 18 21,5 E28 31 21,2
S2	**Soil 2**	S26 18 36,1 E28 31 11,2
S3	**Soil 3**	S26 18 39,5 E28 31 10,9
S4	**Soil 4**	S26 18 42,3 E28 31 05,9
S5	**Soil 5**	S26 18 44,0 E28 31 04,6
T1	**Tailings 1 Beach**	S26 17 35,6 E28 32 07,6
T2	**Tailings 2 Pond *Juncus sp.***	S26 17 36,0 E28 32 07,6

Table 28: Surface sample soil analysis results from the ERGO Daggafontein tailings impoundment site.

	NH_4OAc Extr. Cations (mg/kg)				NH_4OAc Extr. Cations (cmol(+)/kg)					% of S-value			
Sample	**Ca**	**Mg**	**K**	**Na**	**Ca**	**Mg**	**K**	**Na**	**S-value**	**Ca**	**Mg**	**K**	**Na**
T1	12	180	217	571	0,06	1,48	0,55	2,48	4,58	1,3	32,4	12,1	54,2
T2	9454	340	151	871	47,27	2,8	0,39	3,79	54,24	87,2	5,2	0,7	7,0
S1	3304	150	7	28	16,5	1,2	0,02	0,12	18,89	92,3	6,9	0,1	0,7
S2	689	161	259	7	3,45	1,33	0,66	0,03	5,46	63,1	24,3	12,1	0,6
S3	858	239	347	14	4,29	1,97	0,89	0,06	7,21	59,5	27,3	12,3	0,84
S4	1414	723	269	73	7,07	5,95	0,69	0,32	14,03	50,4	42,4	4,9	2,3
S5	3384	1439	405	521	16,92	11,84	1,04	2,27	32,06	52,8	36,9	3,2	7,1

S1 sample, taken at Windy Corner, seems more like tailings material in its chemical composition than the Tailings 1 (T1) sample. This sample has very high Ca and sulphate levels and very low levels of Mg and K and therefore has a restriction in terms of its crop production potential. Samples S2 to S5 exhibit characteristics expected for natural soils with sulphate levels higher than what is expected from natural background levels. All the soil samples have high levels of micronutrients (especially Zn) and it is not clear what the source of these is.

Table 29: Analysis results of surface soil samples collected from the ERGO Daggafontein tailings impoundment site indicating micronutrients.

			NH$_4$EDTA (mg/kg)				Texture			
Sample	**pH water**	**Resistance (ohm)**	**Cu**	**Fe**	**Mn**	**Zn**	**Sand**	**Silt**	**Clay**	**SO$_4$ (mg/kg)**
T1	4,7	80	7,5	602	46	20	36,5	50,5	13,0	2023
T2	3,8	60	4,3	224	56	30	48,8	38,0	13,2	5089
S1	3,0	100	8,1	887	72	26	78,1	12,2	9,7	7584
S2	5,1	1200	7,2	135	72	54	66,5	13,1	20,4	251
S3	5,3	500	5,0	97	132	60	64,7	16,8	18,5	62
S4	5,5	900	6,6	281	318	162	48,5	22,3	29,3	34
S5	4,4	150	17,7	524	105	54	26,5	25,5	48,0	715

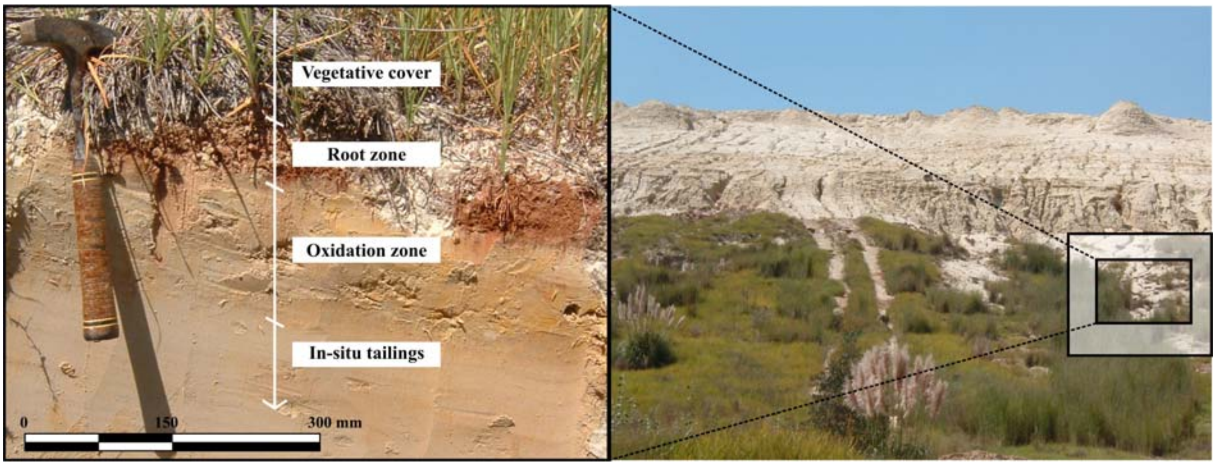


Figure 95: Shallow root zone of a typical profile of the ERGO Daggafontein tailings impoundment surface previously vegetated.

3.3.4 Hydrology

Groundwater quality

Data gathered from monitoring boreholes (Figure 96) at the ERGO Daggafontein tailings impoundment site indicates that conditions within the dolomite aquifer is confined with borehole D-GBH06 being artesian and other dolomite rest water levels lying within 10 m of the surface. Conditions in the overlying Karoo aquifer are unconfined with rest water levels lying within 5 m of the surface. Rest water levels within some areas may have been artificially depressed by the planting of blue gums to control near surface seepage (Blecher and Bush, 1993).

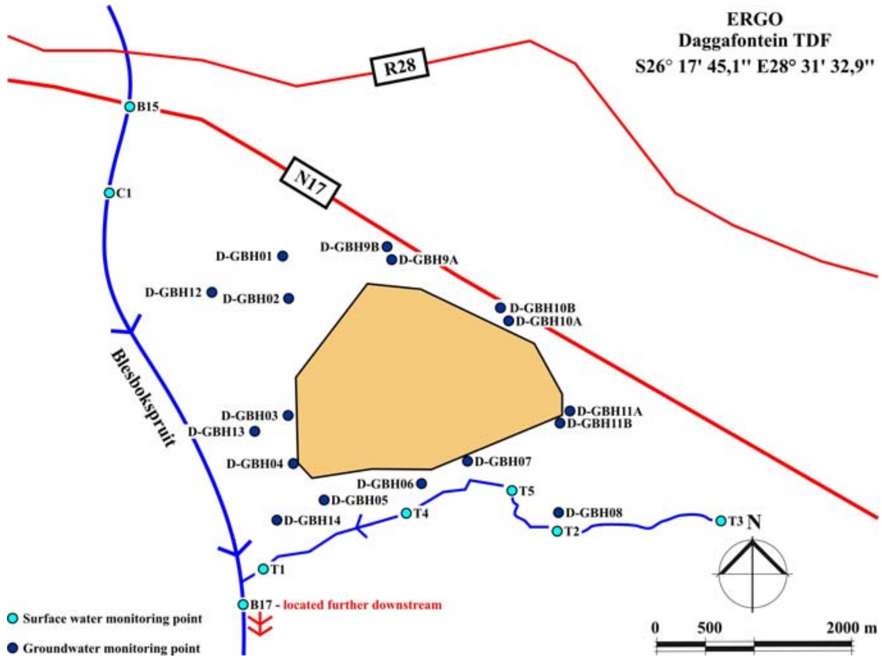


Figure 96: Water monitoring points.

Prior to the onset of cycloning at the ERGO Daggafontein tailings impoundment in 1987, rest water level data recorded in exploration boreholes indicated that groundwater flow took place towards the Blesbokspruit to the West and a tributary of this river to the South (Blecher and Bush, 1993). However, rest water levels determined during December 1995 indicate that groundwater flow in the phreatic Karoo aquifer now takes place towards the north-east and south-east over much of the site, and has a South to south-westerly component in the vicinity of borehole D-GBH07.

Drainage in the underlying dolomite aquifer presently takes place towards the north-east and south-east, and it is significant that rest water levels have dropped by up to 7 m along the eastern margin of the tailings impoundment between 1993 and 1995, whilst water levels determined in monitoring boreholes along the western boundary of the impoundment remained virtually static over the same period (Demmer and Hearne, 1996).

Groundwater quality in the two aquifers which underlie the Daggafontein tailings impoundment has been monitored on an irregular basis over the last ten years in a series of multiple piezometers which are located around the western and southern margins of the site, as indicated by Figure 92 (p. 172).

Surface water quality

Discontinuous surface water quality data is available for many sampling points along the two watercourses in the vicinity of the ERGO Daggafontein tailings impoundment. The following five surface monitoring points are discussed (Figure 96, p. 177):

- Sampling point T1, on the un-named watercourse located to the South of the impoundment, lies just upstream from the confluence with the Blesbokspruit.
- Sampling point T2, on the un-named watercourse located to the South of the impoundment, lies upstream from T1.
- Sampling point C1, on the causeway crossing the Blesbokspruit, is located to the West of the impoundment. The monitoring at C1 was discontinued in 2001.
- Upstream sampling point B15 is at the Blesbokspruit and N17 road crossing.
- Downstream sampling point B17 lies within the Marievale Bird Sanctuary. Other pollution sources exist on the western side of the Blesbokspruit between the impoundment and point B17. These sources are mainly mine residue deposits and are likely to impact on the Blesbokspruit.

The water samples taken from the monitoring points were tested for a broad spectrum of parameters. As high levels of sulphates, chlorides or conductivities in water samples are considered indicative of possible pollution from typical gold mine residue deposits, these parameters were considered in more detail. Levels of these key determinants become elevated due to the oxidation of sulphate-bearing pyrite residues present in the ore body, resulting in sulphuric acid formation and subsequent seepage from the dumps which impacts on both the surface and groundwater systems. The acid water generated may also mobilise other contaminants such as metals, leading to an increase in the total dissolved solids content of the water as reflected by elevated conductivity levels.

An analysis of conductivity, sulphates and pH data indicates that sulphate:

- concentrations have the greatest spatial and temporal variations throughout this area; and
- would be a reliable indicator of pollution from the tailings impoundment.

As samples are taken fortnightly and depending on the weather conditions and accessibility to the sites, it is unlikely that instantaneous pollution events, such as a paddock wall being breached, would be picked up by the monitoring system. Unless the water samples are taken shortly after an incident, pollutants released into the nearby water courses would not be picked up. The other obvious source of surface stream contamination is the visible occurrence of seepage zones along the southern tributary stream and associated areas of salt crystallisation. Salts precipitate along the stream where the perched aquifer daylights. The crystallised salts are flushed into the stream after heavy rains.

Some indication of the tailings impoundment's contribution to surface water salt loads can be obtained by comparing the concentrations of T1 and T2. While upstream areas occasionally contribute to the salt load in the stream, T1 concentrations are significantly higher than those observed at T2 indicating that:

- pollution is entering the system between these monitoring sites T1 and T2; and
- the most likely source is the ERGO Daggafontein tailings impoundment given its size and proximity.

Recurring association between high stream sulphate concentrations and rainfall events are of significance, which suggests that pollution is being flushed into the watercourse as part of the surface runoff. Patches of tailings material were also observed in the southern tributary (spruit) during field investigations.

If the impoundment is the pollution source, it implies that:

- the capacity of existing infrastructure has been exceeded during operation – it must be noted that site surface runoff conditions improved after November 2001 when decommissioning started; or
- pollutants contained in shallow aquifers are mobilized into site runoff during high rainfall events.

The ERGO Daggafontein tailings impoundment has been decommissioned with the following implications:

- no more water and tailings material are pumped or disposed onto the facility; and
- the return water dam, containment structures and canals are maintained to manage seepage water.

Blesbokspruit wetland

The Blesbokspruit wetland area comprises approximately 2000 ha privately and state owned land and is located to the East of Springs. This area covers approximately a 20 km section of the Blesbokspruit, which stretches from Grootvlei in the North to Marievale in the South. The wetland site was given Ramsar status in 1986.

The Blesbokspruit wetland system is currently influenced by:

- man-made structures such as bridges, causeways and embankments crossing the Blesbokspruit and restricting flow; and
- effluent released from mines, industry and waste water treatment works.

Effluent causes water eutrophication favouring vast reedbeds such as those established in the spruit. Reed such as *Phragmites australis* and *Typha capensis*, and sedges such as *Juncus* spp. and *Cyperus* spp. dominate the wetland. *Paspalum dilatatum* fringes the permanently waterlogged sections of the spruit while grasslands dominate drier areas.

Water quality data for the Blesbokspruit was sourced from the 2001 and 2003 Rand Water annual reports and contains a substantial body of data predating the impoundment. The information is useful to determine baseline surface water quality. The Rand Water monitoring sites are positioned both upstream and downstream of the ERGO Daggafontein tailings impoundment site. Sampling point C1 is immediately upstream of the impoundment. Prior to ending the sampling at C1 in October 2001, the total dissolved salts (TDS) concentrations at C1 were all above the unacceptable limit of > 500 mg/ℓ for the Blesbokspruit catchment in-stream target water quality requirements. The Grootvlei mine has permission from DWAF to discharge groundwater at a maximum rate of 96 Mℓ/day into the Blesbokspruit which contributes to the elevated salt concentrations measured at C1.

Levels of sulphates at points B17 are similar or better to those found further upstream at point B16. Sampling point T1 along the un-named watercourse located to the South of the impoundment and immediately upstream from the Blesbokspruit confluence have recorded high and elevated levels of sulphate mainly due to spillages and mismanagement at the impoundment.

Although the water quality in the Blesbokspruit's mini sub-catchment is improving, as measured at the catchment outflow (B17), it cannot be determined what influence the ERGO Daggafontein tailings impoundment has had, or is having on the water quality without sampling at additional points along this section of the Blesbokspruit.

Surface runoff

The ERGO Daggafontein tailings impoundment is situated within the catchment of the Vaal Barrage in the East Rand, and is contained within the boundaries of Rainfall Zone C2A, Catchment Zone C21E and Evaporation Zone 11A with a mean annual S-Pan evaporation depth of 1650 mm (Midgley, Pitman and Middleton, 1994). The closest registered rainfall measuring station to the site is that at Springs RWB (Midgley et al., 1994; Station No. 0476 736). The next closest rainfall measuring station is that at Nigel (Midgley et al., 1994; Station No. 0476 835). The statistics are given in Table 30 below.

Conceptual water control

Section 4 of Regulation No. 704, promulgated in terms of the National Water Act No. 36 of 1998 (NWA), requires that a mine residue deposit, i.e. tailings impoundment, must be located outside the 1:100 year flood line or 100 m from the centre of a watercourse. The ERGO Daggafontein tailings impoundment complies with this requirement. Section 5 of Regulation 704 also requires that the capacity of a dirty water system be designed to accommodate the 1:50 year recurrence interval event, and that any dam or holding facility shall have an additional 0,8 m freeboard above full supply level.

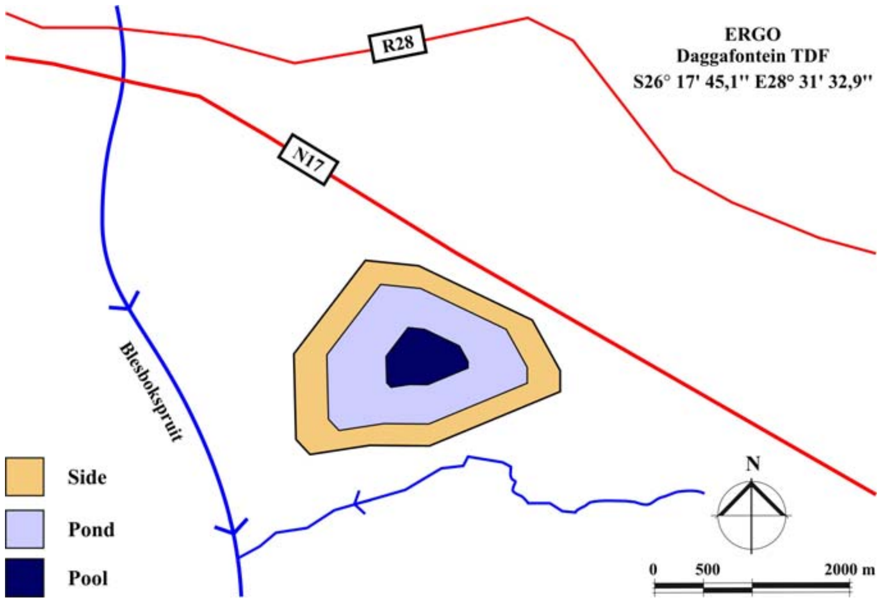


Figure 97: Delineation of the impoundment catchments for quantifying runoff.

Considering the site itself, if a configuration with an approximate physical footprint of 300 ha is chosen portions will be covered by the side slopes, pond and pool. The areas are indicated on Figure 97 and it can be assumed that the entire area contribute to runoff.

Table 30: Springs RWB and Nigel - 1 measuring station localities (Midgley et al., 1994).

Station	Lat.	Long.	MAP (mm)	Years of record
Springs RWB	26°16'	28°25'	658,7	60
Nigel - 1	26°25'	28°28'	705,7	73

Table 31: Preliminary estimate of surface runoff over pond surface, basin and embankment.

	Rain	Rainfall MAP	Evaporation	S-Pan evaporation rates	Pan factor free surface	Runoff pool surface	Rainfall over basin	Runoff over sides
Date	**%**	**mm**	**%**	**mm**		**m^3**	**m^3**	**m^3**
Jan	17,62	116,1	12,23	183,6	0,84	55124	183748	12543
Feb	13,15	86,6	9,86	148,0	0,88	41140	137133	9361
Mar	11,67	76,9	8,96	134,5	0,88	36510	121699	8307
Apr	6,42	42,3	6,55	98,3	0,88	20085	66950	4570
May	2,79	18,4	4,94	74,1	0,87	8729	29095	1986
Jun	1,13	7,4	3,78	56,7	0,85	3535	11784	804
Jul	1,11	7,3	4,22	63,3	0,83	3473	11575	790
Aug	1,05	6,9	6,12	91,9	0,81	3285	10950	747
Sep	3,62	23,8	8,61	129,2	0,81	11325	37751	2577
Oct	10,09	66,5	10,97	164,7	0,81	31567	105222	7183
Nov	15,71	103,5	11,39	171,0	0,82	49149	163829	11183
Dec	15,64	103,0	12,37	185,7	0,83	48930	163099	11133
Total	100,00	658,7	100,00	1501,0	-	312851	1042835	71185

A preliminary water balance was prepared based on regional average monthly rainfall and evaporation statistics obtained from Midgley et al. (1994) (Table 31, Figure 98). It is estimated that approximately 71 000 m^3 will fall on the side slopes, 310 000 m^3 run from the pool to the pond and 1 043 000 m^3 will fall directly on the entire basin.

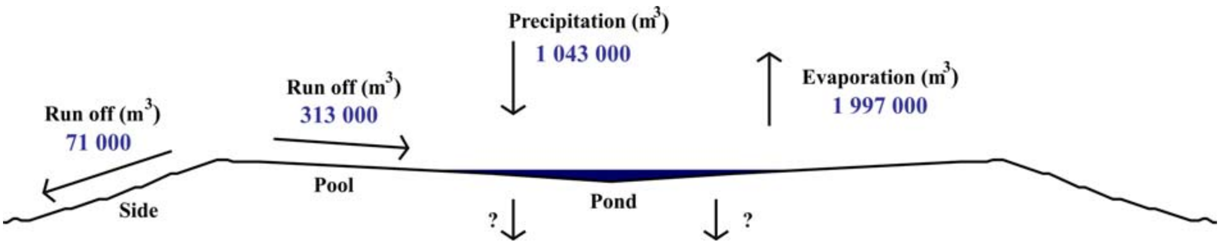


Figure 98: Conceptual water balance diagram.

The foregoing is only a preliminary theoretical appraisal and does not take local site conditions into account. In addition, the calculation does not allow for extremes. Nevertheless it does give an indication of the apportionment and magnitude of surface runoff which needs to be contained and managed.

3.3.5 Air

Suspended particles

The ERGO Daggafontein impoundment is situated within a region used for agriculture, industry, and mining and includes several primary metal smelters. An emission inventory of scheduled processes in the area is maintained by the Chief Air Pollution Control Officer from the Department of Environment Agriculture and Tourism (DEAT). A major section of the population relies on bituminous coal for domestic energy requirements. Traffic also contributes to emissions. Townships such as Springs and Nigel were established as a result of the underground gold mine operations in the region and are now extensively surrounded with mine residues deposits. Although some of these tailings dumps were vegetated as a pollution prevention measure, many impoundments remain that are not adequately covered. In some cases, the vegetative protective cover has deteriorated to expose bare tailings.

Reclaiming old mine residue deposits exposes sand and tailings to wind which contribute to wind-blown dust. Traffic-generated dust from unpaved roads is a minor secondary source, especially in urban areas and informal settlements. Frontal weather passing over surrounding maize farming areas contributes to intermittent dust storms. Moreover, the area is under the influence of elevated gaseous sulphurous concentrations attributable to emissions from power plants and from industrial and domestic use of coal.

The above sources of contamination have caused the levels of suspended particulates to exceed the annual guideline values for more than 25 % of the time. Domestic coal burning was found to account for about 50 % of the annual average concentration of suspended particulates; road dust for 16 % and industrial emissions for the remaining 34 %. The ambient air quality in the region is generally poor, specifically with regard to fine particulates.

Dustfall

Dustfalls, both near exposed gold mine tailings and at urban control sites, show distinct seasonal variations governed by wind and rainfall. The highest dustfalls occur in spring, caused by increasing wind speeds before the onset of spring rains. Dustfalls in summer are reduced due to rainfall, despite continued high winds. The dry months, March through July, have the lowest dustfalls. Despite the dryness, low wind speeds associated with frequent subsidence inversions result in low dust emissions. Conversely, the inversions contribute to trapping of domestic, traffic and industrial emissions, resulting in highest suspended dust concentrations during winter.

The monthly average dust fallout rates were determined for the Daggafontein tailings facility during the operation stage. A heavy fall-out (501 to 1 200 $mg/m^2/day$) zone was confined to a strip of between 500 m and 1 000 m towards the north-east and south-east of the tailings impoundment. Recent settable dust monitoring (October 2002 to January 2003) indicated that fall-out dust is currently in the slight (less than 250 $mg/m^2/day$) to moderate (251 to 500 $mg/m^2/day$) range.

Sporadic high levels of settable dust can be experienced during the winter months which is attributed to the mechanical re-profiling (earthworks) of the embankment slopes of the tailings impoundment. This will continue until the rehabilitation of the embankments is complete.

PM_{10} ambient air quality

A measured annual average value for PM_{10} at the Springs Old Boys Club for 2006 is 41 µg/m³ and the annual average estimated ambient concentration value, determined by means of modelling, for the ERGO Daggafontein area is 28 µg/m³ (Liebengerg-Enslin, 2006)

Radioactivity

ERGO (2004:4) states that radiation-related studies considered the following main potential exposure pathways:

- inhalation of radon gas containing radon (Rn) and its short lived progeny originating from tailings impoundments;
- inhalation of radio active dusts containing long-lived alpha-emitting nuclides, also originating from tailings impoundments; and
- external exposure to gamma radiation, also originating from tailings impoundments.

Ingestion or consumption of water potentially contaminated with radioactive particulates as well as ingestion of foodstuffs contaminated with radioactive particulates were also investigated and found to be inconsequential.

The findings of the investigations indicated that water is the most likely contributor of radio activity to the public dose. The maximum dose an adult will be exposed to is about 245 µSv/annum, and that of a fifteen year old, is 416 µSv/annum. The dose is the maximum that can be encountered on the site and is well below the internationally accepted public dose limit of 1 000 µSv/annum.

Studies conducted on three mines with high uranium content in their ores, indicated the highest inhalation dose of dust at these mines was only 47 µSv/annum. The findings also indicated that the highest dose due to the ingestion of vegetables is 2 µSv/annum.

The gamma dose is negligible compared to the background dose expected on the tailings impoundments. These areas are forbidden to the public and the dose rate is therefore of no consequence.

3.3.6 Vegetation

Of the more than 1000 species of trees and shrubs found in South Africa, more than 50 occur naturally in this region. The study area is a transitional region between the following two vegetation types (Low and Rebelo, 1996):

- Moist cool highveld grassland; and
- Rock highveld grassland.

Moist cool highveld grassland

Vegetation within the site and surrounding area is classified by Acocks (1988:100) as *Cymbopogon-Themeda* veld and classified by Low and Rebelo (1996) as Moist Cool Highveld Grassland. Dominant species within this tufted grassland include *Themeda triandra, Heteropogon contortus, Eragrostis superba, Elionurus muticus, Cympopogon pospischillii, Setaria sphacelata,* and forbs include large stands of *Crinum bulbispermum* and *Erythrina zeyheri*, *Ipomoea obscura* and *Vernonia oligocephala.*

According to Bredenkamp and van Rooyen (1996), when in pristine condition, *Themeda triandra* dominates this vegetation type.

Tainton (1999) suggests that these grasslands are relatively unstable and readily break down due to mismanagement. Disturbed areas are usually invaded by species such as *Eragrostis curvula, Sporobolus pyramidalis and Cynodon dactylon*. *Hyperrhenia hirta* follows these species in the 'recovery phase' and seems to remain dominant for many years. This is in agreement with Bredenkamp and van Rooyen (1996), who state that Moist Cool Highveld Grassland or *Themeda-Cymbopogon* veld, when overgrazed, replaces *Themeda triandra* (Red Grass) with species such as *Eragrostis curvula*.

Rocky highveld grassland

Rocky Highveld Grassland (Bredenkamp and van Rooyen, 1996) is a transitional vegetation type between grasslands of the high inland plateau and the bushveld of the lower plateau and is therefore also known as the central variation of Bankenveld (Acocks, 1988) that is typical of altitudes between 1 500 and 1 600 m.a.s.l. The ridges of the Witwatersrand and the dolomite plains of Gauteng fall within this vegetation type.

Characteristic grass species include *Diheteropogon amplectens, Trachypogon spicatus, Schizachyrium sanguineum,* and *Panicum natalense.* This vegetation type supports a diverse herbaceous stratum that includes dominant species such as *Senecio venosus, Senecio coronatus, Acalypha angustata, Pearsonia cajanifolia* and *Vernonia oligicephala.* Afromontane affinities are also evident through the presence of species such as *Alloteropsis semialata.* Woody elements of Zambezian affinity occur as temperate mountain bushveld and include species such as *Rhus pyroides, Rhus magalismontana, Rhus rigida, Celtis africana, Vangueria infausta, Canthium gilfillanii, Englerophytum magalismontanum, Ancylobotrys capensis* and *Protea caffra* (Bredenkamp and van Rooyen, 1996).

Acocks (1988) maintaines that the climax of this vegetation type would have been characteristic of woodland or open savannahs dominated by *Acacia caffra* were it not for the regulatory role of fires. Unfortunately, this grassland type is under severe threat from urbanisation, industrialisation, mining and agriculture, especially in Gauteng. Very few reserves have been proclaimed or set aside to protect this vegetation type within the Gauteng province and only a mere 1,38 % is conserved, while approximately 65 % is already transformed (Bredenkamp and van Rooyen, 1996).

ERGO Daggafontein impoundment site

Prior to the establishment of the ERGO Daggafontein tailings impoundment, the vegetation on the site consisted mainly of short grassland and the cultivated areas were used to plant maize and beans. The typical plant species occurring presently on site are shown in Table 32.

Table 32: Plant species that occur on site.

Botanical name	**Common name**
Acacia karroo	Soetdoring
Acalypha angustata	
Asparagus suaveolens	
Berkheya radula	Boesmanrietjie
*Bidens pilosa**	Black jack
*Cortaderia jubata**	Pampas grass
*Cortaderia selloana**	Pampas grass
Crassula capitella	Plakkie
Cymbopogon pospischillii	Turpentine grass
Cynodon aethiopicus	Star grass
Cynodon dactylon	Couch grass or "kweek"
Cyperus spp.	Sedge
*Datura stramonium**	Common thorn apple
Digitaria eriantra	Smuts finger grass
Eragrostis curvula	Weeping love grass
*Eucalyptus sp.**	Blue gum
Hyperrhenia hirta	Common thatch grass
Hypoxis hemerocllidea	African potato
Juncus spp.	Sedge
Ledebouria spp.	Slime onions
Panicum maximum	Blue buffalo grass
*Pennisetum clandestinum**	Kikuyu
Pennisetum macrourum	Hippo grass
Phragmites australis	Common reed
*Tagetes minuta**	Tall khakiweed
*Tamarix ramosissima**	Pink tamarisk
Temeda triandra	Red grass or "rooi gras"
Typha capensis	Bullrush

* denotes exotic plant sepcie.

3.3.7 Wildlife

Birds

Some birds migrate seasonally to and from an area, while others are resident to the area. In dry and wet years birds may migrate to different areas, according to their foraging, breeding, resting and nesting needs. Rainfall therefore plays a major role in the distribution of birds in an area. At least 286 bird species have been recorded in the Blesbokspruit reserve. The Blesbokspruit supports significant numbers of waterfowl, including yellow-billed duck (*Anas undulata*), redbilled teal (*Anas erythrorhycha*) and spur-winged geese (*Plectropterus gambensis*) in the dry season, when water levels are maintained artificially at a high level. Water provides food for greater flamingo (*Phoenicopterus ruber),* lesser flamingo (*Phoenicopterus minor*) and goliath heron (*Ardea goliath*). Other notable birds include avocet (*Recurvirostra avosetta*), purple heron (*Ardea purpurea),* spoonbill (*Platalea alba*), gloss ibis (*Plegadis falcinellus*) and yellow-billed stork (*Mycteria ibis*). The African marsh harrier (*Circus ranivorus*), which has been displaced from veld areas, maintains a strong population here. Table 33 below lists the most common bird species likely to be found on site.

Table 33: Commonly occurring bird species.

Scientific name	Common name	Scientific name	Common name
Actitis hypoleucos	Common Sandpiper	*Lanius collaris*	Common Fiscal
Amadina erythrocephala	Red-headed Finch	*Larus cirrocephalus*	Grey-headed Gull
Anas capensis	Cape Teal	*Lybius torquatus*	Black-collared Barbet
Anas erythrorhyncha	Red-billed Teal	*Milvus [migrans] parasitus*	Yellow-billed Kite
Anas smithii	Cape Shoveller	*Motacilla capensis*	Cape Wagtail
Anas undulata	Yellow-billed Duck	*Netta erythrophthalma*	Southern Pochard
Anhinga rufa	African Darter	*Onychognathus morio*	Red-wing Starling
Apus caffer	White-rumped Swift	*Passer domesticus*	House Sparrow
Ardea cinerea	Grey Heron	*Passer melanurus*	Cape Sparrow
Asio capensis	Marsh Owl	*Phalacrocorax africanus*	Reed Cormorant
Batis molitor	Chinspot Batis	*Phalacrocorax lucidus*	White Breasted Cormorant
Bostrychia hagedash	Hadeda Ibis	*Phoenicopterus ruber*	Greater Flamingo
Bradypterus baboecala	Little Rush-Warbler	*Phoeniculus purpureus*	Green Wood-hoopoe
Bubulcus ibis	Catte Egret	*Plectropterus gambensis*	Spur-winged Goose
Burhinus capensis	Spotted Thick-knee	*Plegadis falcinellus*	Glossy Ibis
Centropus burchellii	Burchell's Coucal	*Ploceus capensis*	Cape Weaver
Ceryle rudis	Pied Kingfisher	*Ploceus xanthops*	Golden Weaver
Chlidonias hybrida	Whiskered Tern	*Porphyrio madagascariensis*	African Purple Swamphen
Chlidonias leucopterus	White-winged Tern	*Pycnonotus tricolor*	Dark-capped Bulbul
Cisticola fulvicapilla	Neddicky	*Recurvirostra avosetta*	Pied Avocet
Cisticola tinniens	Levaillant's Cisticola	*Saxicola torquatus*	African Stonechat
Colius striatus	Speckled Mousebird	*Scopus umbretta*	Hamerkop
Columba guinea	Speckled Pigeon	*Serinus atrogularis*	Black-throated Canary
Cypsiurus parvus	African Palm-Swift	*Spreo bicolor*	Pied Starling
Delichon urbicum	Common House-Martin	*Streptopelia capicola*	Cape Turtle-Dove
Dendrocygna bicolor	Fulvous Duck	*Streptopelia semitorquata*	Red-eyed Dove
Elanus caeruleus	Blacks-houldered Kite	*Tachybaptus ruficollis*	Little Grebe
Emberiza capensis	Cape Bunting	*Threskiornis aethiopicus*	African Sacred Ibis
Estrilda astrild	Common Waxbill	*Trachyphonus vaillantii*	Crested Barbet
Euplectes orix	Southern Red Bishop	*Tyto alba*	Barn Owl
Falco naumanni	Lesser Kestrel	*Tyto capensis*	African Grass-Owl
Fulica cristata	Red-knobbed Coot	*Upupa africana*	African Hoopoe
Gallinago nigripennis	African Snipe	*Urocolius indicus*	Red-faced Mousebird
Gallinula chloropus	Common Moorhen	*Vanellus coronatus*	Crowned Lapwing
Himantopus himantopus	Black-winged Stilt	*Vidua chalybeata*	Village Indigobird
Hirundo fuligula	Rock Martin	*Vidua macroura*	Pin-tailed Whydah
Hirundo semirufa	Red-breasted Swallow	*Zosterops capensis*	Cape White-eye

Mammals

Mammals are a group of fur-bearing animals that suckle their young and maintain constant body temperature by generating metabolic heat. Possibly the most outstanding feature of mammals is their extraordinary range of size, shape and habits. In this respect they are unique among all groups of animals. There are about five thousand species of mammals on earth, belonging to some 20 orders. Of these, only seven orders are still represented in the Eastern Gauteng area. They are:

- bats (small flying mammals);
- primates (highest order of mammals including man);
- hares (medium size mammals with short tails, long ears and hind legs longer than fore ones);
- rodents (small mammals such as mice and rats);
- carnivores (large flesh-eating mammals including cats and dogs);
- hyrax (small rabbit-like mammals); and
- insectivores (small long-snouted mammal feeding mostly on insects).

Table 34 lists some of the common mammal species that occur on site.

Table 34: Commonly occurring mammal species.

Specie name	Common name
Canis mesomelas	Black-backed Jackal
Cryptomys hottentotus	Common Mole-rat
Lepus saxatilis	Scrub Hare
Mastomys coucha	Multi-mammate Mouse
Raphicerus campestris	Steenbok
Rhabdomys pumilio	Striped Mouse
Sylvicapra grimmia	Common Duiker

Reptiles and amphibians

Over time, the reptile species have dwindled in both size and variety until, out of seventeen orders, only four are left:

- crocodilians;
- lizards;
- snakes;
- chelonians (tortoises and turtles); and
- amphibians.

Reptiles are characterized by their scaly integument. They are exothermic, which means their body remains at the same temperature as their surroundings. This distinguishes them from the higher classes of vertebrates, birds and mammals. Reptiles have come to occupy almost all available niches in their environment through some remarkable adaptations. Eastern Gauteng is no exception, and a variety of reptiles remain in this area. Some of the more commonly occurring species are listed below in Table 35.

Table 35: Commonly occurring herpetofauna.

Specie name	Common name
-	Worm Snake (various spp.)
Agama hispida	African Spiny Agama
Bufo gutturalis	Guttural Toad
Bufo rangeri	Raucous Toad
Cordylus vittifer	Transvaal Girdled Lizard
Dasypeltis scabra	Common Egg-eater
Duberria variegata	Southern Slug-eater
Geochelone pardalis	Leopard Tortoise
Gerrhosaurus flavigularis	Yellow-Throated Plated Lizard
Hemachatus haemachatus	Rinkhals
Lamprophis inornatus	Olive House Snake
Mabuya striata	Striped Skink
Pelomedusa subrufa	Marsh Terrapin
Psammophylax tritaeniatus	Striped Skaapsteeker
Pseudaspis cana	Mole Snake
Varanus niloticus	Water Monitor

Fish

Many species of fish live and breed in the rivers and its system of tributaries, in Eastern Gauteng. From time to time several of these species move up into the headwater streams which drain Eastern Gauteng. The different species described in this chapter are those which are commonly found here. More fish would probably occur here was it not for water pollution by humans, factories, mines and industries. Urban engineering in the form of concrete canals and sewers has also contributed to the paucity of both the numbers and variety of fish species. Table 36 below lists commonly occurring fish found in the rivers of Eastern Gauteng – confirmed by specialist input and Skelton (1993).

Table 36: Typical fish species that occur in the rivers of Eastern Gauteng.

Specie name	**Common name**
Anguilla bengalensis labiata	African Mottled Eel
Barbus spp.	Minnow (Various spp.)
Clarias gariepinus	Sharptooth Catfish
*Cyprinus carpio Linnaeus**	Carp
*Gambusia affinis**	Mosquitofish
Labeo capensis	Orange River Mudfish
Labeo umbratus	Moggel
Labeobarbus aeneus	Smallmouth Yellowfish
*Micropterus salmoides**	Largemouth Bass
Oreochromis mossambicus	Mozambique Tilapia
Pseudocrenilabrus philander	Southern Mouthbrooder

* denotes exotic fish specie

3.4 Visual

3.4.1 Introduction

This part of the research examines the visual impacts of tailings impoundments in order to express them in quantifiable terms rather than descriptive terms as it has not been done before and is required for inclusion in the overall costing system. The visual impact forms part of the overall environmental impact and engineering cost model for the rational evaluation of tailings impoundments with an emphasis on post-closure land use.

The overall environmental impact and engineering cost model provides a framework that:

- informs the planning and design process when considering tailings impoundment configuration alternatives;
- provides a platform for constructive discussion with relevant regulatory authorities; and
- provides a neutral basis on which to consult with stakeholders.

This study determines the level of visual perception over viewing distance within the zone of visual influence (ZVI) and utilizes the nominal group technique (NGT) study method. The technique is used to reach consensus on results within a field of study often considered to be subjective.

The research aims to determine the following three critical perception thresholds where:

- a viewer becomes aware of a deposit within the landscape;
- a deposit is detected as a man-made landform within the natural landscape; and
- a deposit is recognized as a tailings impoundment.

The thresholds are obtained through projecting computer simulated images with modified visual attributes such as shape, surface, size, and landscape type within a controlled environment. Analysis reveals average and specific thresholds of high reliability.

The NGT study method, a specific application of the Delphi technique, was applied using participants knowledgeable in this field to reach consensus on the thresholds. This NGT is one of many methods used for combining expert knowledge and is appropriate especially where intensive field sampling cannot be undertaken under prevailing time and cost constraints. All the participants were planning professionals and most were landscape architects with experience in environmental planning and visual impact assessment.

Viewing distance, context and landscape character are all factors that influence the visibility of a tailings impoundment. Intuitively the visibility of an impoundment will decrease with increasing viewing distance. An impoundment can either dominate an environmental setting (contrast significantly with the landscape character) or be dominated by elements within the landscape (be visually absorbed by the landscape).

3.4.2 Visual impact

Aesthetics is generally accepted to be a subjective matter. The Department of Minerals and Energy (DME) requires that a tailings impoundment should blend into the landscape and the visible portions of the impoundment suitably covered. The lack of specific regulation bears testimony to the difficulty in prescribing solutions, for what may be regarded as primarily, a subjective matter.

In part the research attempts to reduce this subjectivity and introduce a rational approach which can express the potential visual impacts in terms of cost and thus form a manageable component of the general engineering model.

Theoretically the problem is twofold:

- rational assessment of the potential visual impact of a proposed tailings impoundment (or that of an existing impoundment) eliminating the concepts of aesthetic value judgements; and
- conversion of the assessed or measured impact into a cost which can be compared with other environmental impact costs and accounted for in the total project costs.

The following section of the study concentrates on the former aspect of impact measurement. The cost aspect although only briefly discussed here is dealt with in more detail in Section 6.2 of the thesis.

3.4.3 Mitigation

Debate often arises when attempting to classify an impact as being significant or non-significant. Significant means "...an impact large enough to require consideration and possible mitigation...", while non-significant means "...too small to be worth consideration" (Stamps, 1997:250). This classification is important to the stakeholders responsible for implementing mitigation measures, as it could mean extensive financial commitments. Many environmental practitioners distort the purpose and implementation of mitigation. Any scheme should be seen as an extension of the existing landscape and should respect the local environmental context. Consequently, mitigation should be an iterative part of the design process in order to improve its success (Figure 99).

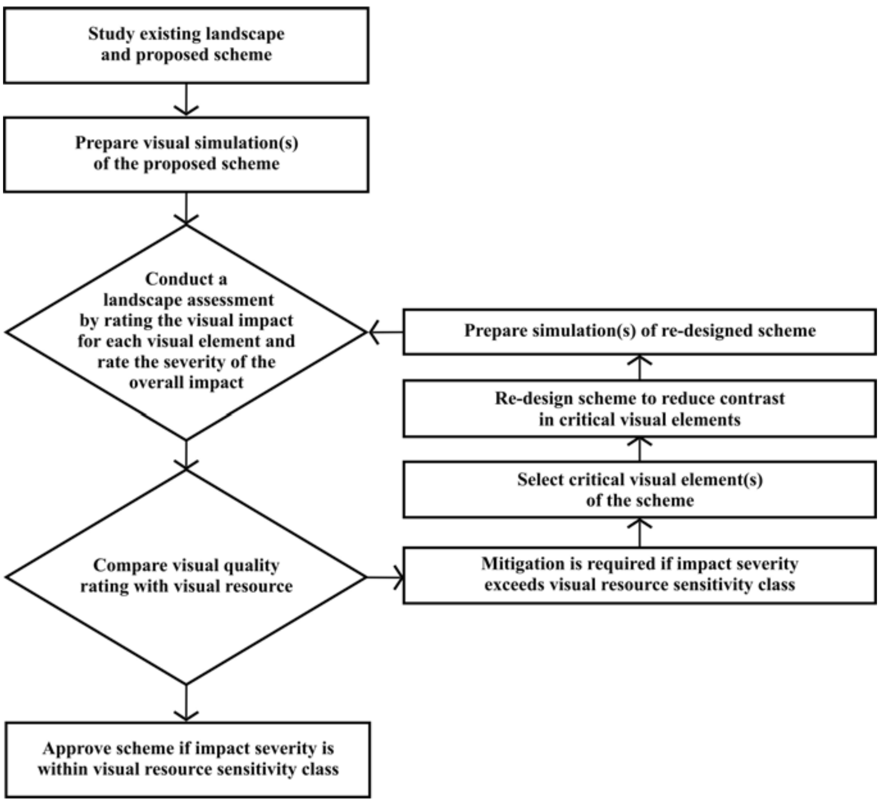


Figure 99: Mitigation procedure for a typical scheme (Smardon et al., 1986:216).

The purpose of mitigation is to avoid, reduce, and where possible, remedy or offset any significant adverse effects on the environment arising from a scheme. If integrated environmental planning and design principles are applied, together with a flexible approach to design, a high degree of mitigation can be proactively built into a scheme from the outset, thereby reducing the extent or scale of adverse effects (Landscape Institute, 2002:43).

Mitigation measures can be divided in two categories:

- Primary measures. An intrinsic part of the scheme design through an iterative process.
- Secondary measures. These specifically address the residual negative effects of the final scheme.

Mitigation is often relied on to reduce visual and also other impacts to acceptable levels. It is a common misconception that mitigation is remediative, attempting to resolve negative impacts once identified. The true value of mitigation can only be appreciated when it is part of an iterative integrated planning and design process.

Some of the more common mitigation measures include:

- the sensitive choice of site and location of an impoundment; and
- the choice of an appropriate configurations when designing a tailings impoundment.

Many tailings impoundments cannot be screened nor is it always desirable or practicable to do so. In such circumstances it is important to camouflage or disguise a scheme. Tailings impoundment design can incorporate visual attributes such as form (shape and size), line (silhouette), colour (shine, shadow and shade), and texture (surface) to reduce the visual influence and result in a landform that blends more readily into the landscape (Figure 100).

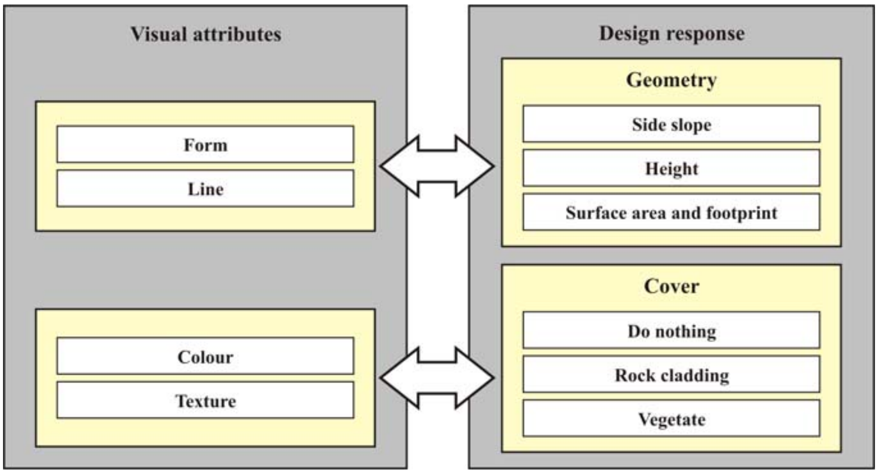


Figure 100: Visual configuration attributes and corresponding design responses for a tailings impoundment.

3.4.4 Study method

The visual zone of influence study method comprises the following steps and is covered in the section indicated in the subtitles:

Visualisation of various impoundment configurations (Section 3.4.5 to 3.4.8)

- Define the configurations to be visualised.
- Select a test impoundment.
- Photograph the test impoundment.
- Manipulate photographs to simulate different impoundment configurations.
- Present the visualisations to a panel of experts.

Analysis of data (Section 3.4.9)

- Analyse the results using the nominal group technique (NGT) and develop visual perception distance data for the various impoundment configurations.

Illustration of the results by example and confirmation of findings (Section 4.2.1)

- Apply the results in the field to test its efficacy.
- Confirm the results and findings by presenting such to a panel of experts.

3.4.5 Configurations

The final impoundment material layer can consist of the following:

- tailings in situ (no cover);
- topsoil (imported soil suitable to sustain plant growth);
- rock cladding (rip-rap); and
- armouring (cover consisting of a rock and soil mixture)

The vegetation cover on the tailings impoundment consists of:

- grass; and
- diverse vegetation (diversity of plant species).

An overall embankment slope of 1:3 (vertical to horizontal) is the current practice for most upstream deposited tailings impoundments. A 1:6 slope configuration was chosen as an alternative as it is considered to enhance vegetation establishment as well as to test the common opinion that flatter embankment side slopes reduces visual impact. The visual perception scenarios simulated for the study are summarised in Table 21 (p. 162).

3.4.6 Selection of test impoundment

In order for the study to deliver conservative results, a tailings impoundment representative of the typical impoundment height, shape, side slope configuration, and cover had to be located. It is also preferred that the test impoundment site should be within an environment with a low visual absorption capacity (low capacity to camouflage the visual impact of the impoundment). It was therefore important to find a landscape:

- with a relatively flat topography covered with typical grassland;
- which allowed direct lines of sight to the impoundment; and
- with little or no clutter caused by other visual elements.

The ERGO Daggafontein tailings impoundment complies with the criteria and was therefore chosen. The impoundment lies within a typical highveld grassland environment with a rural, relatively flat and rolling topography, minimal visual clutter as a result of man-made structures such as buildings, roads and transmission lines. Unobstructed photographs could be taken up to distances of 8 km. It is an exceptionally large tailings impoundment allowing the testing of worst-case scenarios and expecting conservative results. The impoundment is at different rehabilitation stages with a variety of surfaces.

This particular impoundment is one of the largest of its kind in the world and covers an approximate area of 450 ha extending for about 2,8 km along an east-west axis and 2,2 km along its north-south axis. It was designed as a free-standing upstream cycloned ring-dyke impoundment with the outer perimeter wall built from coarse cycloned underflow impounding the fine tailings overflow. The toe of the tailings impoundment at the south-western corner is also the lowest point with an elevation of about 1578 m.a.s.l. and a maximum height of about 68 m (Figure 86, p. 165).

The impoundment is in various stages of rehabilitation with the embankments slopes being mechanically flattened to an approximate step-in angle of 19° with 13 m vertical steps and 7 m wide benches. The flattened embankment slopes are covered with a mixture of topsoil and rock applied as armouring against wind and water erosion. It has been proposed to return the impoundment to a wilderness land use category once establishment with grass (Wates et al., 2001).

The impoundment is surrounded by agricultural land used for grazing and cultivation of maize, sunflowers and beans. The Blesbokspruit and associated wetlands are located to the West. A tributary to the South joins the Blesbokspruit at the northern boundary of the Maryvale bird sanctuary. The regional topography is fairly flat and rolling with the site sloping gently in a westerly direction towards the Blesbokspruit (Figure 101).

[1] Looking north-east over ERGO Daggafontein tailings impoundment.

[2] Looking South towards ERGO Daggafontein tailings impoundment. Photographs [1] and [2] with courtesy of AngloGold Ashanti.

Figure 101: Landscape setting of the ERGO Daggafontein tailings impoundment.

3.4.7 Photography of test impoundment

The ERGO Daggafontein tailings impoundment was photographed from distances ranging between 800 m and 8300 m. Global positioning system (GPS) points were taken around the base of the impoundment with a Garmin eTrex Personal Navigator GPS and photographs were then taken in a straight line from the GPS points to the impoundment (Figure 102) providing distance readings.

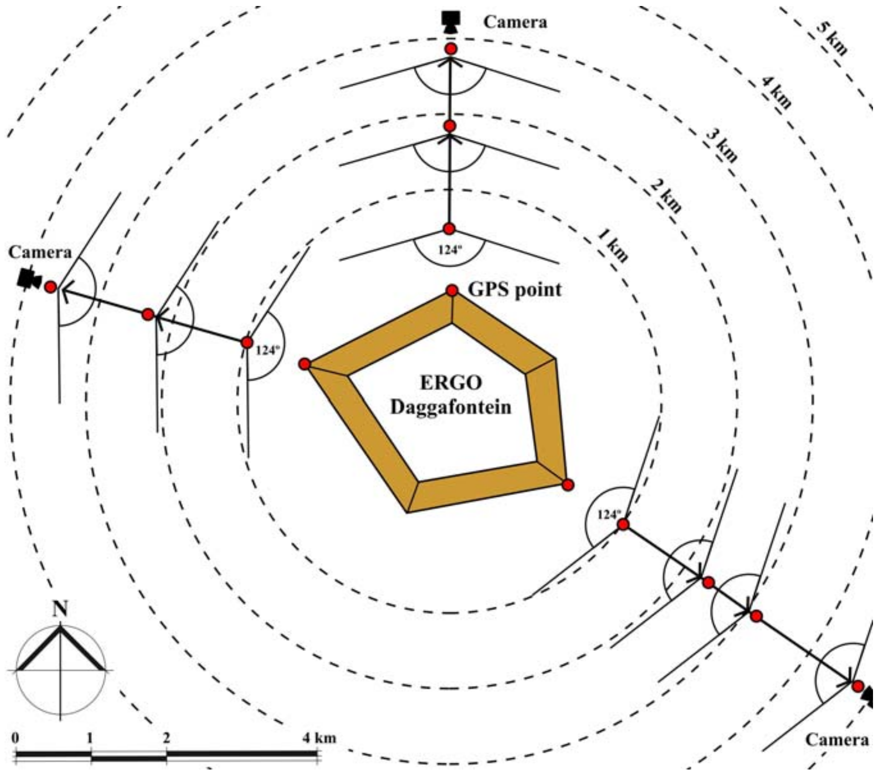


Figure 102: The test impoundment was photographed at various distances.

Effort was made to exclude major interfering man-made structures such as roads, masts and buildings in order to keep the photographs uncluttered. However, minor elements such as power lines, fences and farm buildings appear in some of the photographs. A Sony Cybershot P-92, 5 mega pixel high resolution digital camera was used in this study to give maximum clarity for computer manipulation and projection purposes.

Two sets of photographs were taken; one during late summer (13 May 2004) and the other during late winter (15 August 2004) since the surrounding landscape changes as a result of farming practices and seasonal changes.

Haze and smog experienced early in the day as a result of pollution and atmospheric conditions necessitated that photographs be taken late mornings on clear days. Photographs 1 and 2 in Figure 103 to Figure 105 indicate the same views during summer and winter respectively with the effect of smog clearly visible in the photographs taken during winter. Figure 103 (p. 195) compares two photographs of one of Grootvlei Proprietary Mine's impoundments taken from the same viewpoint and is a good example of the influence of seasonal change on visibility.

Figure 103: Looking South to a Grootvlei Proprietary Mine tailings impoundment.

Figure 104 and Figure 105 are both of the ERGO Daggafontein tailings impoundment and illustrate the influence of seasonal change on the visibility of an impoundment in the landscape. The dashed red lines are included to indicate the outline of the impoundment in the photographs.

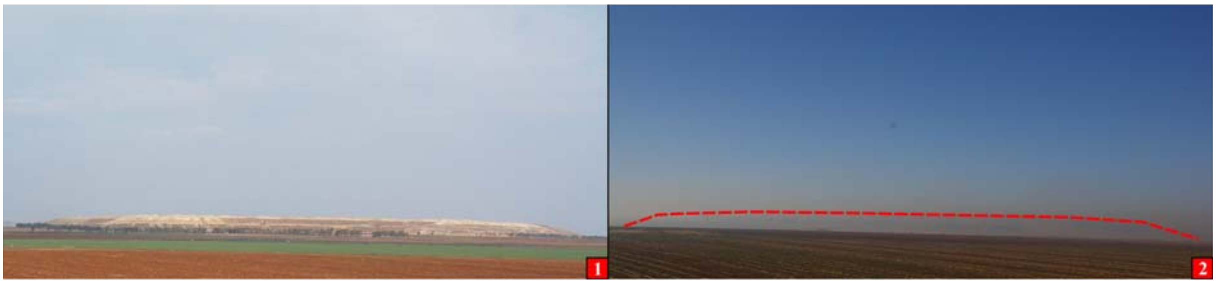


Figure 104: Looking south-east towards the ERGO Daggafontein tailings impoundment.

Figure 105: Looking north-west towards the ERGO Daggafontein tailings impoundment.

Photograph panoramas were composed by (Figure 106, p. 196):

- using a high resolution camera placed at eye level on a tripod to take the photographs;
- taking enough photographs to cover the 124º binocular human field of vision;
- expressing as much as possible of the vertical dimension of the scene within this field by taking photographs in portrait format;
- stitching the photographs together using PixMaker Pro (Developer Edition) Version 1,0; and
- cropping the stitched photographs into the final photograph panorama format for further electronic manipulation.

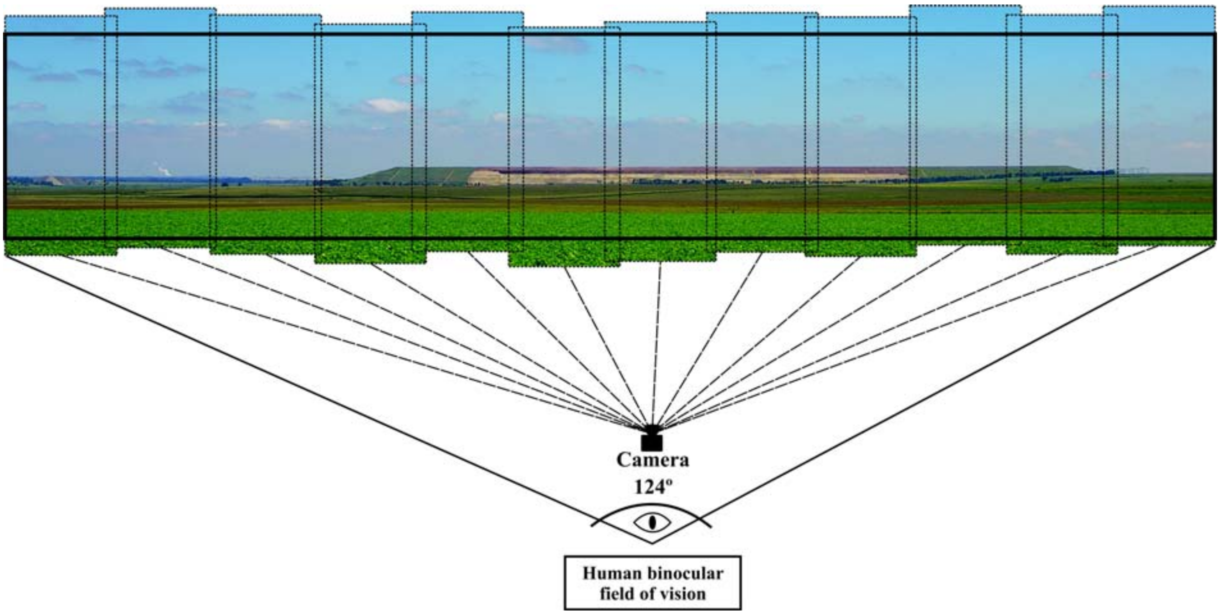


Figure 106: Photographs taken to form a 124° panorama scene.

3.4.8 Manipulation of site photographs

From the various visualisation techniques referenced, manipulating photographic panoramas is the most suitable approach within the context of this study. The methodology to evaluate different impoundment configurations has to be simple, time efficient, and reliable. Enough photographs of the ERGO Daggafontein tailings impoundment were taken making sure that a library of textures could be compiled and the appropriate ones isolated for later use. These textures were superimposed on to ERGO Daggafontein tailings impoundment photograph panoramas thus manipulating images directly and visualising different impoundment configurations (Figure 107 to Figure 109). This was done by retouching or painting the desired textures and colours utilising a photo editing software package such as Adobe Photoshop 7.0 onto the original photo image. Sixty-eight different tailings impoundment configurations were graphically produced and presented to a panel of experts who evaluated the different visualisations through the NGT study method.

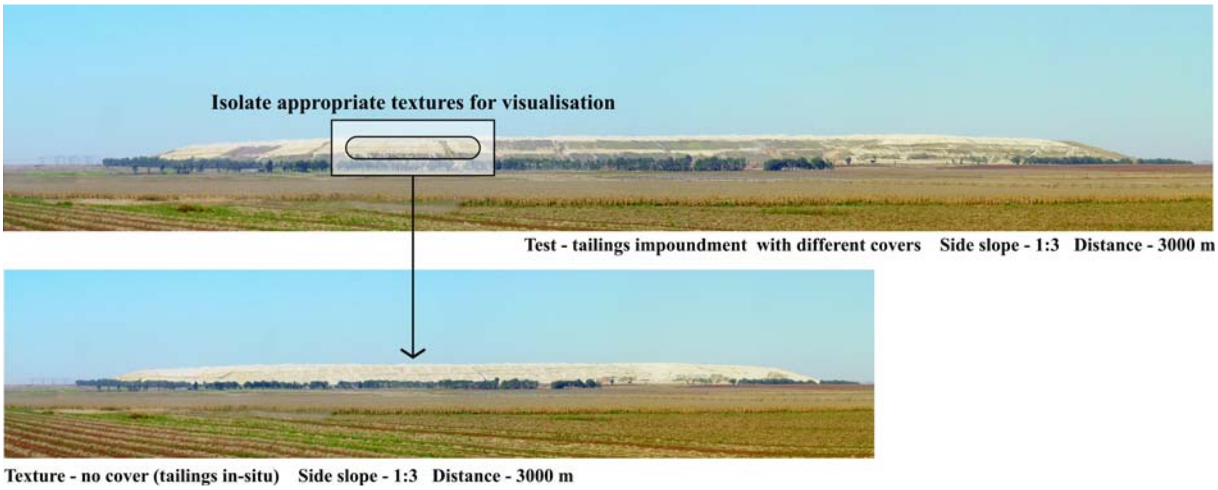


Figure 107: Visualisation of impoundment with no cover.

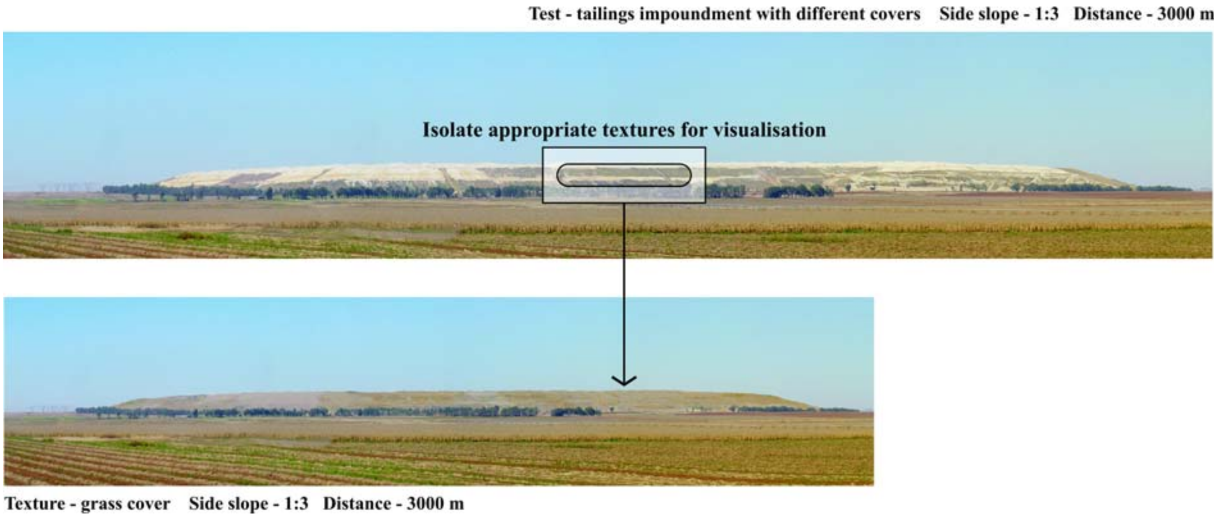


Figure 108: Visualisation of grass covered impoundment.

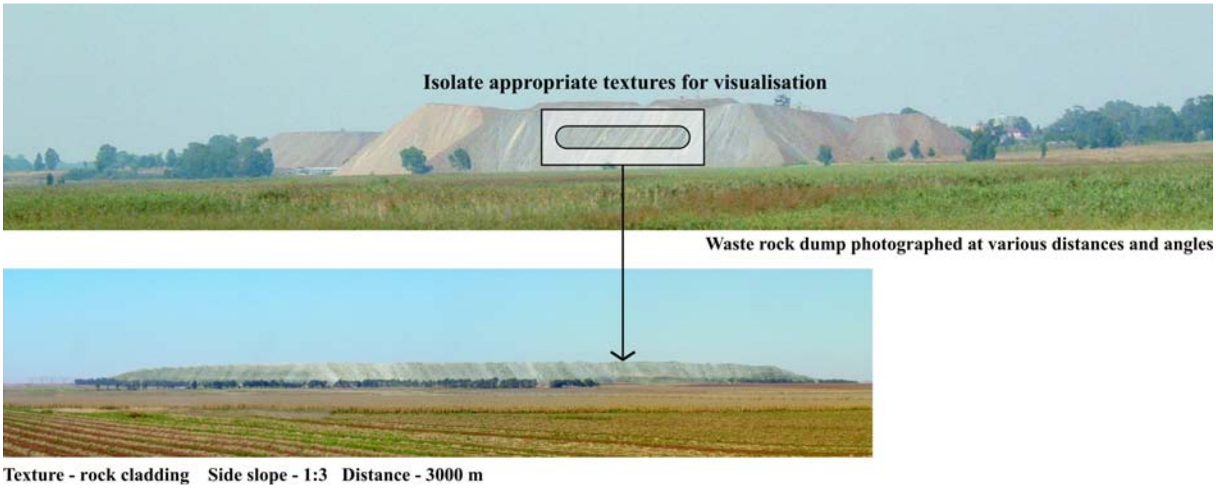


Figure 109: Rock-clad tailings impoundment visualisation.

Photo manipulation (the electronic visual photo simulations or also referred to as visualisations) could be done with high precision and in less time relative to the other techniques discussed in Section 2.10.2. Photographic manipulation of panoramas was also made possible because the impoundment was in various stages of rehabilitation allowing isolation of different covers at various distances. It was therefore possible to isolate textures from areas previously grassed, covered with rock armouring, and uncovered tailings impoundment and apply these photo realistically to the test impoundment at various distances. The greatest challenge was to portray the appropriate colours and textures of the various covers at the viewing distances reliably. The required haze factor could also be realistically applied.

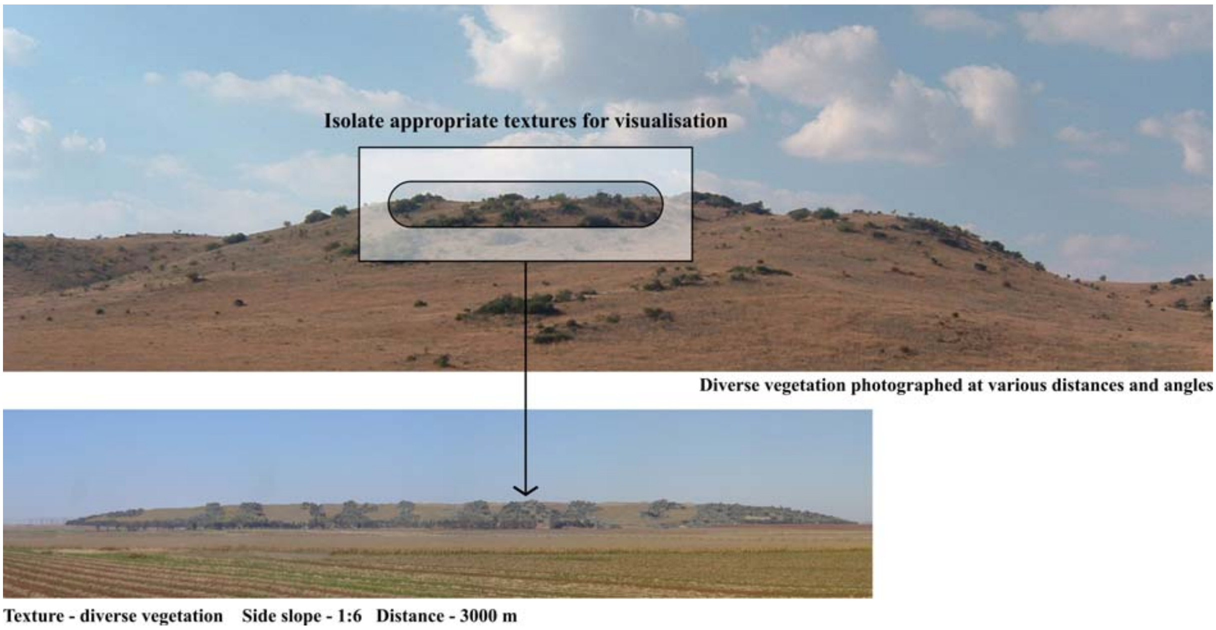


Figure 110: Visualisation of tailings impoundment covered with diverse vegetation.

The manipulated photo simulations could then be viewed using a 15" Proline Crystal View 7Klr computer monitor fitted with a NVIDIA GeForce 2MX/MX 400 graphics card. It is important that the size of the image on the screen must relate to the apparent size a viewer would see in the field at the particular view distance. Equation 31, 32 and 33 were applied assuming that the viewer's head would be approximately 0,45 m from the computer monitor.

$$Tan(\beta_1 / 2) = s_1 / 2d_1 \tag{31}$$

and

$$Tan(\beta_2 / 2) = s_2 / 2d_2 \tag{32}$$

where

$$\beta_1 = \beta_2$$

therefore

$$s_2 = s_1 . d_2 / d_1 \tag{33}$$

By keeping the visual angle the same the size of the impoundment on the screen could be calculated to represent the visual magnitude at that specified distance (Figure 111).

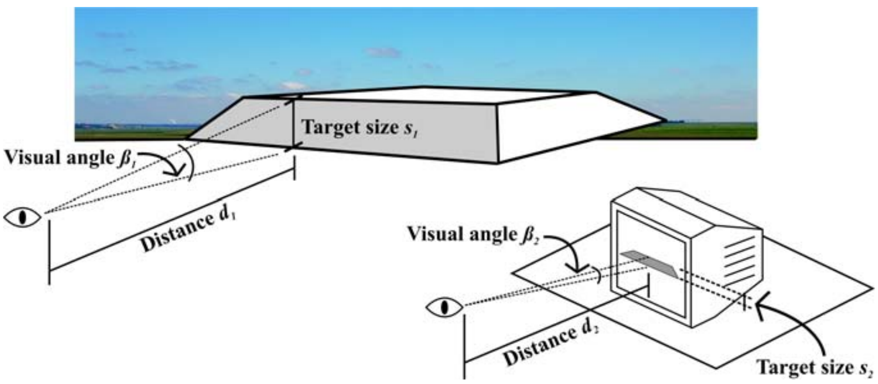


Figure 111: Determining the computer screen viewing target size.

3.4.9 Assessment of visualisations

The nominal group technique (NGT) study method is an application developed from the Delphi technique and was used to assess the visualisations and develop the visual perception distance curves. Delphi was the name of a site in ancient Greece where Oracles (people through whom a deity was believed to speak) met, held discussions and made wise and authoritative decisions. The United States Air Force first applied the modern day Delphi process to a strategic planning exercise in about 1953 (Dalkey and Helmer, 1963). More recently it has been applied to reach expert-opinion-based consensus on qualitative research aspects.

Crance (1987:1) states that a Delphi exercise is based on the premises that:

- opinions of experts are justified as inputs to decision making where absolute answers are unknown;
- consensus of a group of experts provide a more accurate response to a question than a single expert; and
- the process is repeatable and is used by researchers to produce defendable data.

If these assumptions are valid or acceptable to those that will receive and act on the product of the exercise, the conclusions reached should have value. Civil engineers have used this technique, albeit less formally, for the quality assessments of work for a long time such as road pavement surveys.

Both the Delphi technique and its derivative, NGT, are tools that assist researchers in generating a base for evaluation. They are methods designed to:

- increase the creative productivity of group action;
- facilitate group decision;
- help stimulate the generation of critical ideas; and
- give guidance in the aggregation of individual judgements.

The NGT takes the form of a structured group meeting which follows a prescribed sequence of problem-solving steps. The process is described in detail by Delbecq, van den Ven and Gustafson (1975:43) and employs face-to-face meetings and discussions by knowledgeable participants to obtain and combine expert opinion in order to reach consensus. The advantage of using the NGT approach is that, if the participants have the time and are within reasonable travelling distance, the information can be collected rapidly. However, the Delphi technique is applied where experts are not readily available or not within close proximity and has to be polled through electronic or other means of correspondence.

Although the NGT can accommodate large numbers of participants, Delbecq et al. (1975:26) recommends a limit of approximately nine members. Crance (1987:2) states that a panel of ten experts is probably ideal but that more than ten may be used if desired.

For this project names were found through contacting and asking engineering consultancies whom they consider as experts within the field of aesthetics and visual analysis. Each of these potential panellists was asked to participate and recommend someone whom they considered to be highly knowledgeable; the process was repeated until no new names were suggested. Twelve experts participated in the study. Nine were landscape architects with specific expertise in the field of visual impact assessment and the other three were in the engineering or architectural planning professions. Appendix A.1 contains the particulars of each panellist whom participated in the NGT study.

The iterative decision-making process during the NGT study followed the steps recommended by Crance (1987:2):

- the experts were polled on the visualisations by capturing their independent ratings in writing and without discussion (Figure 112);
- the responses were keyed into an MS Office Excel spreadsheet and the results were presented back to the experts using graphs; and
- the group of experts re-evaluated their initial ratings in light of the information generated by the aggregate responses until consensus was reached among the respondents.

Visualisation X

Question 1

Do you detect a manmade landform within this landscape? [Yes] [No]

Question 2

If the answer is 'Yes', assign a rating between 1 and 5 to indicate the level of perception.

[1] [1,5] [2] [2,5] [3] [3,5] [4] [4,5] [5]

Level of Perception

- **1 Low** - Virtually undetectable as a foreign landform in the landscape
- **2 Medium Low** - Detectable as a foreign landform in the landscape, but with effort
- **3 Medium** - Easily detectable as a foreign landform in the landscape, but not recognizable as a MRD
- **4 Medium High** - Recognizable as MRD, but with effort
- **5 High** - Effortless recognition as a MRD

Note: MRD - Mine Residue Deposit

Figure 112: Example of questionnaire to assess each visualisation.

The initial rating of the 67 (Table 37) visualisations was undertaken individually. Each visualisation had a 15 second lapsed time indicator to remind the panellist to finalise the viewing of the particular slide as well as capture comments and ideas in writing and proceed to the next slide. The individual judgements were pooled, collated, summarised and presented to the group, ending the first iteration.

Table 37: Breakdown of visualisations by slope, season and cover.

Total Visualisations (67)

1:3 Side Slope (37)											1:6 Side Slope (30)									
Summer (11)						Winter (26)					Summer (10)						Winter (20)				
T	G	R	Tl	D		T	G	R	Tl	D	T	G	R	Tl	D		T	G	R	Tl	D
3	2	2	2	2		10	4	4	4	4	2	2	2	2	2		4	4	4	4	4

T – Test G – Grass R – Rock Tl – Tailings in situ (no cover) D – Diverse vegetative cover

During the second iteration panellists were given the opportunity to discuss the findings within a structured group discussion process. In light of the results generated by the collective responses to the first iteration the group then sequentially discussed, verbally clarified and eliminated misunderstandings, provided logic behind arguments and disagreements, recorded differences of opinion and lastly re-evaluated each slide in turn until consensus and an acceptable level of agreement was reached. The results and their interpretation are given in Section 4.2.

3.5 Air

3.5.1 Introduction

The aim of the fugitive impact modelling was to determine the area of impact due to wind blown dust from tailings impoundments in terms of nuisance and human health impacts. The air quality impact potential of dust from tailings impoundments depends on:

- the amount of material being entrained from the impoundment;
- the dispersion potential of the material in the atmosphere;
- its removal by deposition; and
- its proximity to sensitive receptors.

Fugitive dust emission rates, atmospheric dispersion potential and deposition rates are largely a function of:

- tailings characteristics such as moisture content and particle size distribution; and
- the prevailing meteorology, particularly the wind field, atmospheric stability regime and precipitation and evaporation rates.

In order to quantify the emissions and determine the potential impacts the following methodology was followed:

- Estimate emission rates from a gold tailings impoundment using the airborne dust dispersion from area sources (ADDAS) model.
- Determine the dispersion of wind entrained dust using the US EPA approved Industrial Source Complex Short Term (ISCST3) dispersion model.
- Plot the areas of impact as isopleths, i.e. contours, using Surfer. Surfer supports the import of data from a number of applications to generate contours. It generates contour maps of surface plots and was used in this study to calculate surface area of influence in hectares.

The following air quality modelling objectives have been set:

- to quantify the air quality influence zone for various tailings impoundment configurations;
- determine the environmental cost for resulting zones of influence; and
- compare the different configuration cost results and draw conclusions.

3.5.2 Calibrating the emission estimation software

During the initial runs to estimate the emissions for various impoundment scenarios using the Airborne Dust Dispersion from Area Sources (ADDAS) software package it became apparent that:

- the software requires the user to input physical characteristics of the tailings impoundment; and
- the roughness height input parameter required calibration.

ADDAS is a software programme developed by Airshed Planning Professionals for ESKOM, South Africa's largest provider of electricity, to estimate the emissions from residue deposits. The equations used in the ADDAS model and described in Section 2.11.4 requires various source specific input. ADDAS quantifies an emission rate for every hour of the period for which meteorological data is provided. For the purpose of the roughness height calibration, a period of one year of meteorological data was used. This included hourly wind speed, wind direction and temperature data. Stability classes and mixing depths are then calculated for each hour. The hourly emissions file generated by ADDAS and the meteorological data are then used as input into the dispersion model.

It was realised that an impoundment with available and reliable dustfall monitoring data must be used to calibrate the surface roughness height input parameter in ADDAS. The DRD 2L24 impoundment of Durban Roodepoort Deep (DRD) was selected for the purpose as:

- dust fallout monitoring data from around the impoundment was available to assist with the calibration;
- the impoundment has a low percentage cover; and
- permission to access the site was granted by DRD in order to take samples of the cover material for characterisation.

1 Looking East over a section on the top surface of the DRD 2L24 tailings impoundment which had been ridge ploughed.

2 Dune formation downwind of one of the compartments of the DRD 2L24 tailings impoundment.

Figure 113: DRD 2L24 tailings impoundment top surface.

All source parameters could be obtained through physical measurements and sample analysis except for the surface roughness height. It was therefore decided to calibrate the surface roughness height by using different roughness heights while keeping the rest of the inputs the same and then comparing the predicted dust fallout levels to actual measured dust fallout data.

1 Looking north-west towards the southern slope of the south-western compartment of the DRD 2L24 tailings impoundment.

2 Looking East towards the western side of the DRD 2L24 tailings impoundment showing the remains of a vegetation trial area. The remainder of the slope is characterised by deep erosion gullies (photograph courtesy of SEF).

Figure 114: Views of the DRD 2L24 tailings impoundment embankment.

The DRD tailings impoundment offered the perfect site to assist with the calibration of the roughness height. DRD currently operates 23 dust fallout buckets located around the tailings impoundment. Seven of these dust fallout buckets have been operational since November 2002 with 7 new buckets installed during September 2005.

In order to calibrate the roughness height parameter samples were taken from the DRD 2L24 impoundment to determine the physical characteristics of the tailings. Once the physical material characterisation was complete a process of iterative re-estimation of fugitive dust emissions was undertaken until the modelled dispersion zone of influence correlated with the dust fall monitoring data collected from the single bucket fallout monitors.

DRD 2L24 environmental setting

The DRD 2L24 impoundment lies directly North of Soweto and South of Roodepoort on the western outskirts of Johannesburg, Gauteng (Figure 115, p. 203). The impoundment is located 1 500 m East of the R558 and 2 500 m South of the R41. The site falls within the jurisdiction of the City of Johannesburg Local Municipality and the approximate site co-ordinates are 26°11'57,2" S and 27°50'21,6" E. The impoundment was constructed on DRD mining land and is no longer operational. Sections that had previously been vegetated are either showing signs of stress or have died off completely resulting in an impoundment that is largely uncovered. It is estimated that the percentage cover on the side slopes are less than 30 %.

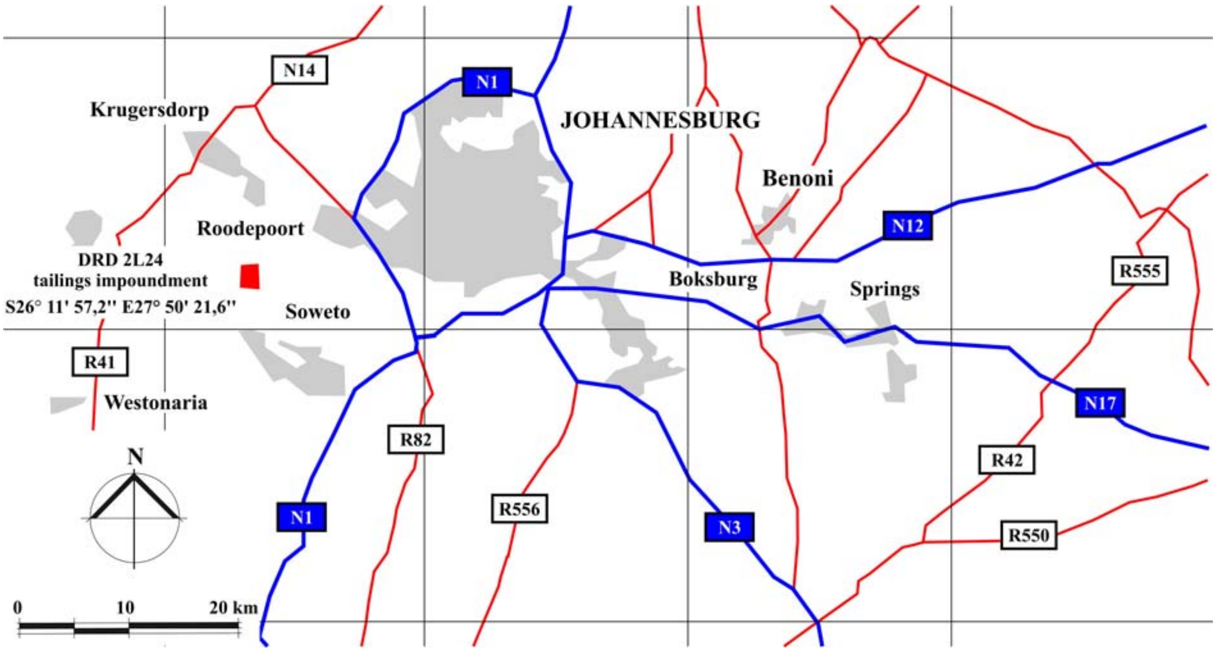


Figure 115: Regional locality of the DRD 2L24 tailings disposal facility.

The impoundment is situated along the mining belt that forms the transition between Soweto and Roodepoort. Bram Fischerville township extensions surround the impoundment (Figure 117, p. 204) and Meadowlands and Dobsonville, suburbs of Soweto, lie approximately 2,5 km to the south-east.

Surrounding environment

The location and land use of the impoundment is important as it can impact on both current and future surrounding land use. The area has a typical Highveld climate characterised by warm, wet summers and cool dry winters. The summer rainfall averages between 650 – 750 mm/annum and temperatures range from 12°C to 39°C with an average of 16°C (Bredenkamp and van Rooyen, 1996). The site is surrounded by township establishments and typical Highveld grassland most suitable for grazing with some areas suitable for arable agriculture. Acocks (1988) describes the vegetation as the northern variation of Cymbopogon-Themeda veld. Low and Rebello (1996) refer to this veld as Moist Cool Highveld Grassland.

The open veld surrounding the impoundment is degraded and has low species diversity. Species such as *Seriphium plumosum*, *Tagetes minuta*, *Bidens pilosa*, and *Stoebe vulgaris* occur and is indicative of overuse and disturbance. Alien invasive species such as *Cortaderia selloana* (pampass grass), *Acacia dealbata* (silver wattle) and *Eucalyptus sp*. (blue gum) occur within the impoundment site. Land surrounding the impoundment shows no evidence of sensitive habitats or species of conservation concern and since no ecologically significant landscape elements occur it is unlikely that any sensitive or protected species will be found. The site is thus considered to be of low ecological and conservation value.

[1] Looking East towards Bram Fischerville township extensions surrounding the DRD 2L24 tailings impoundment.

[2] A view towards the toe of the impoundment with the low cost houses, typical of Bram Fischerville, in the foreground (photograph courtesy of SEF).

Figure 116: DRD 2L24 tailings impoundment environmental setting.

There are no prominent geomorphological features in the study area and the landscape undulates slightly in the northern parts of the study area decreasing in height towards the South. The Klip river floodplain is situated to the West of the impoundment.

Figure 117: Current and proposed extensions of Bram Fischerville adjacent to the DRD 2L24 impoundment.

Rainfall

Rainfall data for the site was obtained from the Roodepoort weather station (Figure 118). The mean annual rainfall for the area is 721,4 mm and falls mainly in the summer between October and March in the form of thunderstorms. The wettest month of the year is January with an average rainfall of 128,4 mm. On average January also has the largest number of days with rain and the most rainfall recorded in a 24 hr period was 163,5 mm. The driest month is June with an average of 6,7 mm.

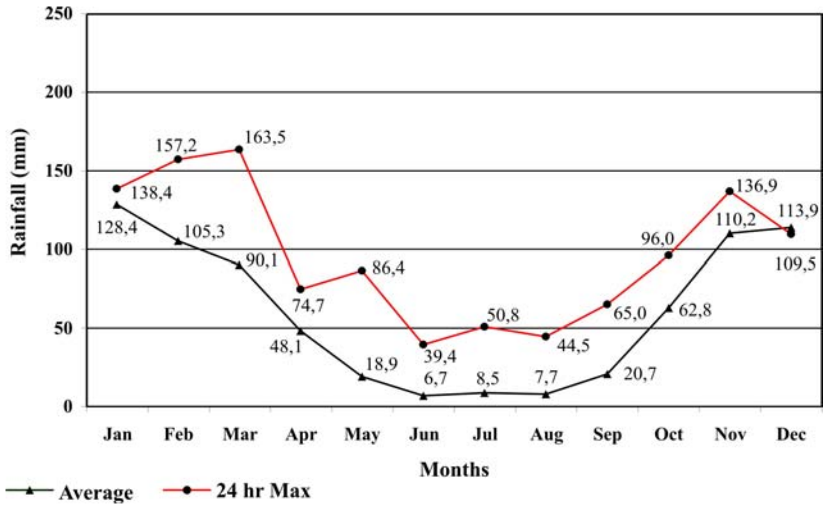


Figure 118: Monthly rainfall data for the Roodepoort weather station.

Temperature

The impoundment falls within a climatic region that experiences moderate fluctuations in seasonal temperature (Figure 119).

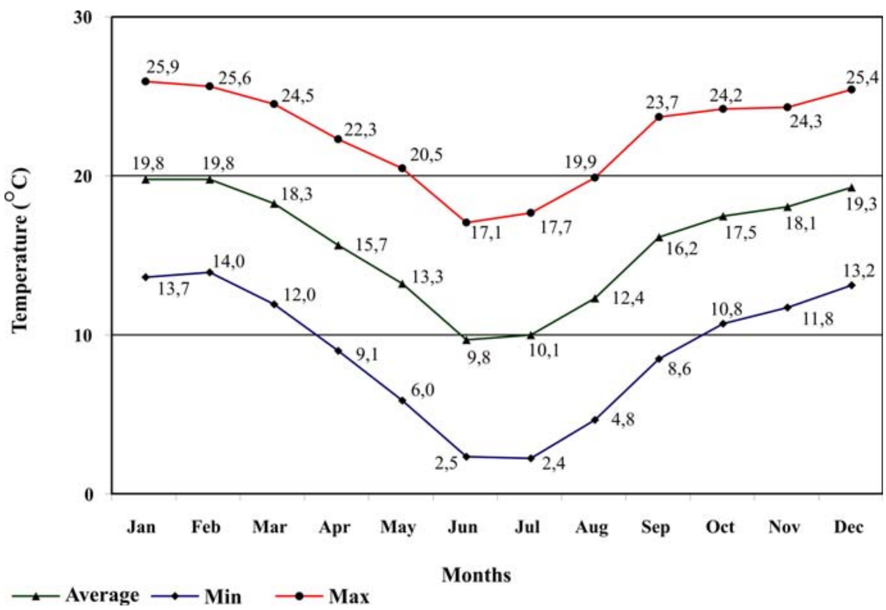


Figure 119: Temperature data for the Roodepoort weather station.

October to March reflect a mean temperature range of between 17 °C and 20 °C with the warmest temperatures occurring during January and February. Temperatures range between 9 °C and 17 °C for the months April to September with June being the coldest month of the year. The site is affected by temperature inversions during winter nights (where cold air is trapped near to the surface) so that the temperature increases with height. Temperature inversions also trap pockets of pollution close to the surface.

Wind

The wind speed does not vary much throughout the year. The winds most frequently occurring blow from the North and north-west and winds blowing from the south-east are the least frequent. Frequency statistics indicate that August, September and October are the windiest months. For approximately 30% of the year, little or no wind is experienced. Generally winds are light except for short periods during thunderstorms.

Summary

The impoundment is a prominent man-made landform within the surrounding landscape showing signs of both wind and water erosion. Sheet, rill and gully erosion off the side slopes is visible and it can be expected that erosion will increase with the decrease in cover. This is not surprising as the impoundment:

- is not suitably shaped and covered to prevent erosion from taking place;
- lies within a region that experiences heavy rainfalls in summer resulting in increased runoff; and
- is located in an area where the dominant north-westerly wind has the potential to liberate dust from the impoundment impacting on land use to the East and south-east.

DRD 2L24 source characteristics

The purpose of determining the tailings impoundment's physical and chemical properties is to establish the material's wind erosion and toxicity potential and hence the air quality zone of influence. Information regarding the characterisation guided the choice of parameters which needed further investigation. Nine grab samples were taken at different strategic points on the DRD 2L24 tailings impoundment and analysed using:

- laser diffraction to determine the physical characteristics; and
- X-Ray fluorescence to determine the chemical characteristics of the tailings.

Physical characteristics

Emissions from impoundments depend on various factors such as:

- the prevailing meteorological conditions; and
- the physical properties of the exposed surface material, i.e. the material covering the surface of the impoundment.

The latter is the topic of this section. The overall objective of the sampling and analysis program is to determine the:

- nature of the source;
- percentage of exposed surface area; and
- type of material on the DRD 2L24 impoundment.

This is done by:

- collecting representative grab samples of the material;
- analyzing the samples to determine the physical properties; and
- combining analytical results with material throughput and meteorological information in an emission factor model.

The nine samples collected were analysed for:

- particle size distribution;
- clay content; and
- moisture content.

Collecting grab samples

Effort was made to take representative samples from the following exposed surfaces of the impoundment:

- the top surface;
- the middle embankment side slope; and
- the bottom of the impoundment.

The sampling positions are indicated on Figure 121, and the coordinates included in Table 38. The following procedure was used to collect samples from the DRD 2L24 tailings impoundment (US EPA, 1995):

- A sketch plan and aerial photograph of the impoundment was studied to determine if any portion of the impoundment is not accessible. The plan was also used to identify possible sampling points. The US EPA recommends that a minimum of 6 samples must be taken.
- The material was collected with a small garden spade, and stored in a clean, labelled container of suitable size with a sealable lid (Figure 120, photograph 1). The container size was amenable to the SGS South Africa (Pty) Ltd. laboratory analysis requirements.
- The samples were collected by skimming the surface in an upwards direction. Sampling did not exceed a depth of 2,5 cm and did not avoid collecting larger pieces of aggregate present on the surface.
- The required information was recorded on a sample collection sheet.
- The sampling coordinates were captured using a geographical positioning system (GPS) and indicated on a map.

[1] A garden spade was used to skim tailings from the top surface in an upward direction and not exceeding a depth of 2,5 cm.

[2] Typical close-up view of the impoundment surface denude of vegetative cover.

Figure 120: Sampling of tailings for particle distribution analysis.

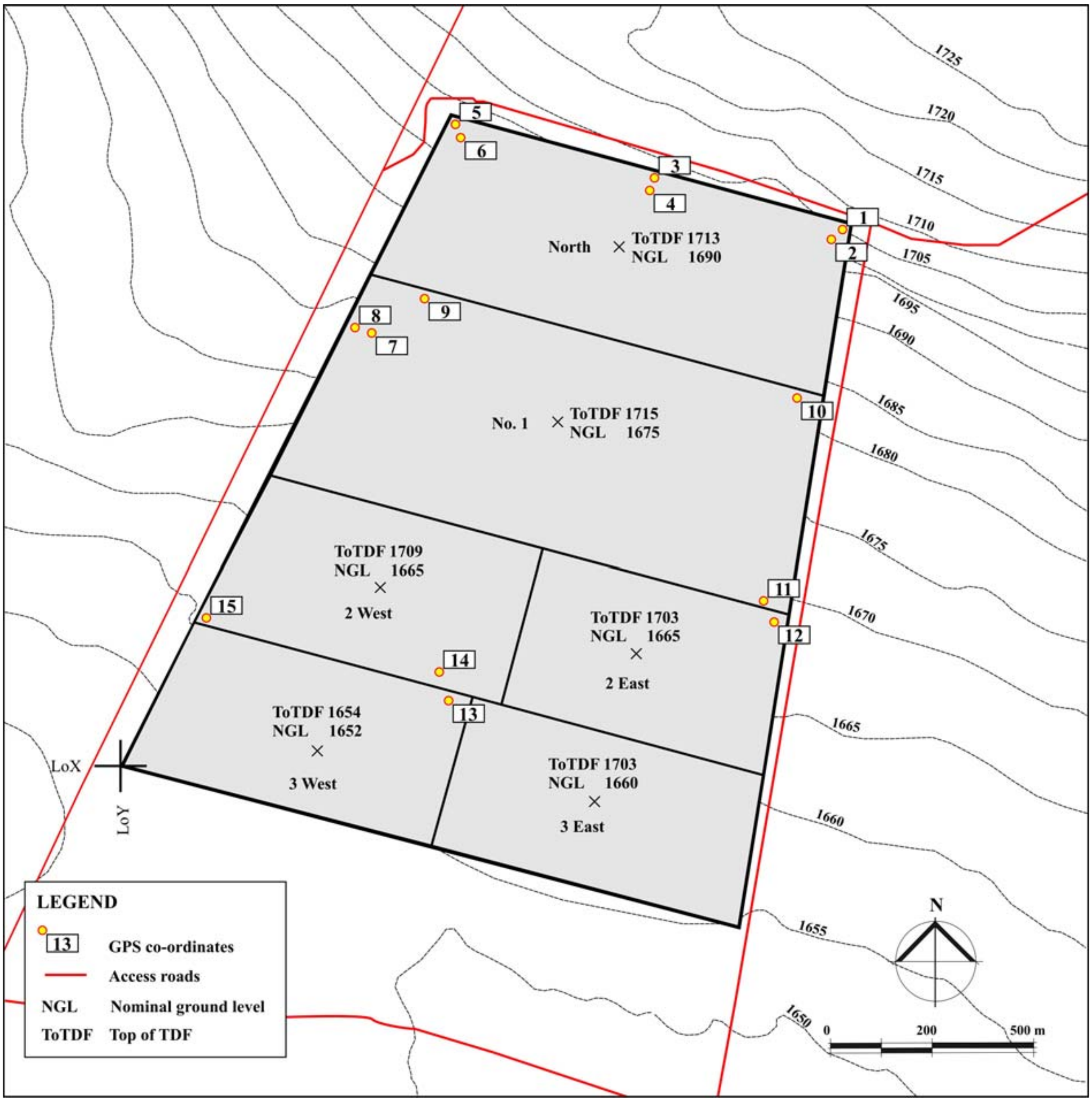


Figure 121: DRD 2L24 layout plan indicating the sampling points.

The sampling method can be summarised as follows:

- Sampling device: Collect increments by skimming the surface in an upwards direction using a garden spade.
- Sampling depth: Do not skim the surface deeper than 2,5 cm and do not avoid collecting larger pieces of aggregate present on the surface.
- Sample container: Use a clean plastic bottle with tight fitting lid to place the tailings in.
- Gross sample specifications: Sampling for wind erosion purposes requires at least 6 samples.

Table 38: GPS points and coordinates of the DRD 2L24 tailings samples.

		Latitude	Longitude
Sample number	**GPS Point**	**South**	**East**
	1	26° 11' 42,96"	27° 50' 41,16"
	2	26° 11' 43,26"	27° 50' 40,44"
1	**3**	26° 11' 38,76"	27° 50' 22,92"
2	**4**	26° 11' 40,26"	27° 50' 22,98"
	5	26° 11' 35,46"	27° 50' 7,56"
	6	26° 11' 36,12"	27° 50' 7,56"
3	**7**	26° 11' 55,74"	27° 50' 1,50"
4	**8**	26° 11' 54,24"	27° 49' 59,76"
5	**9**	26° 11' 49,50"	27° 50' 8,34"
6	**10**	26° 11' 57,00"	27° 50' 35,94"
7	**11**	26° 12' 11,88"	27° 50' 35,76"
	12	26° 12' 11,94"	27° 50' 35,76"
8	**13**	26° 12' 20,52"	27° 50' 10,26"
9	**14**	26° 12' 16,38"	27° 50' 8,10"
	15	26° 12' 14,70"	27° 49' 45,72"

Physical characterisation of the grab samples

The objective of the physical characterisation of the tailings material is to determine the following parameters:

- particle size distribution;
- bulk density;
- roughness height;
- particle density;
- fractions of impoundment surface area open;
- clay content; and
- moisture content.

Particle size distribution

When characterizing a material's particle size it is important to assess whether the chosen method of analysis is fit for the purpose. This requires the analyst to determine which parameters are critical to quality, i.e. why size analysis must be performed, and whether the chosen size analysis technique can be used to assess these. Within this the robustness of the technique must also be assessed, both as part of the process of determining if the technique can be reasonably applied, and for the purposes of specification setting. Laser diffraction, more correctly called Low Angle Laser Light Scattering (LALLS), is a widely used method used for analysing particles ranging from 0,05 µm to 3,5 mm. The basic principle is that the diffraction angle is inversely proportional to particle size and the instrument consist of:

- A laser of coherent intense light of fixed wavelength. He-Ne gas lasers are most common with a wavelength of 0,63 µm.
- A suitable detector. Usually this is a slice of photosensitive silicon with a number of discrete detectors.
- Some means of passing the sample through the laser beam.

Laser diffraction is one of the most widely used techniques for particle size analysis. Its flexibility, wide dynamic range, and speed of operation yield significant advantages compared to traditional techniques such as sieving. However, as the ease of use of the technique has progressed to the point at which systems require virtually single-button operation, it is easy to forget the requirements for accurate analysis in terms of sample preparation. If the processes of preparing a sample are not controlled, errors far beyond those associated with the laser diffraction technique itself will result. This can lead to results that are at best insensitive to changes in product quality and at worst are completely inaccurate.

Laser diffraction systems provide a rapid, accurate, and precise method for measuring particle size distributions. However, this relies on the following of standard operating procedures (SOPs) that take into account the way that samples are obtained and then dispersed within the instrument.

SGS South Africa (Pty) Ltd., an accredited laboratory, ensured that:

- the dispersion of the material with the laser diffraction system was controlled;
- the samples were measured in a stable, reproducible state of dispersion;
- wet dispersion was used as it represents the most robust method for measuring accurate particle size distributions.

Dispersion for wet analysis involves a two stage process. First, the particles must be fully wetted by the dispersant. This is aided by the choice of the most appropriate dispersant, by vigorous stirring, and by the application of ultrasound. Following this, the particles need to remain in a stable state. This will be dependent on the nature of the dispersant and the use of surfactants and other additives to prevent agglomeration.

The LALLS results indicate that on average more than 70 % of the material is smaller than 75µm and about 7 % is less than 10µm in diameter. An important conclusion from this is that the DRD 2L24 tailings impoundment can be considered as being an unlimited reservoir of fugitive particulate matter. Mizelle (1997) states that if more than 60 % of the material is less than 0,25 mm in size that it qualifies as having the potential to be a reservoir of unlimited fugitive particulate matter.

Table 39: Mean fraction of the particles smaller than 75 µm.

			Fraction of sample									
	Size (µm)	**Size (m)**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Mean fraction**
< 75µm	**76**	**0,0000760**	0,34	0,18	0,41	0,20	0,19	0,49	0,28	0,48	0,20	0,30
	56	**0,0000560**	0,35	0,23	0,29	0,31	0,23	0,25	0,29	0,32	0,24	0,28
	30,53	**0,0000305**	0,08	0,11	0,06	0,13	0,12	0,03	0,09	0,03	0,12	0,09
	19,31	**0,0000193**	0,05	0,12	0,05	0,11	0,14	0,04	0,08	0,03	0,13	0,08
	10,48	**0,0000105**	0,04	0,11	0,03	0,08	0,11	0,03	0,06	0,03	0,09	0,07
	5,69	**0,0000057**	0,04	0,10	0,04	0,06	0,08	0,03	0,05	0,02	0,08	0,06
	2,65	**0,0000027**	0,03	0,05	0,04	0,04	0,05	0,04	0,05	0,03	0,06	0,04
	1,06	**0,0000011**	0,07	0,10	0,09	0,07	0,08	0,09	0,09	0,06	0,09	0,08

Table 40: Mean fraction of the particles smaller than 10 µm.

			Fraction of sample									
	Size (µm)	**Size (m)**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Mean fraction**
< 10µm	**10,48**	**0,0000105**	0,24	0,31	0,17	0,32	0,34	0,15	0,24	0,19	0,30	0,25
	5,69	**0,0000057**	0,21	0,28	0,18	0,24	0,26	0,16	0,21	0,17	0,25	0,22
	2,65	**0,0000027**	0,19	0,15	0,21	0,16	0,15	0,22	0,20	0,23	0,18	0,19
	1,06	**0,0000011**	0,36	0,26	0,44	0,28	0,25	0,47	0,35	0,41	0,28	0,34

Bulk density

Measurements of settled dried densities range between 1250 and 1650 kg/m^3 as a function of depth. A value of 1450 kg/m^3 is generally used for design purposes. The settling dry density of tailings of an impoundment used in a study was reported to be 1500 kg/m^3 (Mizelle, 1997:34). In situ dry density quoted in Vermeulen (2002:2-67) and described by Blight, Rea, Daldwell and Davidson (1981) is given as 1835 kg/m^3. A bulk density of 1800 kg/m^3 was used for the purposes of this study.

Roughness height

In most earth sciences applications the logarithmic law takes a more general form that employs (Z_0), the aerodynamic roughness height, sometimes also referred to as roughness length, above the bed at which flow velocity tends to be zero (Lee and Zobeck, 2002). The drag coefficient and the roughness height (Z_0) are interchangeable descriptions of roughness. A classical approach consists in characterizing the roughness height of the erodible surface in relation to the size of the erodible particles (D_P)(Bagnold, 1941:50; Marticorena and Bergametti, 1995:16.425).

$$Z_0 = D_P / 30 \tag{33}$$

Table 41: The typical range of roughness heights.

Various surfaces	**Roughness height (Z_o) (m)**
Wheat field[1]	0,04
Plowed field[1]	0,01
Natural snow[1]	0,001
Overburden[2]	0,003
Ground coal[2]	0,0001
Fine coal dust on concrete pad[2]	0,002

[1] Cowherd, Muleski, Englehart and Gilette (1985)

[2] US EPA (1996)

Particle density

Ritcey (1989:222) provides a mean particle density value of 2,91 g/cm^3 with a range of 0,01 – 4,29 g/cm^3. It was decided that the value of 3,6 g/cm^3 will be used for the type of tailings material.

Impoundment surface area open fractions

Uniform percentages were used assuming that a particular cover technology can achieve a uniform reduction in exposed surface.

Clay content

The clay fraction is the fraction of the particles in the sample less than 2 µm in diameter. The arithmetic mean of the nine samples is 3,46 % (Table 42).

Table 42: Percentage (%) of particles smaller than 2 µm, i.e. clay particles.

Sample	Particle diameter (µm)	Percentage of sample (%) less than < 2µm
1	1,95	3,42
2	1,95	4,35
3	1,95	1,62
4	1,95	5,29
5	1,95	4,58
6	1,95	1,32
7	1,95	3,96
8	1,95	1,88
9	1,95	4,72
Arithmetic mean		3,46

Moisture content

The moisture content input parameter was taken as 0,18% which is the arithmetic mean of values from the nine samples measured by SGS. Mizelle (1997:66) reported moisture contents of between 0,83 % and 5,04% on the benches, outer or side sloped of the embankments and the top walls (dividing and crest walls). The moisture content varies considerably over the impoundment and depends on the characteristics of the tailings, position on impoundment, aspect of embankment and management practices.

DRD 2L24 chemical characteristics

Certain chemical elements and compounds have adverse effects on human health, wildlife and infrastructure. Information on the chemical composition of the tailings from impoundments helps to determine the risk associated with the release of particulates.

The objective of the chemical characterisation of the material was to determine and document the chemical make-up of the tailings at the DRD 2L24 tailings impoundment. The same grab samples used for the physical characterisation was analysed at the Geochemical Laboratory at the Department of Geology, University of Pretoria, using a standard ARL 9400XP+ Wavelength dispersive X-Ray fluorescence (XRF) spectrometer with Rh tube. The composition of five samples was determined for:

- chemical oxides; and
- single heavy elements.

XRF is an analytical technique to do qualitative and quantitative elemental analysis on inorganic samples. Elements between F and U on the periodic table can be analysed in concentration ranges from a few ppm to 100%. Organic material is X-Ray transparent, but due to the low mass absorption coefficient of such substances, inorganic impurities can be analysed to very low detection limits.

The source grab samples that were analysed had the advantage of already being crushed and ground through metallurgical processes. This avoids unnecessary contamination which can easily be incurred by crushing and grinding.

XRF analysis

Samples were taken on the impoundment and analysed using XRF analysis. The coordinates and sample numbers are indicated in Table 43.

Table 43: Coordinates of samples and GPS points for XRF analysis.

		Degrees Minutes Seconds	
		Latitude	**Longitude**
Sample Number	**GPS Point**	**South**	**East**
2	**4**	26° 11' 40,26"	27° 50' 22,98"
3	**7**	26° 11' 55,74"	27° 50' 1,50"
6	**10**	26° 11' 57,00"	27° 50' 35,94"
7	**11**	26° 12' 11,88"	27° 50' 35,76"
9	**14**	26° 12' 16,38"	27° 50' 8,10"

XRF analysis procedure

The XRF spectrometer was calibrated using certified reference materials. NBSGSC fundamental parameter program was used for matrix correction of major elements as well as Cl, Co, Cr, V, Sc and S. The Rh Compton peak ratio method was used for the other trace elements.

The samples were dried and roasted at 1000ºC to determine the percentage loss on ignition. Major element analyses were executed on fused beads, following the standard method used in the University of Pretoria XRF laboratory, as adapted from Bennett and Oliver (1992:67-93).

About 1 g of each sample was mixed with a 6 g lithium tetraborate flux in a 5% Au/Pt crucible and fused at 1000ºC using a muffle furnace swirling the sample occasionally. The sample dissolves rapidly after which the mixture was poured into a pre-heated Pt/Au mould to form the fusion disks. As soon as the fusion disks were ready, they were mounted in the spectrometer for surface analysis. Trace elements were analysed on pressed powder pellets, using an adaptation of the method described by Watson (1996: 173-174), using a saturated Mowiol 40-88 solution as binder.

XRF analysis results

The chemical characterisation indicates that the material contains mainly silica, enriched with chromium, zirconium and barium. This is similar as to what was measured by Mizelle (1997).

Table 44: XRF results of elements as oxides in DRD2L24 tailings samples.

%	GSNcert	GSN	Sample 2	Sample 3	Sample 6	Sample 7	Sample 9
SiO_2	65,80	65,31	93,16	94,37	93,25	93,73	90,33
TiO_2	0,68	0,65	0,21	0,20	0,25	0,21	0,19
Al_2O_3	14,67	14,57	2,68	2,58	2,74	2,55	5,05
Fe_2O_3	3,75	3,69	1,01	1,12	0,97	1,23	1,59
MnO	0,06	0,05	0,01	0,02	0,02	0,02	0,01
MgO	2,30	2,19	0,13	0,09	0,09	0,09	0,17
CaO	2,50	3,00	0,07	0,16	0,06	0,29	0,35
Na_2O	3,77	3,69	0,06	0,14	0,14	0,22	0,15
K_2O	4,63	4,70	0,19	0,16	0,14	0,11	0,12
P_2O_5	0,28	0,29	0,02	0,02	0,02	0,02	0,02
Cr_2O_3	0,008	0,008	0,02	0,03	0,01	0,03	0,02
NiO	0,0043	0,0034	0,01	0,01	0,02	0,01	0,01
V_2O_5	0,01	0,01	0,00	0,00	0,00	0,00	0,00
ZrO_2	0,03	0,03	0,03	0,03	0,03	0,03	0,04
LOI	1,32	1,29	1,02	1,12	0,79	1,57	2,17
Total	99,82	99,48	98,62	100,05	98,53	100,12	100,23

Table 45: XRF results of elements present in the DRD2L24 tailings samples.

ppm	GSNcert	GSN	Sample 2	Sample 3	Sample 6	Sample 7	Sample 9
As	1,6	3	10	19	14	16	84
Cu	20	21	12	12	11	24	19
Ga	22	18	3	3	3	5	5
Mo	1,2	1	1	1	1	1	1
Nb	21	23	4	4	3	5	5
Ni	34	33	18	14	11	26	26
Pb	53	55	31	11	8	57	23
Rb	185	184	5	5	3	4	7
Sr	570	578	12	15	11	12	16
Th	42	42	3	3	3	3	3
U	8	12	3	3	3	3	3
W*	450	452	1028	1395	944	1377	905
Y	19	13	9	8	8	14	9
Zn	48	52	17	14	14	27	37
Zr	235	237	158	148	138	238	169
Cl*	450	499	8	10	8	8	8
Co	65	57	436	291	234	1089	198
Cr	55	45	101	90	88	146	116
F*	1050	1177	877	923	828	808	609
S*	140	556	1737	610	491	4371	1792
Sc	7	6	2	3	2	4	3
V	65	63	17	17	17	17	17
Cs	5	6	9	9	9	9	9
Ba	1400	1417	34	36	32	30	38
La	75	60	33	31	29	34	30
Ce	135	138	29	29	31	38	31

DRD 2L24 calibration input parameters

The physical parameters determined and described in the previous section were used as input parameters in ADDAS and ISCST Breeze to estimate and disperse the emissions for the various impoundment configurations. The following input parameters were used in ADDAS to estimate emissions for the DRD 2L24 impoundment and calibrate the roughness height:

- Bulk density: 1800 kg/m^3
- Mean particle size distribution: Table 39 and Table 40 provide a detailed breakdown of the mean particle size distributions and mass fractions.
- Average moisture content: The arithmetic mean value of 0,18% was determined and used from the nine samples measured by SGS.
- Tailings impoundment dimensions: The tailings impoundment input dimensions used for the DRD 2L24 calibration is provided in Table 46.
- Roughness height: A value of 0,00012 m was used for the simulation of the various impoundment configurations provided in Section 3.2. The calibrations process is described in Section 3.5.2.
- Clay content: The arithmetic mean value of 3,46 % was used (Table 42).
- Moisture content: The moisture content input parameter was taken as 0,18% which is the arithmetic mean of values from the nine samples measured by SGS.

Table 46: DRD 2L24 tailings impoundment dimensions.

Horizontal clockwise angle	14°
North-South length (m)	1775
East-West length (m)	1294,5
Compartments surface area (ha)	
North	46
No. 1	67
2 West	29
2 East	26
3 East	29
3 West	29
Total	227

DRD 2L24 dispersion calibration results

No site-specific ambient air quality monitoring data is available for the DRD 2L24 impoundment and reference is therefore made to results from bucket dust fallout monitoring stations in the vicinity of the impoundment. It must however be noted that likely sources contributing to the total dust collected in the dust buckets include:

- tailings dust from the DRD 2L24 impoundment;
- domestic coal burning emissions from neighbouring townships;
- fugitive dust from more distant tailings impoundments and mining operations; and
- vehicle entrained dust from unpaved roads in the area.

The material in the dust fallout buckets were evidence of the different sources with the colour ranging from brown to yellowish-grey. Gold tailings from the DRD 2L24 impoundment is homogeneous in composition and yellowish-grey in colour.

Dust fallout monitoring data

A total of 23 dust fallout buckets are currently operated by the DRD in the vicinity of their operations. The dust fallout buckets of Modise, Louis Spaza Shop, Leon Biko, Yvonne Meno, Thandeka Twani and Anna contained mainly tailings material. The location of the dust fallout buckets are shown in Figure 122 with Table 47 indicating the coordinates of the buckets used for calibration. The monitoring stations indicated in yellow were used to calibrate the models.

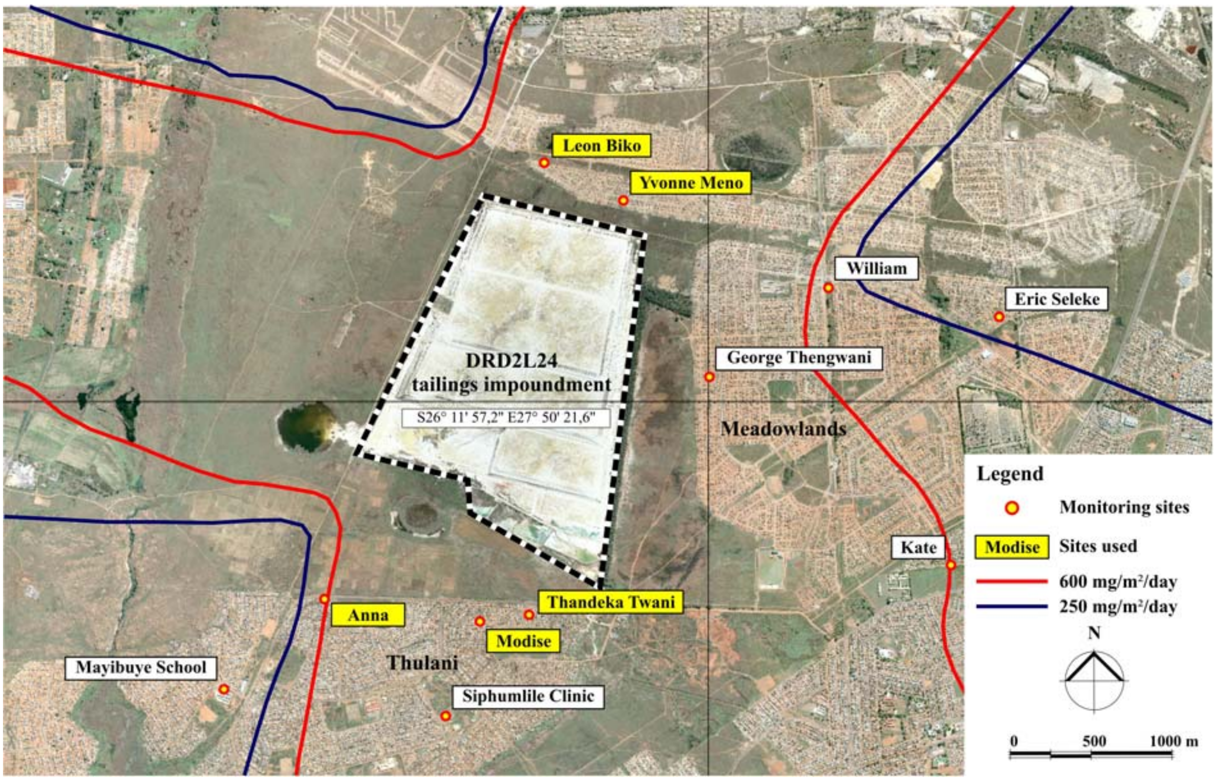


Figure 122: Dust fallout monitoring sites in the vicinity of the DRD tailings impoundment. Predicted total daily average dust fallout (mg/m^2/day) from the DRD tailings impoundment.

The highest dust fallout rates were recorded at Modise House and Mayibuye School which are located within Thulani on the southern side of the DRD tailings impoundment. Due to the high dust fallout recorded, the mine commissioned two additional dust fallout buckets in this area (Anna and Thandeka Twani). Additional buckets were also commissioned in other areas surrounding the tailings impoundment. The new buckets were commissioned during September 2005 with heavy dust fallout levels recorded within the first two months. Very heavy dust fall was recorded at Thandeka Twani during the month of October 2005. Only these two months of data for the newly commissioned stations was available for use during the calibration exercise.

Table 47: Dust fallout bucket coordinates.

		Latitude	Longitude
Site location	Site No.	South	East
Modise House	3	26° 12' 59,03"	27° 50' 4,88"
George Thangwani	17	26° 12' 9,73"	27° 50' 55,16"
Leon Biko	20	26° 11' 27,67"	27° 50' 19,03"
Yvonne Meno	21	26° 11' 35,27"	27° 50' 38,08"
Thandeka Twani	22	26° 12' 57,33"	27° 50' 15,89"
Anna	23	26° 12' 55,36"	27° 49' 29,84"

The dispersion simulations were done for dust fallout and depicted as total daily levels over a monthly average. This is for comparison to the dust fallout levels which is measured for a period of 28 to 31 days and then calculated as daily fallout levels. The predicted dust fallout levels are given for the main indicator buckets indicated (Figure 122, p. 216). Table 48 provides the predicted results for comparison to measured data.

Table 48: Modelled data compared to measured data from the DRD Tailings Impoundment. A surface roughness height of 0,0012 m provided the best correlation.

		Measured data		Modelled data	
		Maximum monthly (x)	Annual average	Monthly (y)	Ratio
Site location	Site No.	(mg/m²/day)	(mg/m²/day)	(mg/m²/day)	(y:x)
Modise House	3	812	575	362	0,45
George Thangwani	17	2060	746	3700	1,80
Leon Biko	20	703	531	3008	4,28
Yvonne Meno	21	4546	758	2109	0,46
Thandeka Twani	22	1633	1002	3220	1,97
Anna	23	5597	1817	6245	1,12

As discussed under Section 2.11.2, the range of uncertainty of the US EPA developed ISCST Breeze can range between -50% to 200%. The measured data compared favourably to the predicted results and are considered to be within the same range. Modise House, Thandeka Twani and Yvonne Meno were considered the most representative and fell within the range of -50% and 200% accuracy resulting for a surface roughness height of 0,0012 m (Figure 122, p. 216). Isopleth plots are used to spatially compare the highest daily and annual average PM_{10} concentrations and highest daily and annual average dustfall levels with the data from the bucket dust fallout monitoring stations.

3.5.3 Summary

ADDAS software was successfully calibrated using the DRD 2L24 impoundment site following a process whereby predicted results were compared to monitoring data. The calibration process provided a means to determine the surface roughness height for a typical uncovered gold tailings impoundment and is in the order of 0,0012 m. The calibrated ADDAS model can be used to predict the emissions for the different ERGO Daggafontein tailings impoundment scenarios.

3.6 Water

3.6.1 Introduction

The objective of this section of the study is to model the mass flux (sulphate flux) and contaminant (sulphate) concentration for different tailings impoundment configurations using a simple mass balance spreadsheet model. The literature review presents information on the modelling of groundwater flow, contaminant transport, and typical contaminants. Two dimensional groundwater models are discussed which assumes steady state, isotropic, and homogeneous conditions. Various approaches to groundwater modelling are also briefly discussed. The water model which was developed and used in this study calculates the mass-flux and does not consider the following:

- effects of hydrodynamic dispersion;
- chemical interactions between contaminants, the foundation and aquifer solid matrix;
- effects of multi-layered and confined aquifers;
- interactions between groundwater and surface water;
- consequences of anisotropic and non-homogeneous materials; and
- compressible fluids.

3.6.2 Predictive modelling of impacts

The scenarios defined and modelled are given in Table 23, p. 163. The configuration of a tailings impoundment could affect the off-site impact on the water resource. The geometry and cover which in turn affect the surface stability of the outer top surface and side slopes of tailings impoundments is central in assessing the impact of tailings impoundments on the environment. Two primary decision considerations comprise the possible impacts on the groundwater through seepage and the surface water as runoff (Figure 54, p. 109). The objective of this section is to predict the change in mass-flux using a simple mass balance spreadsheet model. It provides a reasonable estimate of seepage from an impoundment.

3.6.3 Water impact model

Objectives

The objective of the investigation was to develop a first order methodology to determine the water related impacts from a tailings impoundment, given various slope and cover closure configurations. An important requirement is that the method can be integrated with other environmental aspects such as visual and dust impacts. It should be used as a decision-making tool to inform the choice of tailings impoundment configurations.

Approach

To determine the potential water related impacts, an analytical mass balance model was developed for surface water and groundwater that could be used on a spreadsheet. This will allow integration and comparison with other environmental aspects such as the visual and dust impacts. The model is aimed at evaluating the post-operation impacts against different rehabilitation options. A steady-state approach was followed as it is able to emulate the long time scales that are associated with post-operation planning.

Model development

The analytical water flow and mass balance model has been developed for a tailings impoundment located in a surface water and groundwater catchment. The aim of the model is to:

- account for the water and mass balance components for the tailings impoundment, and
- evaluate the impact on the surface water and groundwater in terms of concentrations and mass load for the various configurations.

The model is based on the ERGO Daggafontein tailings impoundment which is located in the Blesbokspruit catchment was used for this purpose (Figure 81, p. 158).

Conceptual model

The first step in the development is the formulation of a conceptual model based on the field situation. The status quo is that the impoundment is operational and located 800 m up gradient from the Blesbokspruit. Rainfall on the basin and embankment slopes of an impoundment drives the contamination potential to surface water and groundwater. When rain falls on the impoundment, it infiltrates, runs off as surface water or evaporates. The component that infiltrates can seep out laterally as toe seepage or migrate downward towards the groundwater table. All three pathways would react with the tailings material and transport contaminants to the receiving surface water body. Surface water runoff would directly reach the stream while toe and groundwater seepage would have a lag which is controlled by the permeability and porosity of the tailings and subsurface lithologies.

Management options

The post-operation management of the facility should be aimed at minimizing the mass flux to the Blesbokspruit, which is the receiving water body (receptor). Due to net evaporation in the area, mass that reaches the stream, even if it is diluted could build up in downstream where it is dammed up. The mitigation options available during the post-operation stage should be aimed at controlling the contaminant source (tailings impoundment). A total of sixteen configurations were evaluated with the model. There are four different slope configurations with four different covering options for the tailings impoundments.

Analytical model

The conceptual model used to quantify the water flow and mass balances uses a simple analytical approach. Due to the fact that the evaluation is done for the post-closure stage of the scenarios and steady-state conditions are assumed.

Assumptions

The water balance assumptions for the four scenarios are listed below, numbers 13 – 18, 26, 28 and 30. The assumptions are important and were made based on the shape of the impoundment and the permeability of the capping material. The surface runoff, evapotranspiration losses and infiltration into the tailings impoundment must balance. A balance check is built into the model for verification. Some of the assumptions are qualified using the groundwater quality data from the monitoring boreholes and permeability values of the soil and tailings material (Figure 96, p. 177). The assumptions are considered conservative in that estimates produce higher mass fluxes to the environment.

Flow and mass balance calculations

The model is based on important input parameters. Reference is made by cross referencing assumptions and qualifications in Table 49 (p. 221) to the model input and calculated parameters by denoting the corresponding number e.g. (1) in Table 50 (p. 222). All the water and flow balances were calculated in annual terms but expressed in daily or annual volume and mass. The mass flux assessment was done by using sulphate as a tracer. The model development (

Table 50) is schematically presented below in Figure 123.

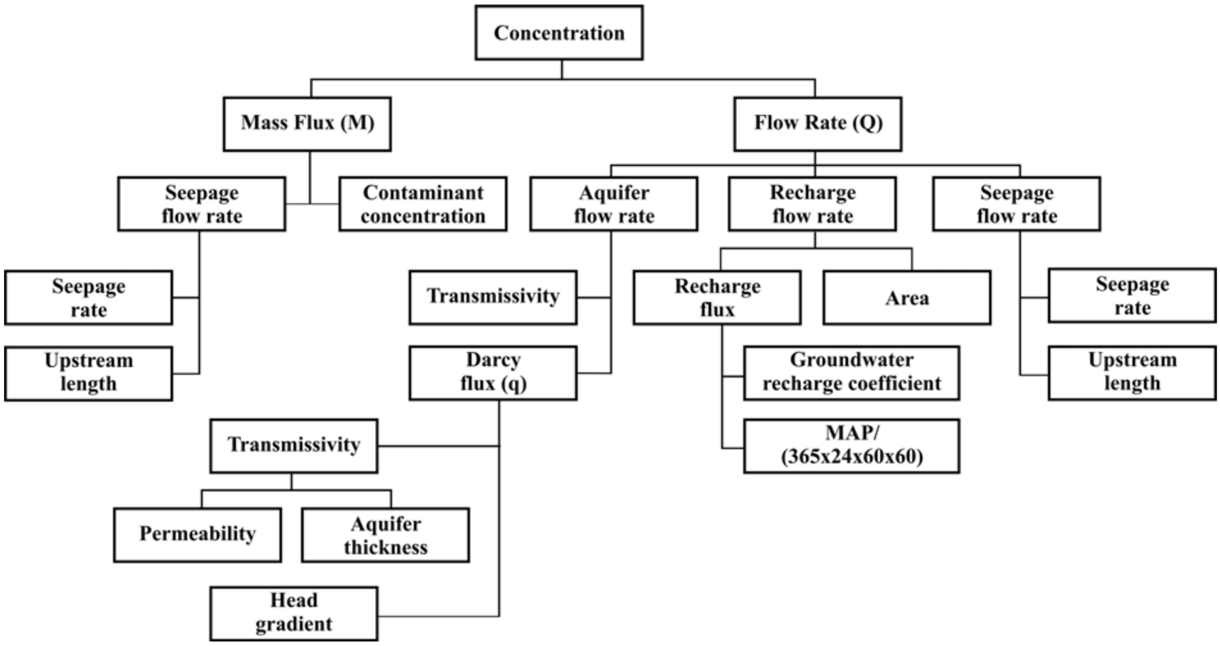


Figure 123: Schematic representation of the model.

The mass flux is calculated using the relationship:

$$M = Q.C \qquad (34)$$

Where:
M = mass flux
Q = flow rate
C = concentration

All of the assumptions made and qualifications on each parameter are provided below. The idea is that this numerical list can be used together with the numerical model.

Table 49: Analytical water flow and mass balance assumptions and qualifications.

(1)	Input of mean annual precipitation (MAP) in mm/annum.
(2)	Input of mean annual evaporation (MAE) in mm/annum.
(3)	Calculation of actual annual evaporation (mm/annum) is based on the assumption in (15).
(4)	Input of the tailings impoundment surface area that varies as the slope changes (ha).
(5)	Input of the waste material permeability at surface (m/day).
(6)	Input of the upstream length of the facility (m). The upstream length influences the down gradient groundwater concentration.
(7)	Input of soil permeability below the impoundment (m/day).
(8)	Input of aquifer permeability below the impoundment (m/day).
(9)	Input of aquifer thickness below the impoundment (m).
(10)	Calculation of aquifer transmissivity (*T*). *T=k.D* measured in m^2/day. Where *k* is the permeability and *D* is the saturated aquifer thickness.
(11)	Input of measured groundwater head gradient (dh/dl).
(12)	Calculation of Darcy flux (*q*). $q = k.\frac{(h_1 - h_2)}{L}$ measured in m/day. Refer Equation (19) Section 2.12.10.
(13)	Assumption on site runoff coefficient as % of total water on site.
(14)	Assumption on site infiltration as % of total water on site.
(15)	Assumption on site evaporation losses as % of total water on site. Note that (13) + (14) + (15) must equal 100 %.
(16)	Assumption on site toe seepage component as % of infiltration (14).
(17)	Assumption on site groundwater seepage component that together with toe seepage (16) must equal 100 % of infiltration.
(18)	Assumption on off-site, down gradient groundwater recharge component as % of MAP.
(19)	Calculation of the total volume of surface water on site.
(20) - (24)	Calculation of the surface water runoff, infiltration and evaporation loss volumes.
(25)	The site groundwater unit seepage should not exceed the tailings, soil or aquifer permeability.
(26)	Assumption on runoff concentration in mg/ℓ. This value can be validated by measurements.
(27)	Calculation of site runoff mass flux [= (20) x (26)] in g/day.
(28)	Assumption on toe seepage concentration in mg/ℓ. This value can be validated by measurements.
(29)	Calculation of toe seepage mass flux [= (23) x (28)] in g/day.
(30)	Assumption on groundwater seepage concentration in mg/ℓ. This value should be comparable with the toe seepage concentration or can be measured.
(31)	Calculation groundwater seepage mass flux [= (27) x (34)] in g/day.
(32)	Calculation of groundwater unit seepage mass flux [= (31)/(4)] in g/m^2/day.
(33)	Input of groundwater background concentration in mg/ℓ.
(34)	Input of low flow volume in river in m^3/day. The low flow will provide the maximum impact on concentration, which is a conservative approach.
(35)	Input of average upstream or background surface stream concentration in mg/ℓ.
(36)	Calculation of low flow stream background mass flux in g/day.
(37) - (39)	Calculation of increase in stream concentration due to surface water, toe seepage and groundwater mass fluxes by mixing the respective mass flux with the flow volumes.
(40) - (42)	Calculate the impact as % increase in concentration.
(43)	Calculate the downstream concentration with mixing of total mass with total flow volume.
(44)	Calculate the cumulative impact of mass flux as % increase of background concentration.
(45) - (49)	Calculates and summarize the annual mass flux from the source to the receiving water body in t/annum.

Table 50: Daggafontein tailings impoundment water and mass balance model.

			Slope (1:1.5)			
	Type		No cover	Rock (300 mm)	Grassed armouring	Diverse vegetation
	Scenario reference		WS1	WS6	WS11	WS16
No	**Description**	**Unit**	**Quantity**			
1	Mean annual precipitation	mm/annum	680	680	680	680
2	Mean annual evaporation	mm/annum	1500	1500	1500	1500
3	Actual evapotranspiration rate	mm/annum	204	136	272	408
4	Surface area (status)	ha	303	303	303	303
5	Tailings permeability at surface	m/day	0,001	0,001	0,001	0,001
6	Upstream facility length	m	1739	1739	1739	1739
7	Soil permeability (below impoundment)	m/day	0,01	0,01	0,01	0,01
8	Aquifer permeability	m/day	0,45	0,45	0,45	0,45
9	Aquifer thickness	m	40	40	40	40
10	Aquifer transmissivity	m^2/day	18	18	18	18
11	Groundwater head gradient	*l*	0,018	0,018	0,018	0,018
12	Darcy flux	m/day	0,324	0,324	0,324	0,324
13	Site runoff coefficient	%	30	20	20	10
14	Site infiltration coefficient	%	40	60	40	30
15	Site evapotranspiration and losses	%	30	20	40	60
16	Site toe seepage component	%	20	30	20	15
17	Site groundwater seepage component	%	20	30	20	15
18	Groundwater natural recharge coefficient	%	5	5	5	5

		Water balance				
No	**Description**	**Unit**	**Quantity**			
19	Surface water on site	m^3/day	5,637	5,637	5,637	5,637
20	Site runoff	m^3/day	1,691	1,127	1,127	564
21	Site evapotranspiration losses	m^3/day	1,691	1,127	2,255	3,382
22	Site infiltration	m^3/day	2,255	3,382	2,255	1,691
23	Site toe seepage	m^3/day	1127	1691	1127	846
24	Site groundwater seepage	m^3/day	1127	1691	1127	846
25	Site groundwater unit seepage	m/day	1,66E-04	2,49E-04	1,66E-04	1,24E-04

		Mass balance (Sulphate)				
No	**Description**	**Unit**	**Quantity**			
26	Site runoff concentration	mg/ℓ	1200	1200	1200	1200
27	Site surface water runoff mass flux	g/day	2,0E+06	1,4E+06	1,4E+06	6,8E+05
28	Site toe seepage concentration	mg/ℓ	1200	1200	1200	1200
29	Site toe seepage mass flux	g/day	1,4E+06	2,0E+06	1,4E+06	1,0E+06
30	Site Groundwater seepage concentration	mg/ℓ	1200	1200	1200	1200
31	Site Groundwater seepage mass flux	g/day	1,4E+06	2,0E+06	1,4E+06	1,0E+06
32	Site Groundwater unit seepage mass flux	g/m^2/day	4,47E-01	6,71E-01	4,47E-01	3,35E-01
33	Groundwater background concentration	mg/ℓ	20	22	27	32

Stream Water Quality						
No	Description	Unit	Quantity			
34	Low flow in stream	m^3/day	7,00E+05	7,00E+05	7,00E+05	7,00E+05
35	Average upstream stream background concentration	mg/ℓ	200,00	202,00	207,00	212,00
36	Low flow stream mass flux	g/day	1,40E+08	1,41E+08	1,45E+08	1,48E+08
37	Concentration increase due to surface water mass flux	mg/ℓ	2,410	1,605	1,597	0,795
38	Concentration increase due to toe seepage mass flux	mg/ℓ	1,608	2,405	1,597	1,192
39	Concentration increase due to groundwater mass flux	mg/ℓ	1,608	2,405	1,597	1,192
40	Impact due to surface water runoff	%	1,205	0,794	0,771	0,375
41	Impact due to toe seepage	%	0,804	1,191	0,771	0,562
42	Impact due to groundwater seepage	%	0,804	1,191	0,771	0,562
43	Downstream stream concentration during low flow	mg/ℓ	205,61	208,39	211,77	215,17
44	Impact due to cumulative mass load increase in stream	%	2,80	3,16	2,31	1,50

Mass flux summary						
No	Description	Unit	Quantity			
45	Site surface water runoff mass flux	tonnes/annum	741	494	494	247
46	Site toe seepage mass flux	tonnes/annum	494	741	494	370
47	Site groundwater seepage mass flux	tonnes/annum	494	741	494	370
48	Total mass flux to stream	tonnes/annum	1728	1975	1481	988
49	% Mass relative to baseline		0	14	-14	-43

3.6.4 Summary

The previous sections describe the experimental work and modelling for the following environmental aspects:

- visual;
- air; and
- water.

The visual effect of an impoundment is quantified by determining its influence on visual perception. This innovative method of quantifying visual impacts for tailings impoundment is new and is in itself a substantial contribution this field of study.

The influence of tailings impoundments on air quality uses available software which was calibrated following an iterative process of comparing predicted results with monitoring data. The surface roughness height for a typical uncovered gold tailings impoundment has been determined and is in the order of 0,0012 m.

A first order analytical water impact model is described and can be used to calculate a mass balance and mass flux in sulphates. Steady-state conditions are assumed. The model can be used to model the various scenarios at the ERGO Daggafontein impoundment site. The results form the water impact modelling is provided in Section 4.5.

3.7 Engineering cost model

3.7.1 Introduction

This research describes an environmental impact and engineering cost decision-support system for assessing alternative upstream ring-dike tailings impoundment configurations and associated environmental liabilities. The following section of the study describes the engineering cost model which is the result of a collaborative effort with Caroline Holmes (Holmes, 2006). It comprises a hierarchy of spreadsheets using available software which follow the engineering steps of:

- specifications;
- quantities;
- rates; and
- costs (Figure 124).

Input data, quantities and rates can be readily modified so that the sensitivity of total costs to these changes can be examined and if necessary changes made to provide economies.

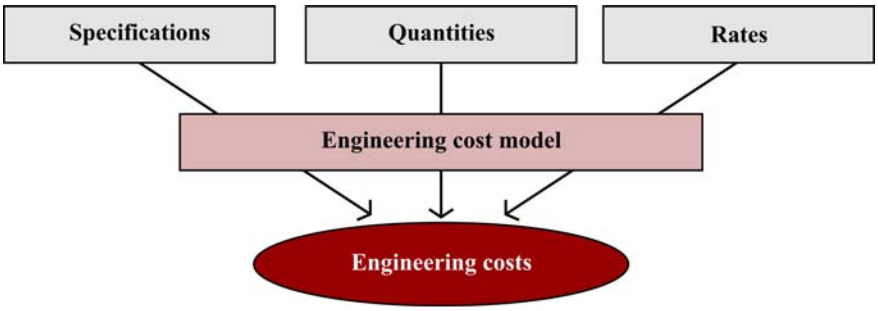


Figure 124: Typical components of the engineering cost model.

The design, construction, operation, closure, and post-closure stages can be considered separately for the purpose of developing a representative engineering cost model for the life cycle of tailings impoundments (Figure 125). The elements of each stage can be defined using conventional civil engineering methodology of estimating costs at standard rates for all the measurable quantities for design and construction (development), operation, closure, and post-closure maintenance and management. These unit costs were procured from recent and current construction contracts.

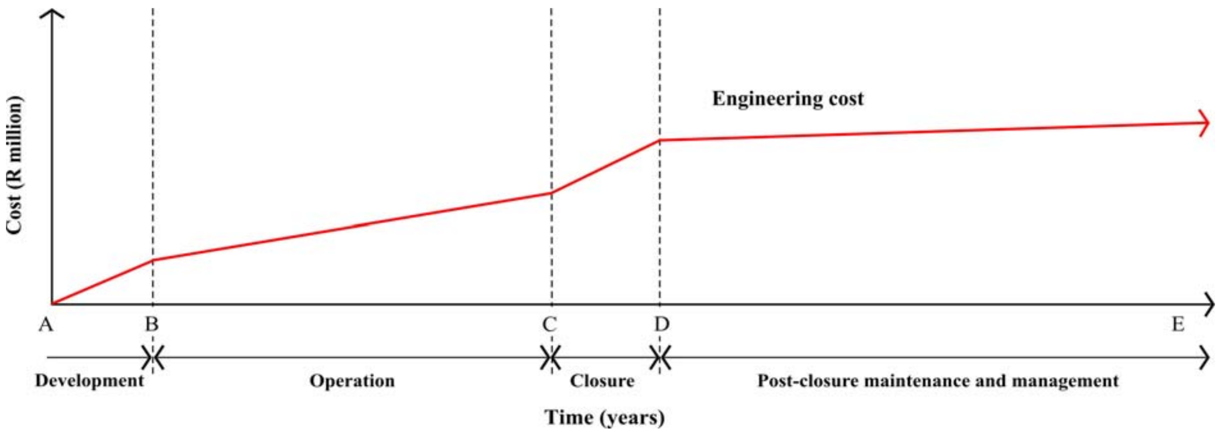


Figure 125: Cumulative engineering costs for the life cycle of tailings impoundments.

The post-closure stage costing represents many different options from return to pristine pre-deposition land use at one end of the spectrum to doing nothing at the other end. Since all closure options have not yet been developed cost estimates will necessarily be somewhat less reliable than those based on current practice and data. Nevertheless whatever option is selected the basic requirements comprise earthworks to reshape, drainage systems and a cover all of which can be costed provided the options are well described in terms of shape and function.

Throughout the life cycle of a tailings impoundment there are costs other than the direct construction costs. Initially there are the planning and design costs, some of which are professional fees for consultants and some are in-house costs primarily also for professional time. These continue throughout the total life cycle process and again may be both external, which are simple to estimate, and internal which may be rather more difficult to establish. In general, of course, the overall design and management costs are a small fraction of the total construction and operation costs hence the accuracy of the estimate of the former is not highly significant.

Tailings impoundment construction may be viewed either as an ongoing process through to completion of the impoundment or construction may be seen as part of the initial development stage with activities such as impoundment footprint preparation, starter walls, trenches, and drains followed by an operation stage when tailings is impounded. Since the initial and operational parts are very different they are divided into separate stages.

Similarly closure and post-closure are divided into separate stages. The former is viewed as simple closure to satisfy the minimum environmental legal requirements. At present this implies what has been called a semi-desirable or unacceptable state where an impoundment is sterile, safe, of original shape, and which most certainly requires some ongoing maintenance. Post-closure includes both the ongoing maintenance and if this happens, the conversion of the site to a desirable, acceptable and sustainable function in keeping with regulatory requirements. It is possible that this sustainable state could result in either a long term cost or a long term benefit.

The conceptual cost modelling methodology for the design, construction, operation, closure and post-closure stages is set out in Table 51 (p. 226).

The engineering cost model was developed to provide for all the necessary significant engineering cost items. Actual costs were obtained from recent tailings impoundment construction and operation projects so that unit costs for each item could be calculated and referred to a base year.

The result from this part of the overall research programme is that a comprehensive engineering cost model for upstream spigotted ring-dike tailings impoundments is available which is sufficiently reliable not only to estimate the overall life-cycle cost but also check costs of for example modifying the overall embankment side slope, cover, and environmental protection measures.

It must be noted that this comprehensive cost model enables trade offs to be determined when comparing various impoundment closure options which at present are necessary to inform the configuration of tailings impoundments.

The engineering cost model runs in conjunction with a parallel environmental impact model so that both costs and impacts are assessed and hence rational decisions made regarding minimising adverse environmental impacts and the preferred sustainable end use of a tailings impoundment.

Table 51: Conceptual engineering model costs the different tailings impoundment stages.

Stage	External Costs	Internal Costs
Planning and design	i) Planning a) Environmental – assess impacts and obtain approval b) Engineering – select site, decide shape, size, type based on assessment of impacts ii) Design a) Engineering – detail design, quantities, tender documents b) Determine and design post-closure land use c) Obtain approval	i) Planning – direct planning and approve, liaison with authorities ii) Design – oversee design and approve iii) Decide on initial post-closure land use
Construction	i) Procurement and construction (consulting fees) a) Call for tenders, adjudicate, award b) Contract documentation c) Supervise contract d) Arrange operating and monitoring system ii) Contract initial construction a) Items off schedule of quantities	i) Oversee construction – approve payments
Operation	i) Consulting fees a) Arrange operation contract b) Supervise contract ii) Operation contract a) Items off schedule of quantities (Separate out environmental control aspects)	i) Oversee operation – approve payments
Closure	i) Consulting fees a) Design closure measures b) Obtain closure permission c) Arrange closure contract d) Supervise closure ii) Closure contract a) Items off schedule of quantities (Separate out environmental control aspects)	i) Oversee closure – liaise with authorities and approve payments
Post-closure	i) Consulting fees a) Refine post-closure land use b) Obtain approval c) Arrange construction contract d) Arrange long term operation and maintenance ii) Post-closure contract a) Items off schedule of quantities	i) Check if post-closure land use will meet the necessary requirements ii) Liaise with authorities iii) Approve scheme – set up financial arrangements iv) Arrange operation and maintenance

The essential criteria for the engineering cost model are that is simple, reliable, flexible, and computer based. The approach begins with a listing of all the physical items which form part of the tailings disposal facility (Figure 20, p. 29) such as:

- access and perimeter roads;
- tailings delivery, ring main and distribution pipelines;
- starter wall;
- toe wall;
- solution trench;
- catwalk;
- penstock;
- catchment paddocks;
- drains;
- silt trap;
- cover; and
- return water dam.

Dealing with each of these to an acceptable standard is an engineering process which can be measured and costed provided that appropriate unit rates are established. Difficulties lie in the adequate definition of acceptable standards and specifications. These difficulties can, however, be readily overcome by providing a list of assumptions and implementing industry best practice.

3.7.2 Components

The basic building blocks (Figure 126) of the cost model are similar to those of a conventional engineering cost estimate and include:

- inputs;
  - user inputs;
  - default model inputs;
- specifications;
- schedule of quantities;
- schedule of rates; and
- cost estimate.

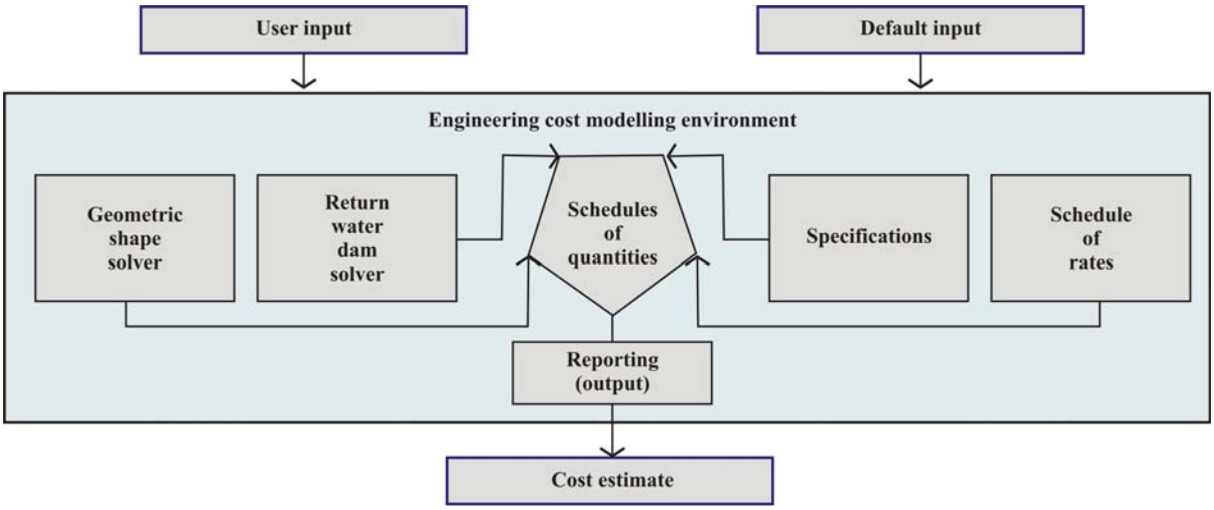


Figure 126: Basic elements of the engineering cost model.

The emphasis is however on the concept that a reliable cost estimate is required and not a detailed schedule for contract purposes. It is possible that the works may be required either next year or in twenty years time and standards and methods of construction may have changed and certainly unit rates for the items will have changed dramatically. Modifying specifications and updating unit rates will ensure the system continues to be reliable for current use and using standard financial methods will provide for future estimated costs based on current prices.

The following three key elements of the engineering cost model is described in the next section of the study:

- specifications;
- schedule of quantities; and
- schedule of rates;

for which the specification requirements are determined by engineering best practice.

Specifications

Arguably this is the most important element of the system since in it the various engineering works are described in sufficient detail to be meaningful for the purpose by inferring or defining the required quality or standards, but at the same time the detail should not be such as to overwhelm the system.

Clearly the criteria may at times be conflicting hence some compromises may be required. In practice this was not found to be the problem provided that the overall broad purpose of the system together with the sensitivity of the total cost to the particular item was considered.

The following list of specifications is included in Appendix C to illustrate the level of detail at which engineering items are specified. It is intended to provide information on the typical works required:

- access and perimeter roads;
- tailings delivery, ring main and distribution pipelines;
- starter wall;
- toe wall;
- solution trench;
- catwalk;
- penstock;
- catchment paddocks;
- drains;
- silt trap;
- cover; and
- return water dam.

This is not an exhaustive list of items included in the engineering cost model and it may well be that should the system be applied for other types of impoundments then further items will be required and some may be deleted. The complete engineering cost model comprises a total of 69 specifications. There are 37 construction stage, 16 operation stage, 8 closure stage and 8 maintenance and aftercare stage details.

All physical, chemical and biological processes for which maintenance has been specified must be monitored until they reach a steady state or as long as deemed necessary at the time of closure. Such processes include erosion of impoundment surfaces, surface water drainage, ground water recharge, air quality, surface water quality, ground water quality, performance of cover, invasion of weeds and colonization by animals. Measures must be implemented to manage, mitigate and monitor environmental impacts and a site that is unstable or hazardous must have a fence erected around the perimeter tocontrol access.

Schedule of quantities

This is a straightforward engineering schedule of quantities of all the items specified and it presupposes that all these items can be readily measured. It is again emphasized that the system is not intended to be equivalent to detailed design costing but is more akin to feasibility planning costing for which an accuracy of say ± 10% is required. Measurement of practically all the items can be made with sufficient accuracy from the quantifications made by the various solvers built into the engineering cost model. The most important factor is producing a reliable schedule of the required work although on the other hand where for example large volumes of earthworks are involved then care must be taken to ensure that the dimensions are accurate. This is particularly so for the vertical dimension of rehabilitation earthworks where what may appear to be relatively small changes have a very large influence on total volumes and hence on total costs, if the item itself constitutes a large proportion of the overall cost of rehabilitation. A typical schedule of quantities is shown in Table 52.

Table 52: Engineering schedule of quantities for selected closure cost items.

Item	Description	Unit	Quantity	Rate with CPI	Amount
Basin profiling (specification sheet R1)					
1	Basin profiling	m^3	0,00	11,00	0,00
2	Evaporation paddock wall construction	m^3	101 902,33	16,50	1 681 388,45
	Sub-total				1 681 388,45
Cladding of tailings dam basin (Specification sheet R7)					
1a	Topsoil to basin	m^3	0,00	22,00	0,00
1b	Vegetation of basin (diverse)	m^2	0,00	44,00	0,00
	or				
1	Rockfill cladding of basin	m^3	0,00	34,65	0,00
	or				
1	Rock armouring with topsoil and grassing	m^3	1 692 307,69	14,08	23 827 692,31
	Sub-total				23 827 692,31
Cladding of tailings dam outer slopes (Specification sheet R8)					
1a	Topsoil to outer slopes	m^3	0,00	22,00	0,00
1b	Vegetation of outer slopes (diverse)	m^2	0,00	44,00	0,00
	or				
1	Rockfill cladding of outer slopes	m^3	0,00	34,65	0,00
	or				
1	Rock armouring with topsoil and grassing	m^3	1 984 060,75	14,08	27 935 575,30
	Sub-total				27 935 575,30
Tailings dam outer slope flattening (Specification sheet R9)					
1	Tailings dam outer slope flattening (cut to fill)	m^3	0,00	11,00	0,00
	Sub-total				0,00

Schedule of rates

This again is a straightforward engineering schedule of rates. Similar comments apply as for the schedule of quantities; it is important to ensure that the whole of any item is included in a rate and that there are no significant extras. An aspect which requires particular attention is construction and rehabilitation materials availability where for example starter wall construction material or topsoil may be in short supply. In this case overhaul can become a major cost and poor planning can result in huge cost overruns. Conventional civil engineering rates were obtained from consulting engineers' and contractors' recent experience of tailings impoundment works. Generally works are carried out on a two cost basis i.e. an establishment item and a quantities related item. Depending on the nature and the extent of the work the former may be a large or small portion of the final cost. For the purpose of this model the rates used include any fixed cost items.

3.7.3 Modelling

The choice, for example, of engineering systems, methods and specifications and the extent they are interpreted for costing purposes depends on practical, economic and legal constraints. This engineering cost model allows the user to test various assumptions and different scenarios and also allows the user to change and test the variables. The engineering cost model (Figure 127) was constructed applying a system consisting of multiple sheets within a spreadsheet, as shown diagrammatically below.

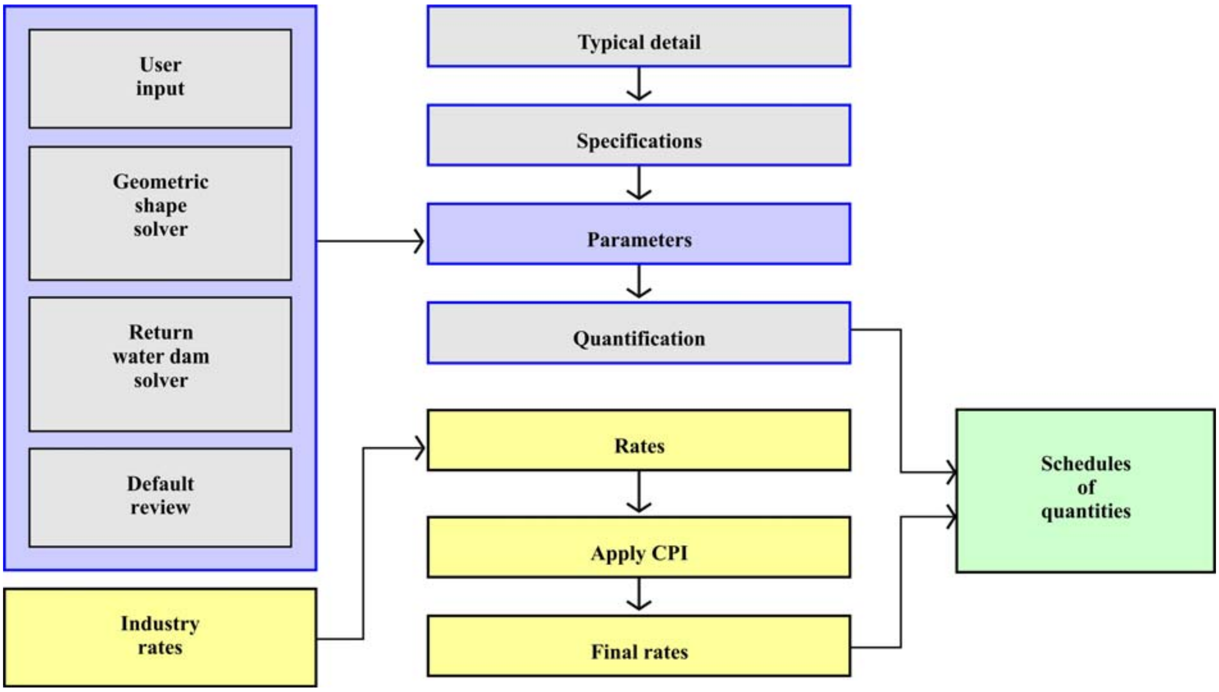


Figure 127: Schematic of the multi-sheet engineering cost model.

Each sheet reports an aspect of the modelled result – rehabilitation variables, general specifications and costs, costs for individual items, development stage summaries and so on. The input and edit sheet allows the users to change the model input variables and adjust any assumptions. The model itself comprises a number of datasheets depending on the amount of specifications within the afore mentioned. The sheets contain the model calculation and formulas.

Input and editing sheet

Each engineering specification input sheet can be adapted and communicates the specification graphically and describing the variables, assumptions, quantifications, rates and inputs that can be changed by the user by selecting a cell within any sheet and viewing the calculations. The model also allows for inflation adjustment by means of applying a consumer price index (CPI) factor. Values and numbers for the current year and all future years are in real or "constant currency" terms, referenced to the most recent complete year. This means that this year, 2007, and any future years are expressed in 2005 Rands until such time as new rates are procured and revised in the system. Input costs can be adjusted for changes in the relevant cost index, as shown in the detailed input and edit cost sheet. The input and edit sheet informs the specification or general costing sheet allowing for additional functionality through providing variables and making certain assumptions. Also, this sheet shows specific assumptions and information which are used at every step to construct the data input sheet.

General costing sheet

The main purpose of the general costing sheet is to automatically calculate the unit rate for each specification. The aspect of specifications has already been covered in the previous section describing each of the system elements.

Summary sheet

This is a summary of the costs captured for each stage and presented in a typical engineering schedule of quantities format. This sheet is in essence also based on an engineering schedule of quantities or bill of goods. The inputs used in this schedule are automatically linked to the general specification and costing as well as the input and edit sheets' outputs. Also, this type of system is based on direct estimates of each item within the specification.

The engineering cost model can be used to model the engineering costs for the various impoundment scenarios at the ERGO Daggafontein site.

3.8 Summary

This section describes the experimental work and the modelling undertaken as required by the overall system for the engineering costs and the visual, dust, and water aspects. ERGO Daggafontein is used to validate the preliminary models and devise rehabilitation options:

- As it is one of the largest free-standing upstream deposited ring-dyke impoundments in the world.
- As reliable information on the study area is available.
- For permission could be obtained to use the site in this research.
- Since it is not in close proximity to other tailings impoundments. This is beneficial when it is required to take unobstructed panorama photographs as part of the visual perception study.

The modelled impoundment final rehabilitation configurations include changing the geometry and changing the cover. The overall impoundment embankment side slopes vary between 1:1,5 and 1:9 and the cover material include tailings in situ (no cover), rock cladding, grassed armouring and diverse vegetation. Important criteria are defined early on in the experiment. The production of the modelled impoundment is 990 000 tpm over a 16 year period requiring a total storage volume of about 105,6 Mm^3. The modelled dry density of the placed tailings is 1,8 t/m^3 and the final height is kept constant at approximately 37 m.

The visual impact experimental work required the development of a method to quantify such impacts. This required the visualisation of the various impoundment configurations and included manipulating panorama photographs to simulate the different options. The Nominal Group Technique (NGT) study method was employed to analyse the results from this part of the research.

Before modelling the impacts on air quality the software used for this purpose needed to be calibrated. The process whereby the software was calibration is described and makes use of an iterative modelling process whereby the roughness height parameter is varied until the predicted results correlate to dust fallout monitoring data. The DRD 2L24 tailings impoundment was used for the necessary field work.

An analytical water flow and mass balance model was developed as part of this research and is used to illustrate the change in water related impacts changing the configuration of an impoundment.

Lastly, an engineering cost model is described which is used to calculate the costs of various engineering aspects during the design and construction (development), operation, closure, and post-closure maintenance and management stages.

The results of the experimental work and modelling are presented in the Section 4.

CHAPTER FOUR: RESULTS

4.1 Introduction

The previous section in the thesis describes the methods, technologies, and models used to predict and quantify the:

- visual perception zone of influence;
- air quality zone of influence; and
- change in mass flux and the impact on water quality.

The visual modelling required the determination of visual perception distances for various slope and cover configurations. It is however necessary to analyse the results and present such results to a panel of experts in order to reach consensus that what was predicted is typically what will be observed in the field. Details on the analysis of the visual perception distance results are provided in Section 3.4.9, followed by a description of the field work undertaken to apply the predicted results to the ERGO Daggafontein site. One of the overall objectives of this study is to identify elements for each of the key environmental aspects which can be either modelled or measured in order to quantify the possible change in environmental influence resulting from the change in impoundment configuration. The elements quantified for the key environmental aspects in this study are listed and summarised in Table 53. Lastly, the section presents the results from the quantification of the environmental aspects. Visual and air quality zones of influence are modelled, mapped and measured and the water quality change in sulphate mass flux predicated and quantified.

Table 53: Quantifiable elements for the various environmental aspects.

Environmental aspect	Description of quantifiable element
Visual	Recognition, detection and awareness visual perception distances are used along with zone of visual influence mapping to determine surface areas of influence. The visual perception area of influence results can be expressed in hectares (Figure 148, p. 252).
Air	Upon calibration of the predictive models both the dustfall (TSP) and concentrations of particulates in the air (PM_{10}) can be modelled, mapped and surface areas of influence determined. The air quality influence area results can be expressed in hectares (Figure 150, p. 254).
Water	An analytical model is described and used to quantify the change in sulphates for the various configurations. Although the technology exists to model the dispersion and zone of influence in three dimensions, it was decided that it is sufficient to calculate the increase or decrease in load for the various configurations. However, a steady-state groundwater flow and sulphate transport simulation was undertaken (Figure 153, p. 258) to determine the anticipated zone of influence and illustrate that it can be expected that the Blesbokspruit and one of its tributaries will capture most of the surface water runoff and discharge to groundwater.
Soil and landform	Best practice requires the construction of stormwater control structures to contain dirty water runoff from embankment side slopes. Although this is an important aspect, especially in terms of the long term stability of side slopes, exact numbers for the change in load have not been quantified as a result of change in embankment configuration.

4.2 Visual perception

The following sections present the results from the Nominal Group Technique (NGT) study method which was used to rate the visualisations of different tailings impoundment configurations. The objective of the study was to express visual impacts of tailings impoundments in quantifiable terms with the purpose of including such in an overall environmental impact and engineering costing system.

The level of visual perception over viewing distance for various impoundment configurations was determined by employing the NGT study method. This technique is used as it presents researchers with a method to reach consensus on results within fields of study often considered to be subjective.

The ERGO Daggafontein tailings impoundment was photographed at various distances. The panorama photographs were manipulated to simulate the different impoundment configurations. The visualisations were presented to a panel of experts within a controlled experimental environment in accordance to steps recommended by Crance (1987).

Each scenario (impoundment configuration) is visualised from different viewing distances. This is done in order to determine the relationship between visual perception and distance. For example, the grass covered 1:3 side slope scenario was visualised at 6 distances ranging between 1000 m to 8200 m (Table 54).

Table 54: Typical scenario descriptions for impoundment with a 1:3 side slope and grass cover.

Slope	Cover	Season	Distance (m)	Reference code	Visualisation reference number	Visualisation slide sequence
1:3	Grass	Summer	2000	2000SG3	10	33
1:3	Grass	Summer	3000	3000SG3	16	46
1:3	Grass	Winter	1000	1000WG3	5	17
1:3	Grass	Winter	3600	3600WG3	21	15
1:3	Grass	Winter	7200	7200WG3	27	58
1:3	Grass	Winter	8200	8200WG3	32	3

S denotes summer   W denotes winter   G denotes grass

Figure 128 and Figure 129 presents the initial results from the individual experts' ratings before discussion and reaching consensus. Figure 128 presents the initial results from the individual experts' ratings for the visualisation of an impoundment with an overall embankment side slope of 1:3 and which is covered with grass whereas Figure 129 presents the results of an impoundment with the same slope but not covered (tailings in situ). Figure 128 shows 33 diamond-shaped result points and Figure 129 indicate 22 points. Although the figures only show 33 and 22 results respectively they represent 72 results each time. There are 12 panellists and 6 distances visualised which provides a total of 72 results presented in each figure. The reduced number of points are, as could be expected, the consequence of an overlap of some of the points which results from experts giving the same rating to the visualisations.

Each visualisation was projected and discussed until consensus could be reached on the rating for each visualisation. The diamond-shape points on Figure 130 and Figure 131 show the consensus results for the same visualisation plotted in Figure 128 and Figure 129 after discussion amongst the experts and consensus has been reached by the panel.

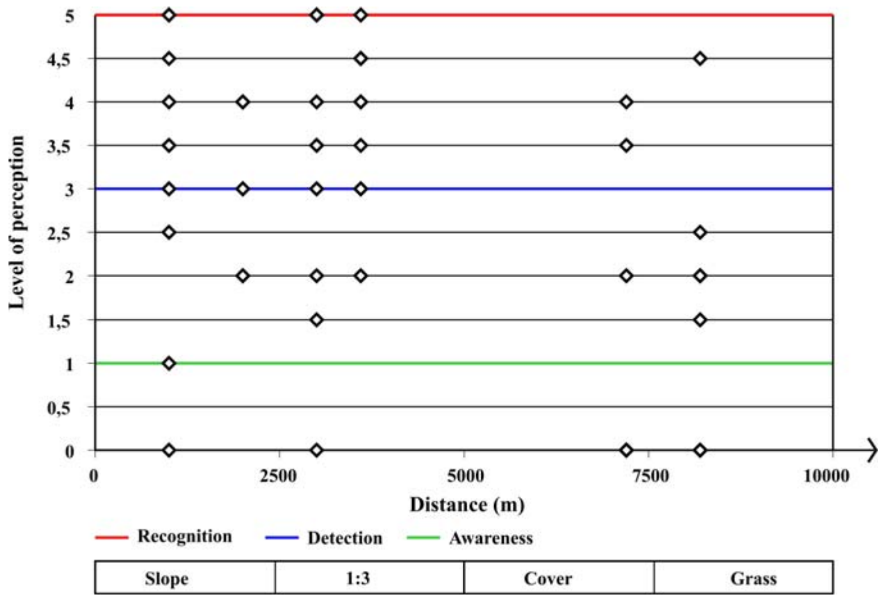


Figure 128: Initial results of all participants for the grass covered 1:3 side slope scenario.

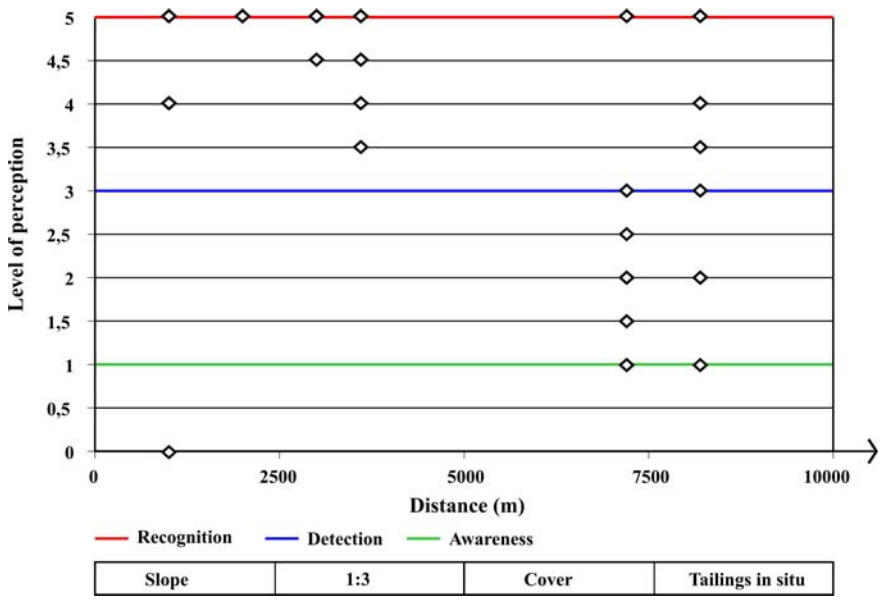


Figure 129: Initial results of all participants for the tailings in situ covered 1:3 side slope scenario.

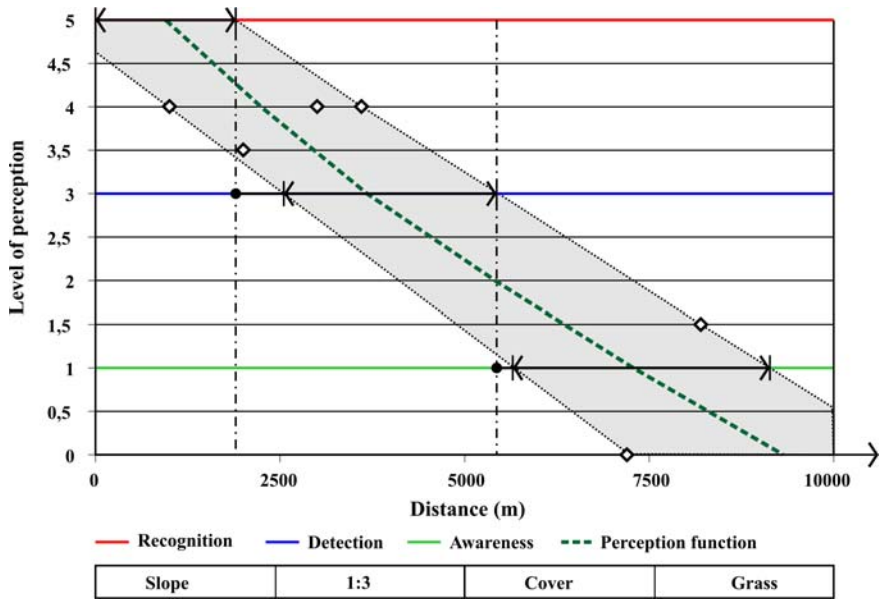


Figure 130: Consensus results and envelope indicating the range of perception level distances for the grass covered 1:3 side slope scenario.

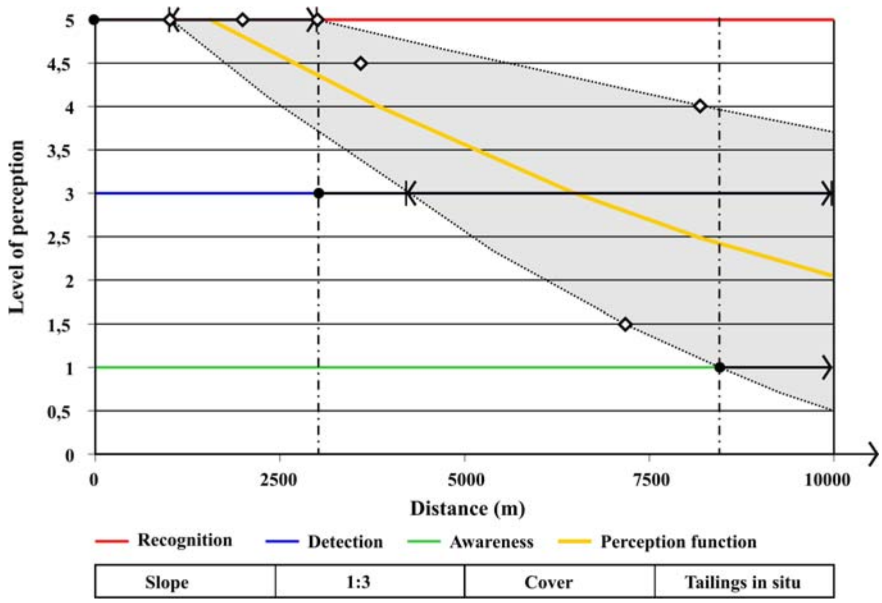


Figure 131: Consensus results and envelope indicating the range of perception level distances for the tailings in situ covered (no cover) 1:3 side slope scenario.

The expert consensus results of the scenario, once enveloped, are shown as an envelope which follows the obvious rational trend that the perception levels are a direct function of the viewing distance. The outer limit consensus results envelope indicates the range of the probable minimum and maximum distances for each perception level.

This approach allows for expected variance resulting from aspects such as:

- differing external environmental factors;
- the reliability of each visualisation; and
- the notion that perception thresholds are rarely an absolute event.

The vertical dashed lines in Figure 130 indicate the outer limit of each maximum perception level distance range and also indicate the starting viewing distance for the following perception level range. A perception over viewing distance envelope and function could be determined for each of the eight scenarios defined in Table 21 (p. 162).

Visual perception distance functions were determined and composed by plotting trendlines through the mean values of the perception ranges such as described by Schroeder (1984:573). The consensus mean visual perception distance functions for all of the scenarios are presented in Figure 132.

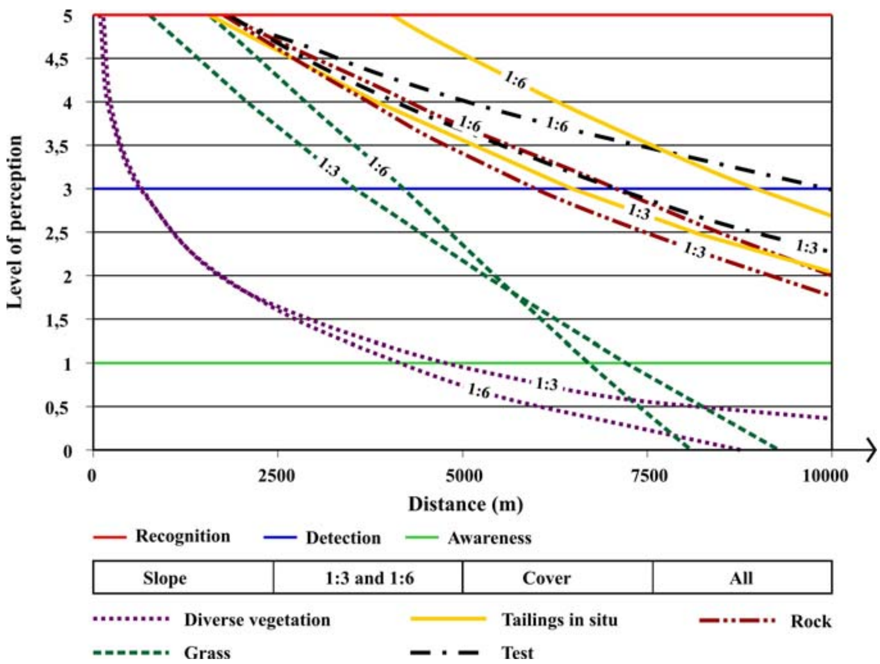


Figure 132: Mean perception over distance functions for all scenarios.

The results presented in Figure 132 were shown to the panel of experts in order to reach agreement as to the findings of the first round of the Nominal Group Technique (NGT) study process. The presentation process of the findings to the panel of experts is discussed in the following section, Section 4.2.1.

4.2.1 Validation of results

The visual perception distance results in Figure 132 were analysed and presented at another seminar to the same group of experts. This was the second and last round of the NGT. The last round of the NGT was a closing seminar at which the results were presented to nine experts and evaluated (Appendix A.1 includes the particulars of the participants). In this part of the study active participation of the experts were crucial.

The objectives of the follow-up session were to:

- discuss the results from the previous round;
- note observations; and
- reach consensus on the:
  - overall experimental procedure;
  - interpretation of the consensus results derived from the first round;
  - application of the results in the field at the ERGO Daggafontein impoundment;
  - ratings of the photographs taken from predicted view points;
  - possible research gaps; and
  - opportunities for future research to be undertaken.

A copy of the slide presentation to the experts is included in Appendix A.3. The application of the interpreted consensus results has not been discussed and requires some discourse. The ERGO Daggafontein tailings impoundment was used to check the reliability of the predicted results.

Although the impoundment was previously photographed and used in the determination of the visual perception distances for various impoundment configurations it was not considered to be a problem applying the results to the same impoundment in the field confirmation exercise as:

- the ERGO Daggafontein impoundment was used to isolate photorealistic textures at the various distances, applying these to the entire impoundment surface; and
- completely different sightlines and viewing distances as what were used in the visual perception distance study were used in the testing of the results.

Applying the results in the field entailed compiling a map (Figure 133, p. 239). The map indicates:

- The zone of visual influence (the locations from which the scheme us visible) which was determined by means of a GIS software package developed for this purpose. The areas shaded in light green presents the surface area in the landscape from which the impoundment is visible.
- The mean visual perception distance values for a 1:3 slope and impoundment covered in grass. This was used for reference purposes, provided scale, and provided general orientation while in the field. The visual perception distance plots also helps to identify candidate points to photograph the ERGO Daggafontein impoundment from.
- Suitable candidate photographing points are indicated on the map. These are determined by overlaying the information on an aerial photograph as well as considering access to the points from which to take the panoramic photographs.

Once the map was compiled another visit to the surrounding landscape was organized during which photographs were taken from the points indicated on Figure 133, p. 239. The base map, prepared prior to further field work, assisted in finding suitable photographing points providing unobstructed views of the ERGO Daggafontein tailings impoundment. The co-ordinates of the viewpoints were captured using a GPS and were used to prepare the map presented in Figure 133.

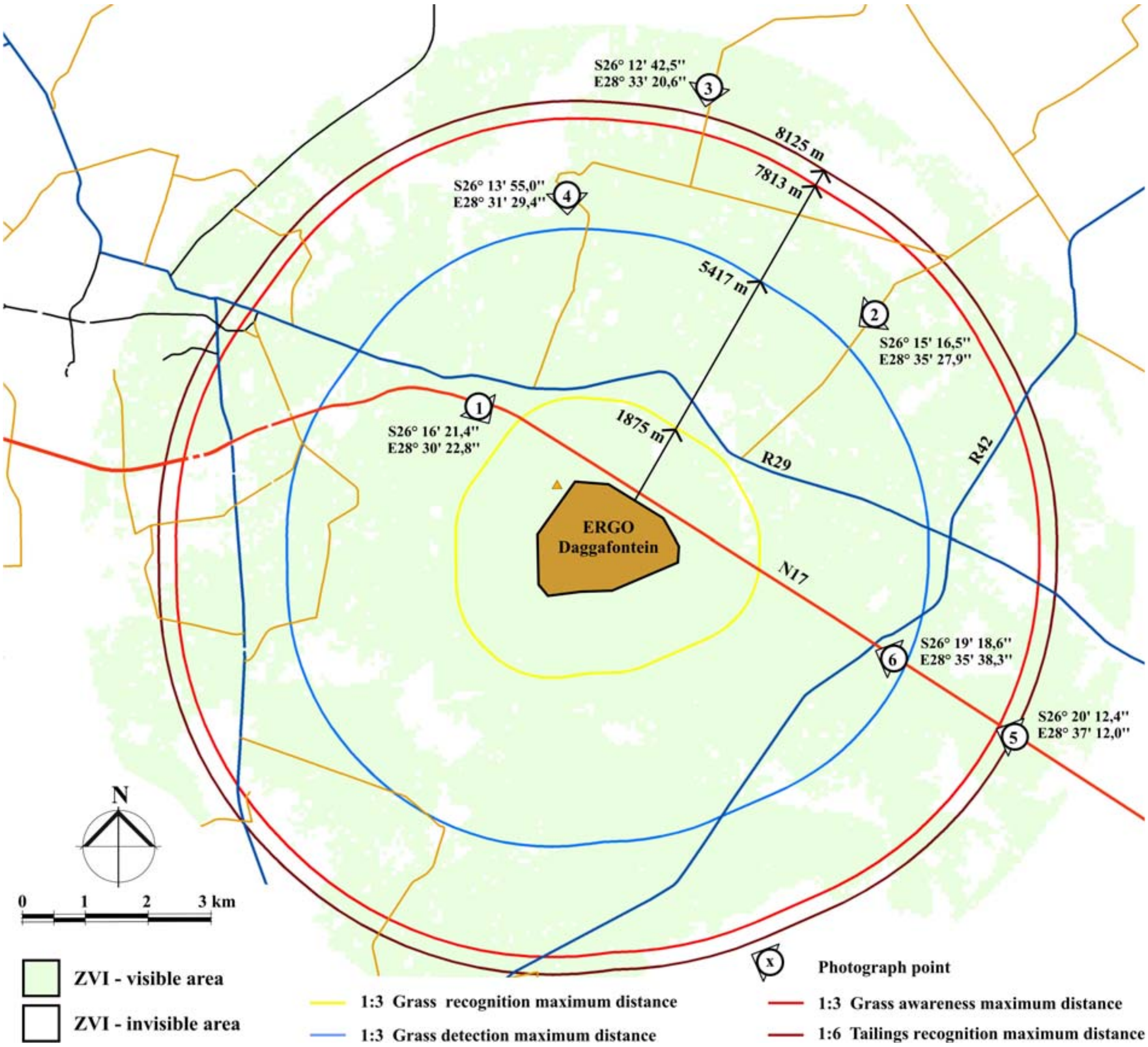


Figure 133: ERGO Daggafontein visibility map indicating photographing points.

Panorama photographs of the ERGO Daggafontein tailings impoundment were taken from six photographing points, stitched, cropped, adjusted to true viewing height, and presented to the panel for further discussion.

Discussions of the panoramic photographs provided information pertaining to:

- what the panel observed;
- the level of perception for each view;
- what could be perceived and whether the impoundment was detectable or recognisable from that particular viewing distance; and
- the factors contributing to the level of perception for each panorama photograph.

The black rectangular boxes on the following images indicate the visible sections of the panorama photographs which were shown to the panel in the slide show. The size of the images on the screen relates to the apparent size of the impoundment in the landscape. Equations 31, 32 and 33 were used to adjust the size of the impoundment on the screen until it represented the true size at that specific photograph viewpoint.

Photograph 1

Effortless recognition takes place at approximately 2700 m. The white appearance of the in situ tailings causes the viewer to not only detect but also recognise the man-made landform to be a tailings impoundment in photograph 1, Figure 134.

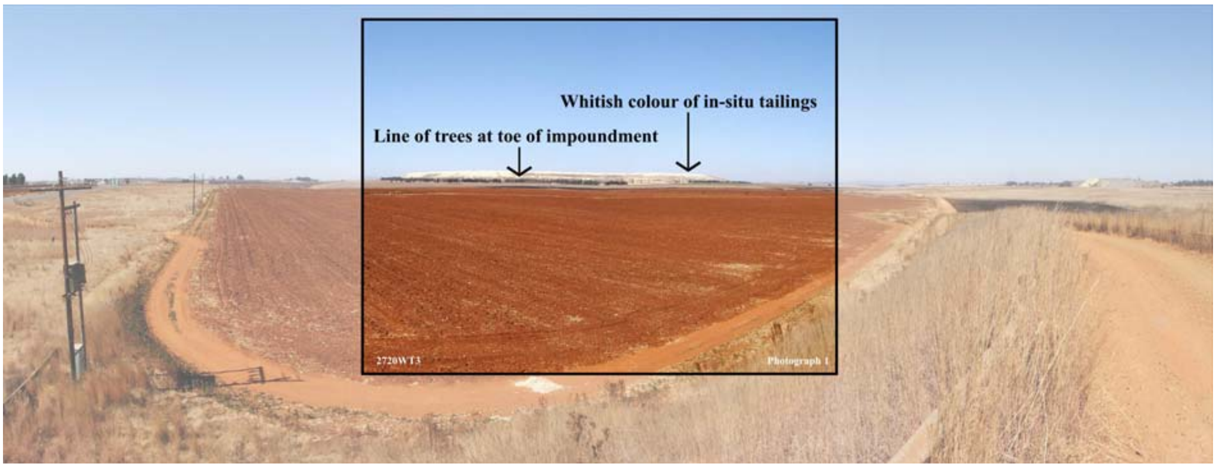


Figure 134: Photograph 1 taken at a distance of 2720 m from the impoundment presents a view of the impoundment looking in a south-easterly direction.

Two key aspects contribute to the recognition, namely the trees planted at the toe of the deposit and the colour of the impoundment's outer surface. The embankment face of the ERGO Daggafontein impoundment, shown in this view, has not yet been rehabilitated and presents a section of the impoundment that can best be described as uncovered and of which the outer surface is the in situ tailings originally deposited. The straight line of blue gum trees at the toe of the impoundment contributes to the effortless recognition of the impoundment as a result of the contrast between the trees and the in situ tailings in the background. Furthermore, it can be argued that trees planted for dust control purposes at the base of mine residue deposits are synonymous with this type of activity in the South African landscape. The whitish colour of the in situ tailings is distinctive and contrasts with the reddish colour of the ploughed land in the foreground of the photograph.

Photograph 2

The white section on the tailings impoundment allows detection to take place at 6500 m (Figure 135).

Although the man-made landform is detected in the natural landscape, it could not be recognized as an impoundment. The impoundment embankment which has been rehabilitated and covered with grass is not detectable. The rehabilitated portion of the embankment lies immediately adjacent to the left of the uncovered impoundment section

A red line is used in the image to indicate the outline of the impoundment on the horizon and arrows indicate the rehabilitated and uncovered portions of the impoundment. It therefore leads to the conclusion that if the tailings impoundment was completely covered in grass it would probably not have created any awareness and, at worst, been detectable with a great deal of effort as a man-made landform within the landscape.

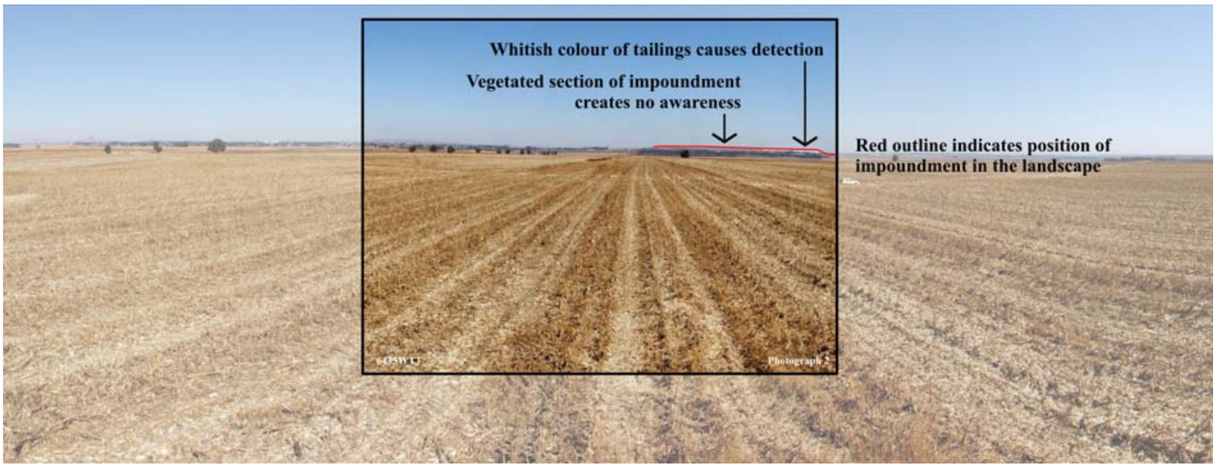


Figure 135: Photograph 2 presents a view at 6435 m of the impoundment looking South.

The results presented in the previous section indicate that one could expect detection to take place up to and exceeding distances of 10 000 m if an impoundment is left uncovered. Also, the results indicated that should the impoundment have been covered with grass that it would not have been detectable. The limit of the detection distance in the visual perception study was given as 5417 m. The distance at which this photograph was taken is just more than 1000 m further at a distance of 6435 m.

Photograph 3

Similar to photograph 2 the white section in photograph 3 (Figure 136), characteristic of uncovered tailings, leads to detection whereas the portion which has been grassed does not even create awareness. The uncovered section of the impoundment is indicated with an arrow on the right in the photograph while the grassed section is on the left. It is expected that an uncovered tailings impoundment will be detectable from distances of about 7800 m and even up to and exceeding distances of 10 000 m.

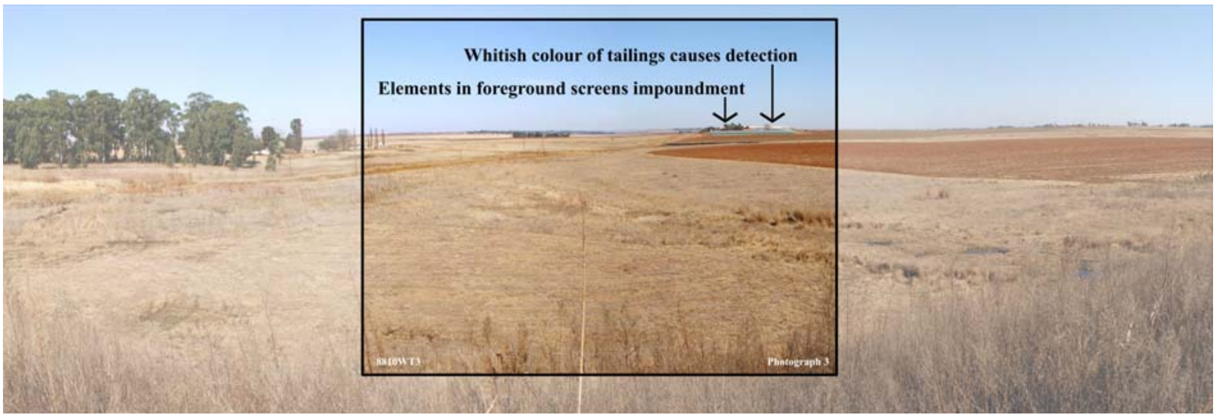


Figure 136: Photograph 3 is a view from 8810 m looking South towards the impoundment.

Photograph 4

Photograph 4, Figure 137, presents the same view at the same distance of two different covers on the impoundment with the grass cover creating no awareness and the tailings in situ leading to detection.

The impoundment is recognizable but with effort at approximately 6200 m as the visible embankment of the impoundment has not been grassed. The in situ tailings cover results in easy detection as a man-made landform in the landscape and although recognition takes place, it is with considerable effort. The results provided a distance of between 4700 m and 6100 m at which one can expect recognition with difficulty to take place.

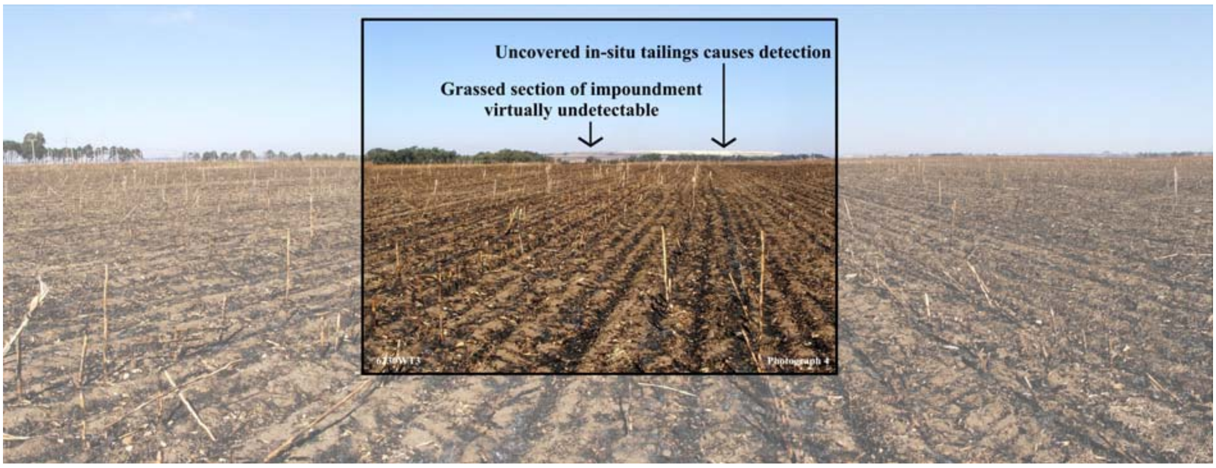


Figure 137: Photograph 4 was taken from 6230 m looking in a southerly direction towards the impoundment.

Photograph 5

No awareness takes place at 8190 m (Figure 138). The impoundment embankment viewed in the photograph is completely rehabilitated and covered in grass.

Figure 138: Photograph 5 was taken looking northwest towards the impoundment at a distance of 8190 m.

The results indicate that awareness is likely only to take place from distances of up to and less than 7800 m. The 8190 m distance is outside this limit and would therefore appear to support this finding. The view angle relative to the impoundment is such that the sides of the impoundment are seen as several surfaces with various textures and colours. From this viewing angle, what may look like a very flat embankment side slope, is in fact, the impoundment sides that disappear into the background.

Photograph 6

A foreign landform is detected in Figure 139, but with effort. This view of the impoundment is similar to that shown in photograph 5, but 3000 m closer.

Figure 139: Photograph 6 was taken towards the a northwest view of the impoundment at a distance of 5150 m.

The panel concluded that there is almost no detection of a foreign landform in the landscape from this distance. This is probably as a result of the effective grass cover on the visible section of the impoundment, the intensity of the light, and the angle of the sun. The photo point is within the expected detection zone. However, due to the reasons mentioned, it is difficult to detect the landform as being foreign.

4.2.2 Observations

The results in Figure 132 (p. 237) were presented to the panel of experts for discussion and input. General consensus was reached that the experimental procedure was sound with a logical progression in methodology combining elements of qualitative as well as quantitative research methodologies. It was observed that a clear distinction between the perception levels for the various covers is apparent.

The background and foreground play an important role and in certain instances can play a more significant role than the cover of the impoundment. Similarly the context and setting of the impoundment can contribute more to the level of perception than that of slope and cover. It can be expected that the horizon plays an important role.

Where the impoundment is below the horizon and has the natural landscape as backdrop it will be more difficult to detect the foreign landform especially if there is very little difference in colour and texture of the element in the foreground (tailings impoundment) and the background (natural landscape).

The visual impact of an object is also a function of the size. It was discussed that the shape and footprint of an impoundment could influence the ability to blend an impoundment into the surrounding landscape as it was argued that nature does not have straight lines. The sharp corners at the intersection between the flat top and the side slopes are unnatural and contribute to the recognition process.

The straight line of trees planted at the toe of the tailings impoundment to screen and control wind erosion is typical of mine residues in the South African landscape and is an element that contributes to recognise a man-made landform as a mine residue deposit. There are many examples where trees are planted to screen schemes visually and control wind erosion. Using trees to screen an object from sensitive viewers is a function of the viewer relative to the object being screened. The contrast in colour between the darkish tree planting at the toe of the deposit and the light coloured tailings in the background contributes significantly to the recognition process and exacerbates the problem. In many cases the impoundment height will exceed the tree tops two-fold, three-fold and, in certain instances, even more. A screen, whether tree planting or any other method, can be positioned in such a manner that it is most effective in fulfilling the intended task of screening sensitive viewers, view-points, or viewing zones from a scheme (Figure 140).

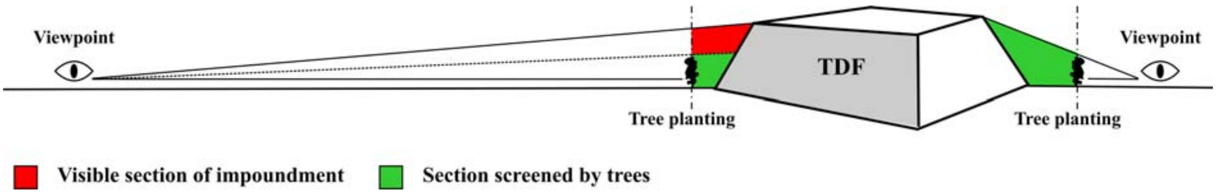


Figure 140: Using tree planting as screening of impoundments.

This research does not test the response or attitude of the viewer to the stimulus. It could be expected that a tourist in a game park will respond differently than a worker in a light industrial area, should both parties be able to recognize a man-made landform as something foreign and out of place. Landscape management zones are important as it controls and manages the types of developments that can or cannot take place within these zones. In certain instances money can maybe more wisely spent by finding sensitive viewpoints within the visual zone of influence and managing such, rather than trying to camouflage the entire impoundment by covering it with grass.

4.2.3 Visual perception results

The results are indicated in envelopes (Figure 130 and Figure 131, p. 237) with the upper and lower results delineating the outer boundaries thereof. When comparing the visual perception distance consensus ratings of the expert panel with the panorama photographs the following becomes apparent:

- The bright colours typical of the in situ tailings surface are better detected over the darker colours of the grass cover contributing to the visibility envelope falling in the perception and detection over further distances.
- The shape of the impoundment in terms of geometry, complexity, and orientation plays an important role in the stimulus, detection and recognition process. Some of the respondents felt that the flat top surface of an impoundment contribute significantly towards the recognition - especially at considerable distance from the impoundment.
- The visual angle and position of the sun, for example illumination, causes a variance in perception of the visualisations.
- The outline of the impoundment (silhouette) creates the initial awareness especially when there is sufficient contrast with the existing terrain.
- It was observed that some of the simulated textures such as the diverse vegetation covers were, maybe, not exactly what would be observed in natural conditions. The diverse vegetation texture, especially at background distances, is an aggregate of small combinations of shapes and colours forming continuous superficial configurations. It was difficult to simulate these accurately for some of the scenarios.

- The scale of the impoundment, that is the relation between the impoundment and its environment, contributes to the impoundment being recognised from far away.
- Tailings impoundment embankment slopes have less of an influence on perception than covers. It appears that the most significant change is brought about changing the impoundment cover.
- Covers contribute significantly towards camouflaging an impoundment, that is its ability to merge the man-made landform with the landscape, is demonstrated in the bar charts (Figure 141 and Figure 142).

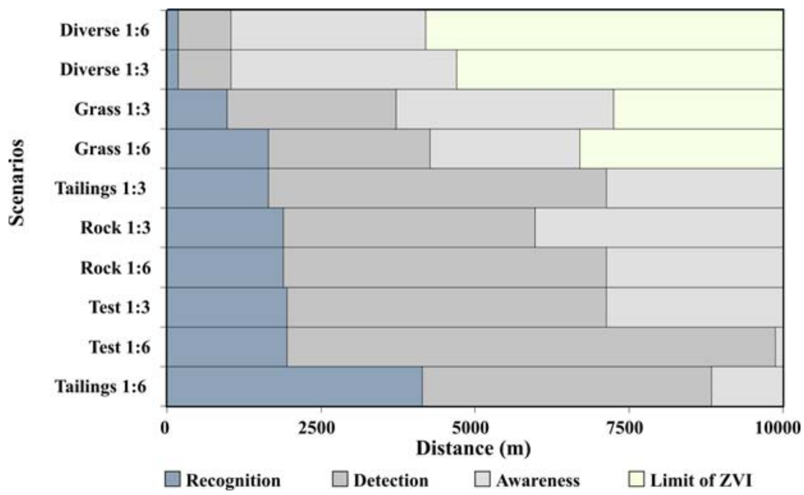


Figure 141: Mean visual perception distances for the scenarios visualised is stacked according to the increase in visual recognition.

When viewing the mean (Figure 141) and maximum (Figure 142) visual perception distance bar chart results it is apparent that for all of the covers (but the tailings in situ cover) the overall side slope has very little effect on visual perception distances.

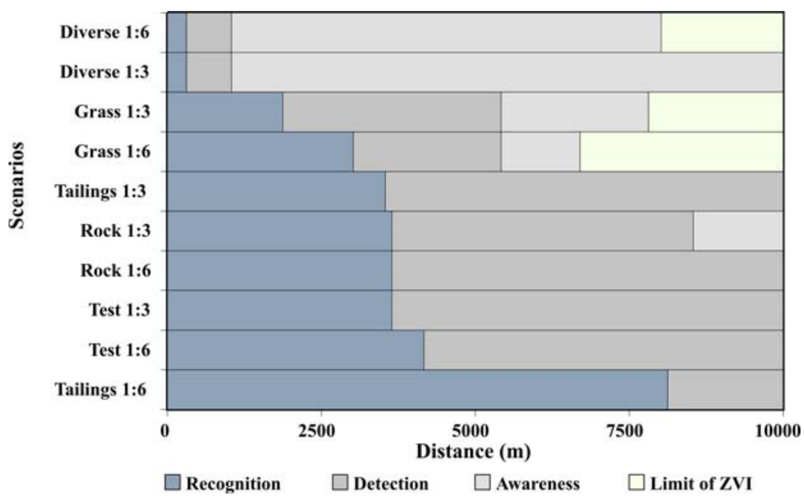


Figure 142: Maximum visual perception distances for the visualisations. The results are arranged according to the increase in visual recognition.

The difference in the maximum distance results between Tailings 1:3 and Tailings 1:6, represented in the bar chart (Figure 142), deserve some comment. Slide 10 (Figure 143) was used to visualise an impoundment with an overall embankment slope of 1:6 at a distance of 8200 m with no cover (tailing in situ). This slide can be compared to the slide which was used to visualise an impoundment with the same cover but with an overall embankment slope of 1:3 (Figure 144).

Figure 143: Visualisation of a view at a distance of 8200 m with an overall embankment of 1:6 and with no cover.

Figure 144: Visualisation of a view at a distance of 8200 m with an overall embankment of 1:3 and with no cover.

Both slides are visualisations of what an impoundment will look like from 8200 m if no cover is applied (tailings in situ). The only difference is the overall embankment side slope. When looking and comparing both these slides it is doubtful that an impoundment can be recognised in either of the slides. On the contrary, it is more likely that a man-made landform is detectable, albeit with effort, in the natural landscape. When the impoundments are seen in context of the full panorama photograph, that is a photograph taken of the 124 ° human binocular field of vision, it is even less likely that the impoundment will be recognisable within the landscape. The experiment projected views, although at the right scale, on a computer screen and did not show the entire panorama photograph due to the limitations of the computer screen width. The portion of the visualisation which was shown to the panel of experts during the experiment is indicated by the black frame in the figures. Although there is some variance in the perception distances when comparing embankment slopes for the same covers (Figure 141, p. 245) it appears that the overall embankment slope on an impoundment does not have a significant influence on the perception thereof. This is counter intuitive to what was originally thought. The curves on Figure 145 (p. 247) are simplified representations of the results presented in Figure 132 (p. 237) after determining the average between the 1:3 and 1:6 slope curves.

Table 55: The following mean perception distance values were used for combined slopes.

	Diverse	Grass	Rock	Test	Tailings in situ
Recognition	180	1310	1890	2890	1950
Detection	1350	3230	6555	7990	8510
Awareness	4450	6975	-	-	-

The modified representation (Figure 145) of the results emphasise the fact that the covers play an important role in the cognitive process of determining the levels of perception distances of an impoundment.

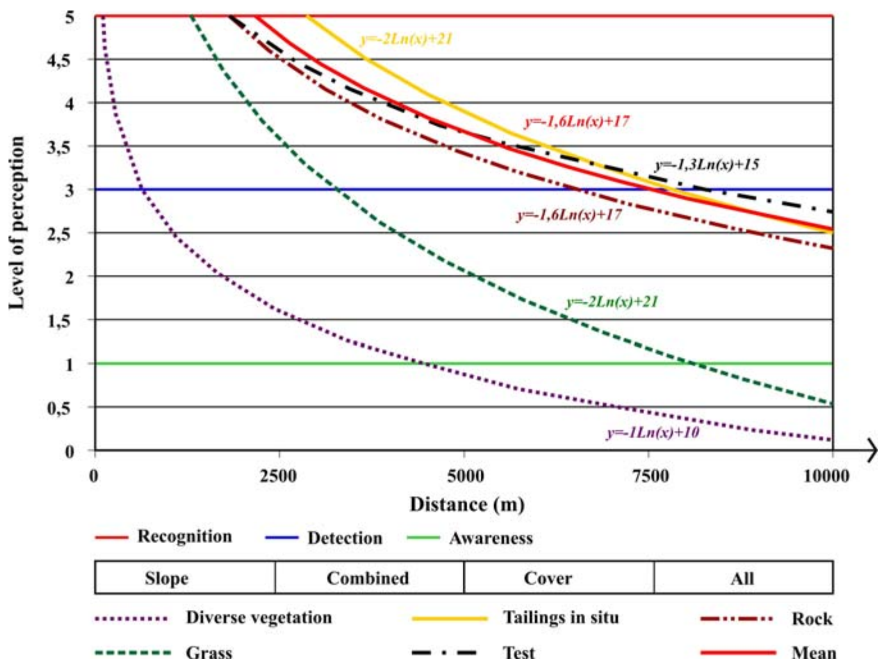


Figure 145: Probable mean visual perception functions of 1:3 and 1:6 slope data combined.

It would appear that the tailings in situ, rock and test covers fall within a similar results envelope and if simplified even further it can be represented by a mean curve indicated in the figure (solid red line). There is a definite decreasing relationship in the level of perception with the increase in distance from the object. This is not entirely surprising as there are many factors that contribute to camouflaging an object.

Some of the factors that influence the camouflaging of an object are:

- form (shape and size);
- line (silhouette);
- colour (shines, shadow and shade); and
- texture (surface);

of which the form and line are determined by the side slope and top configuration and the colour and texture are determined by the cover of an impoundment.

It is suggested in science that the intensity of radiation from a point source in three dimensional space would decline with the inverse of the square of the radial distance from the source. A line source of radiation would decline by the inverse of the distance (Armstrong and King, 1970; Sears and Zemansky, 1971).

Hull and Bishop (1987) found that there is a decreasing and non-linear relationship between distance and what they described as scenic impact. They found that a straight inverse relationship provided the best fit to quantify the results in their study. A logarithmic functional form provided the next best fit with nearly the same statistics as the inverse relationship.
However, the data presented here did not fit either the inverse of the square or straight inverse relationships. It might be that a landform is more complex than a point or line source of radiation. It was therefore decided to use a best fit trendline to represent the data in this study. The proposed equations therefore have no fundamental scientific reason to be logarithmic other than the fact that it best fits the data and could be used for interpolation.

It was not necessary to use the equations for interpolation purposes in this study as all the necessary data was directly available from the Nominal Group Technique (NGT) study process. They are useful to demonstrate the effect of different covers on visual perception. The simplified functions are given in Equations (35) to (40):

Diverse vegetation cover

$$y = -1Ln(x) + 10 \tag{35}$$

Grass cover

$$y = -2Ln(x) + 21 \tag{36}$$

Rock cladding

$$y = -1{,}6Ln(x) + 17 \tag{37}$$

Tailings in situ cover

$$y = -2Ln(x) + 21 \tag{38}$$

Test cover

$$y = -1{,}3Ln(x) + 15 \tag{39}$$

Mean of tailings in situ, rock cladding and test scenarios

$$y = -1{,}6Ln(x) + 17 \tag{40}$$

The results from the visual perception study are presented in two tables, Table 56 and Table 57 (p. 249). Table 56 presents the data of the maximum, mean and function visual perception distances measured from the edge of the impoundment whereas Table 57 presents the same results but using visual perception zone widths. Both these tables present the data for the tailings impoundment with an overall embankment side slope of 1:3.

Table 56: Maximum, mean and function visual perception distances measured from the edge of the impoundment for 1:3 overall embankment side slope.

		Distance from tailings impoundment (object) to perception threshold (m)		
		Recognition	**Detection**	**Awareness**
Grass 1:3	**Maximum**	1875	5417	7813
	Mean	975	3720	7250
	Function	1300	3241	8079
Test 1:3	**Maximum**	4167	10000	10000
	Mean	1950	7135	10000
	Function	1819	8257	37489
Tailings 1:3	**Maximum**	3542	10000	10000
	Mean	1645	7135	10000
	Function	2862	7800	21256
Rock 1:3	**Maximum**	3646	8542	10000
	Mean	1890	5975	10000
	Function	1819	6486	23132
Diverse 1:3	**Maximum**	313	1042	10000
	Mean	180	1035	4700
	Function	103	669	4341

Table 57: Maximum, mean and function visual perception zone widths for 1:3 overall embankment side slope indicating.

		Visual perception zone widths (m)			
		Recognition	**Detection**	**Awareness**	**To ZVI outer limit (10 000 m)**
Grass 1:3	**Maximum**	1875	3542	2396	2187
	Mean	975	2745	3530	2750
	Function	1300	1941	4838	1921
Test 1:3	**Maximum**	4167	5833	-	-
	Mean	1950	5185	2865	-
	Function	1819	6438	29232	-
Tailings 1:3	**Maximum**	3542	6458	-	-
	Mean	1645	5490	2865	-
	Function	2862	4938	13456	-
Rock 1:3	**Maximum**	3646	4896	1458	-
	Mean	1890	4085	4025	-
	Function	1819	4667	16646	-
Diverse 1:3	**Maximum**	313	729	8958	-
	Mean	180	855	3665	5300
	Function	103	566	3672	5659

The difference between the two data sets is that the one presents the results as distances measured from the edge of the impoundment and the other as visual perception zone widths. Figure 146 illustrates the concepts of visual perception distances and visual perception zone widths. The visual perception zone widths for recognition, detection and awareness can be used to calculate the surface areas, measured in hectares, for each perception zone respectively. This can then be used to estimate what the influence of the visual perception zones are on the receiving environment. It is likely that there will be a difference in impact when comparing the influence of an impoundment within for example the recognition and detection zones.

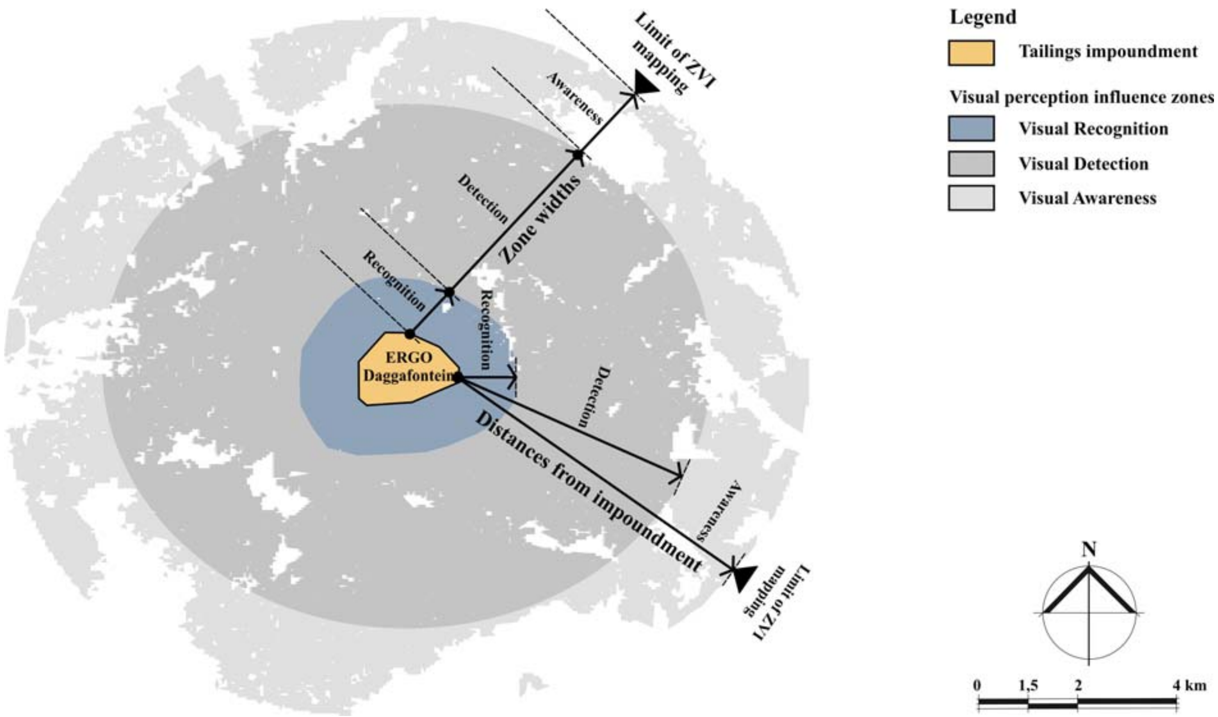


Figure 146: The conceptual illustration of visual perception distances and widths.

Comparing the mean distances of the different covers in Table 56 lead to the following conclusions:

- The diverse cover recognition perception distance is almost five times less than that of grass, and approximately ten times and nine times less than that of rock and in situ tailings covers respectively.
- The diverse cover detection perception distance is almost four times less than the grass cover, six times than the rock cladding and seven times less than a tailings in situ cover.
- The grass cover recognition perception distance is about half of that of rock, test and the tailings in situ cover recognition distances.
- The grass cover detection distance is about three times that of a diverse cover and 1,5 times less than a rock cover and almost twice less half of the tailings in situ cover.
- Leaving an impoundment uncovered (no cover, that is tailings in situ) could lead to recognition distances of 70 % further than for an impoundment covered with grass. The detection distance is 90 % further.

The diverse cover rehabilitation, should this be attainable, is by far better than covering an impoundment in grass, rock, and what could appear to be the worse-case scenario leaving it as is (not covering the in situ tailings). An impoundment covered with a diverse vegetation cover blends the most into the natural landscape.

It can be concluded that cover plays a significant role in the ability to become aware, detect and recognise a tailings impoundment. The data presented in this section is the direct result of making use of the Nominal Group Technique (NGT) study method and can be useful in describing the visual impact of an impoundment on the environment.

4.3 Visual perception zone of influence

The mean visual perception zone widths presented in Table 57(p. 249) were used to determine the visual perception zones of influence for the various impoundment configurations at the ERGO Daggafontein site. Figure 147 illustrates the graphical output generated in GIS for the impoundment configuration with an overall embankment side slope of 1:3 without any cover.

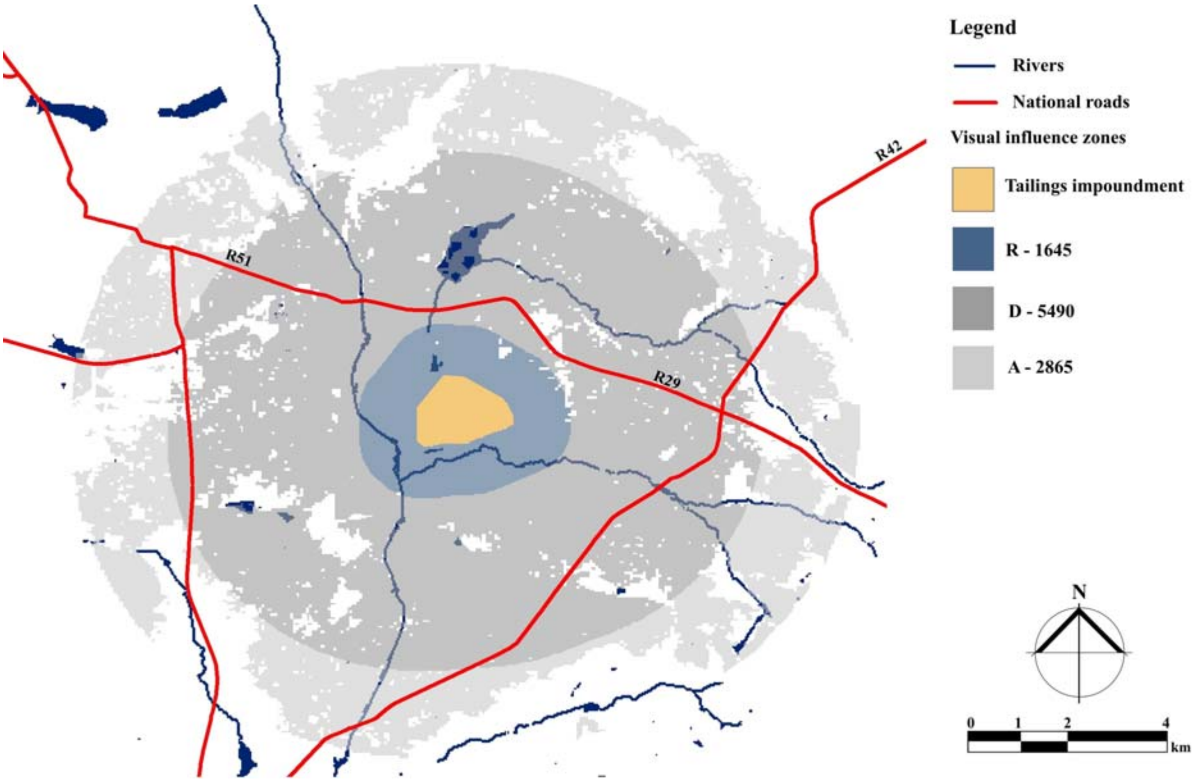


Figure 147: Visual perception zones of influence for an impoundment with a 1:3 overall embankment side slope and no cover.

Perception zone widths of 1645 m, 5490 m and 2865 m were used for the recognition, detection and awareness visual perception zones respectively. The spatially represented results of all eight configurations described in Table 21 (p. 162) are documented in Figures A.1 through A.8 in Appendix A.4. The surface areas for each visual perception zone were determined through:

- buffering the impoundment according to the various visual perception zone widths determined by the research;
- creating shapefiles in GIS using the union command;
- the resulting shapefile was then intersected with the property shapefile in order to run a multiple summary; and
- finally, the property intersects were then intersected with the visibility shapefiles (converted from a grid to a shapefile) and a second multiple summary was run to obtain the final results.

Using the procedure described above, the visual perception zone widths were used to map the surface areas of the zones of visual influence for the various configurations. Figure 148 presents a summary of the results for scenarios VS1 through VS8. The colours in the bar chart correspond with the colours used in the visual perceptions zone of influence maps. For easy reference purposes the bar charts are grouped according to type of cover and the embankment side slopes are annotated.

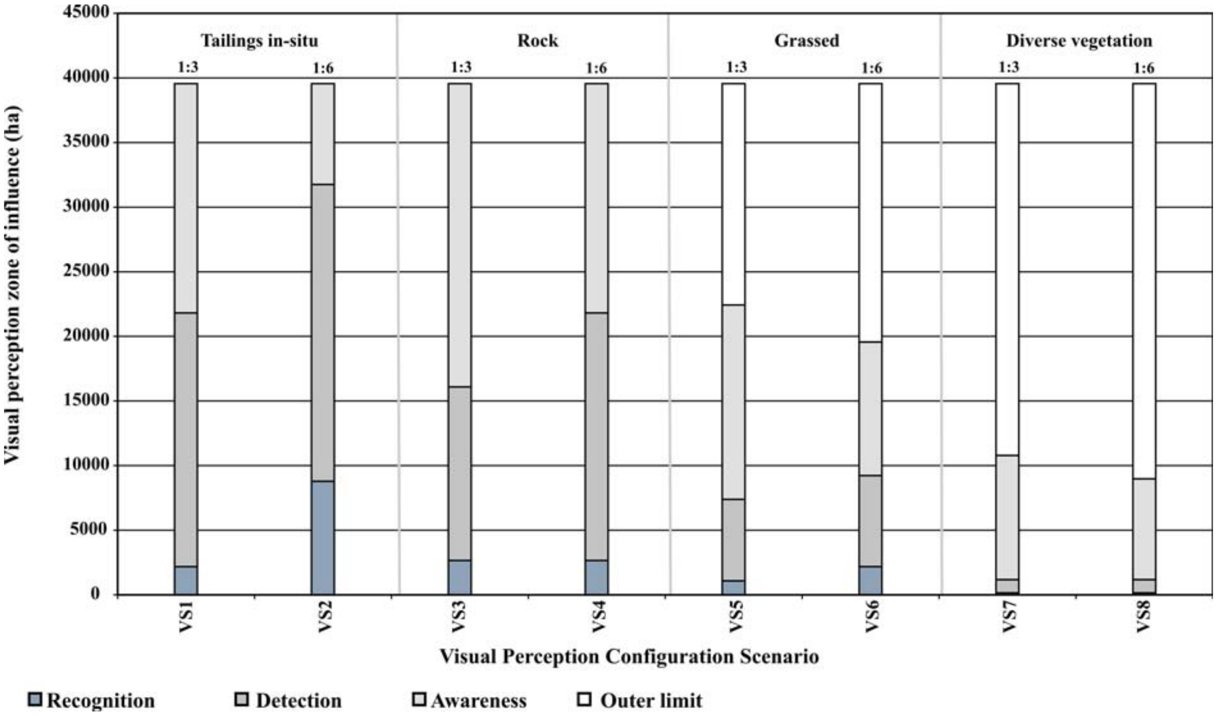


Figure 148: Visual perception surface areas for modelled configurations VS1 to VS8.

4.4 Air quality zone of influence

Once the surface roughness height was determined through the iterative process of modelling the emissions from the DRD 2L24 impoundment and comparing such with the data from the dustfall monitoring stations, the same methodology of emissions quantification and dispersion modelling could be applied to the different impoundment configurations described in Table 22 (p. 163), at the ERGO Daggafontein site.

Meteorological data from the Springs weather station was obtained for 2002, a period of one year. Emission rates for various scenarios were quantified using the now calibrated models. The calibration process of the predictive models used is described in Section 3.5.2.

The calibrated ADDAS model was used to quantify the emissions and the same US EPA dispersion model, ISCST 3 Breeze, was applied to calculate the fallout and concentrations at the ERGO Daggafontein site. All parameters used during the calibration process for the DRD 2L24 tailings impoundment were applied to the ERGO tailings impoundment configurations, with the exception of the physical dump size (length, width, height, side slope angle, and coverage). The variables for this purpose of the study are provided in Table 58, p. 253.

The results of the configurations modelled are used as input into the overall environmental impact and engineering cost model. Six side slope configurations were chosen with three emission scenarios, namely 0%, 80% and 50% control efficiencies. Table 19 (p. 160) and Table 20 (p. 163) contain the information describing the different scenarios' geometries, i.e. AS1 through AS12. Different cover efficiencies (0 %, 50 % and 80 %) or 'open fractions' are applied (1,0, 0,8 and 0,5) to each of the basic geometries resulting in twelve runs for the emissions.

Table 58: Varying parameters of each scenario for the ERGO Daggafontein tailings impoundment configurations.

		Varying tailings impoundment parameters for each scenario				
Scenario Code	**Slope 1V:?H**	**Control Efficiency (%)**	**Height (m)**	**Slope**	**East-West length (m)**	**North-South length (m)**
AS1	**1:1,5**	0[1]	37,28	0,58	2167	1396
AS5		100[2]				
AS9		50[3]				
AS13		80[4]				
AS2	**1:3**	0[1]	37,28	0,318	2203	1461
AS6		100[2]				
AS10		50[3]				
AS14		80[4]				
AS3	**1:6**	0[1]	37,28	0,165	2268	1585
AS7		100[2]				
AS11		50[3]				
AS15		80[4]				
AS4	**1:9**	0[1]	37,28	0,11	2323	1704
AS8		100[2]				
AS12		50[3]				
AS16		80[4]				

[1] 0% control efficiency indicates no cover and controls.

[2] 100% control efficiency indicates measures and controls implemented to ensure that 100% of the surface is not wind erodible.

[3] 50% control efficiency indicates measures and controls implemented to ensure that 50% of the surface is not wind erodible.

[4] 80% control efficiency indicates measures and controls implemented to ensure that 80% of the surface is not wind erodible.

Each scenario was simulated and ground level PM_{10} concentrations and deposition levels predicted. For PM_{10} the highest daily concentrations are depicted for a single isopleth representing 25 µg/m^3. Similarly for deposition, the ground level dust fallout is represented by a 250 mg/m^2/day isopleth. Figure 149 (p. 254) plots the results for an impoundment configuration with an overall side slope of 1:1,5 and no cover.

The complete set of spatial representations for the various configurations is provided in Appendix B.1, Figure B.1 through Figure B.12. Scenarios AS5, AS6, AS7 and AS8 were not modelled using the predictive models as the scenarios are defined as having 100% emission control efficiencies which result in no emissions being released from the impoundment. Once the emissions are dispersed and the isopleths plotted, fallout and concentrations contours can be imported into and mapped in GIS. Using GIS, queries can be run to calculate the surface areas covered by each isopleth. Output summary data for the predicted PM_{10} concentrations and dustfall levels of the various scenarios can then be captured in an EXCEL spreadsheet and presented in the form given in Figure 150 (p. 254).

Similar to the results for the visual perception zones of influence, the air quality isopleths are mapped and used to determine surface areas for the various tailings impoundment configurations. The bar chart presents a summary of the results for scenarios AS1 through AS16. The colours in the bar chart correspond with the colours used in the dustfall and concentration zone of influence maps. The results are grouped for each cover with the embankment side slopes indicated for comparative purposes.

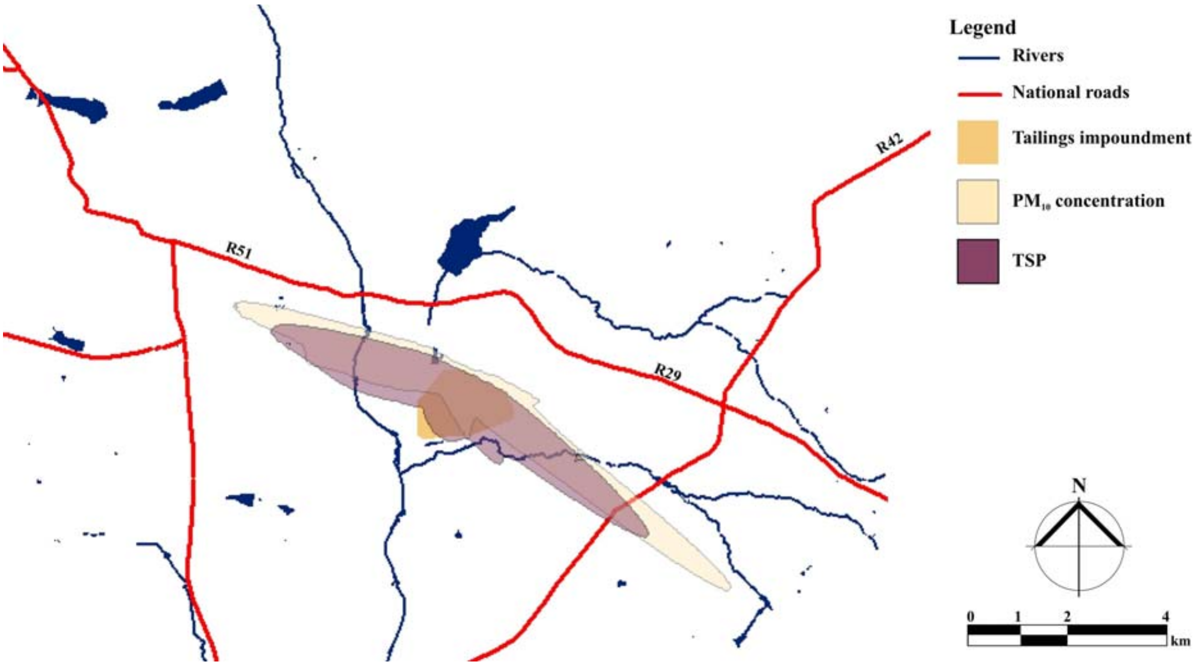


Figure 149: Plot of the dustfall and concentration isopleths for impoundment configuration AS1 with an overall embankment side slope of 1:1,5 and no cover.

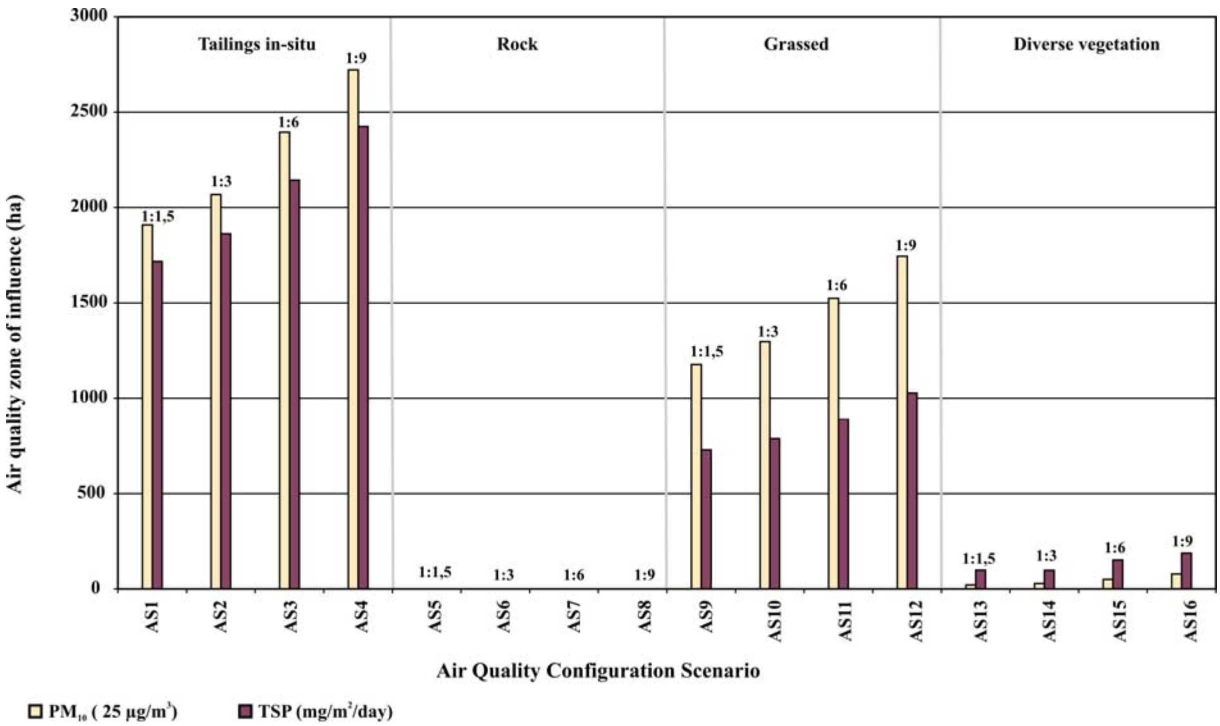


Figure 150: Air quality areas of influence for modelled configurations AS1 to AS16.

Presenting the isopleth data spatially in GIS allows for the accurate calculation of the surface area impacted on and it also communicates the change in influence zone visually. It is intended that the bar chart results can be used along with the zone of influence plots to illustrate how change in impoundment configuration results in change in such zone of influence.

4.5 Water quality influence

An analytical water flow and mass balance model was developed and used to evaluate the tailings impoundment configurations WS1 through WS16. Although conservative assumptions were made with regard to aspects such as the calculation of the water balance of the tailings impoundment, the results presented in the following section are detailed enough to compare the change in environmental impact resulting from the change in impoundment configuration. The following impoundment configurations were simulated using the analytical model previously described in Section 3.6.2. The results in Figure 151 indicate an increase in mass flux of sulphates to the Blesbokspruit ranging between 1000 t/annum to 3000 t/annum and depends on the impoundment configuration.

Table 59: Groundwater quantity and quality modelling configurations.

	Side slope configuration			
Covers	**1:1,5**	**1:3**	**1:6**	**1:9**
No cover (tailings in situ)	WS1	WS2	WS3	WS4
Rock cladding (300 mm)	WS5	WS6	WS7	WS8
Grassed soil-rock armouring (300 mm)	WS9	WS10	WS11	WS12
Diverse vegetation	WS13	WS14	WS15	WS16

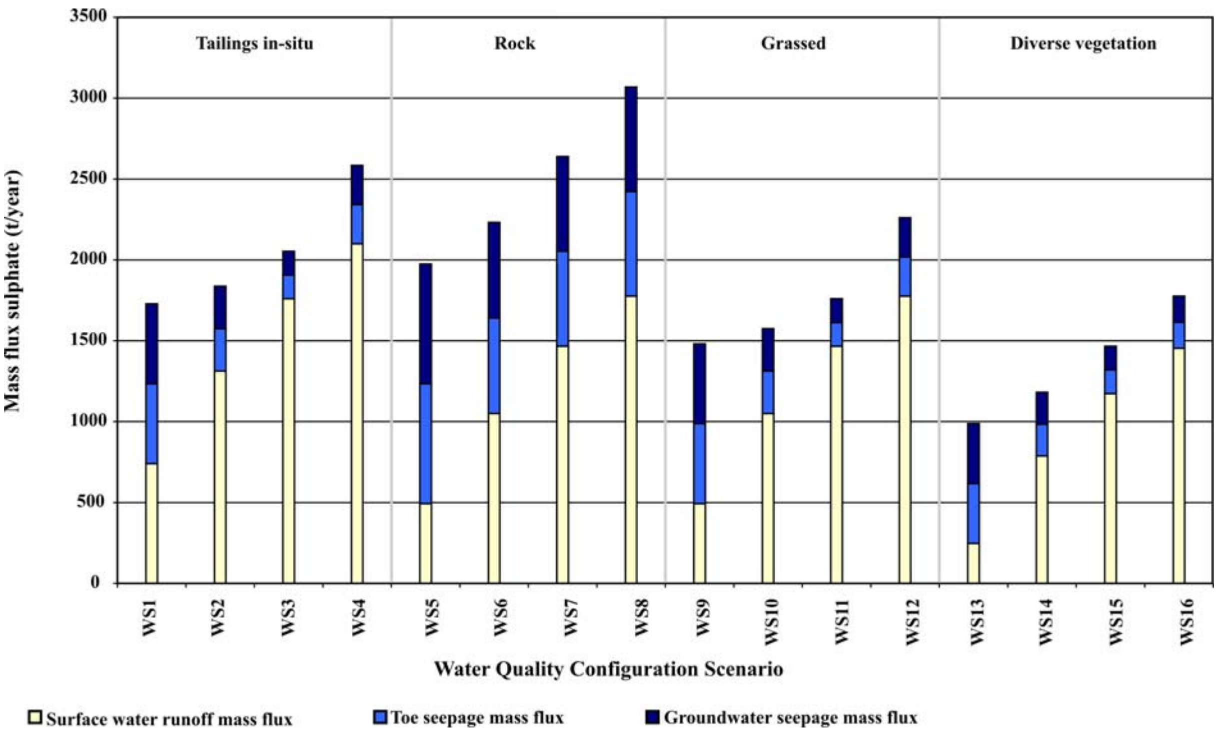


Figure 151: Mass flux for modelled configurations WS1 to WS16.

The base case (scenario WS1) was used as a basis for the measurement of the efficiency of the management options. The model indicates the following:

- Scenario WS1 (base case)
  If no rehabilitation takes place, the mass flux of sulphates to the Blesbokspruit would be in the order of 1700 t/annum. Due to the flow volume and dilution, the increase in the average sulphate concentration of the Blesbokspruit would be very small from 200 mg/ℓ to 205 mg/ℓ.

- Scenarios WS2 to WS4
  Flattening the embankment side slope without capping or covering would increase the mass load by up to 50 % to the Blesbokspruit to 2500 t/annum. It would also increase the average sulphate concentration from 200 mg/ℓ to 210 mg/ℓ. This is due to the greater footprint area and increased infiltration on shallower slopes.

- Scenarios WS5 to WS8
  Flattening the embankment side slope and covering the impoundment with a rock cladding would increase the mass load by up to 80 %, releasing up to 3000 t of sulphate to the Blesbokspruit per annum. It would also increase the average sulphate concentration from 200 mg/ℓ to 215 mg/ℓ. The rock cladding with flattening to a slope of 1:9 seems to be the worst option. This is due to the significant increase in the physical footprint of the impoundment. It is however expected that that the rock cladding will reduce evaporation losses and runoff.

- Scenarios WS9 to WS16
  Reshaping the outer embankment and establishment vegetation would decrease the mass load to the river by up to 40 % to approximately 1000 t/annum. The average sulphate concentration in the river would be less than the baseline case (WS1).

The best case in terms of reducing the mass flux to the receiving water body is WS13, which is configured with a diverse vegetation cover with a 1:1,5 overall embankment side slope.

Table 60 Comparison of the results of the mass flux of sulphates for the various scenarios.

	Side slope configuration			
Covers	**1:1,5**	**1:3**	**1:6**	**1:9**
No cover (tailings in situ)	WS1	WS2	WS3	WS4
Rock cladding (300 mm)	WS5	WS6	WS7	WS8
Grassed soil-rock armouring (300 mm)	WS9	WS10	WS11	WS12
Diverse vegetation	WS13	WS14	WS15	WS16

Decreased mass flux (green) — Increased mass flux (red)

4.5.1 Validation of results

The groundwater component of the water impact model was validated by comparing it with the output results of the accredited model Pmwin 5.3 version of Modflow, MT3D, developed and described by Chiang and Kinzelbach (1999). The simulation results from the numerical model showed that the steady-state mass flux was 1480 m^3/day compared to the results of 1127 m^3/day calculated from the analytical model. The 24 % discrepancy can be ascribed to the 50 m x 50 m finite difference grid size that was used. A finer grid size would be able to assume the footprint of the tailings impoundment more accurately (Figure 152).

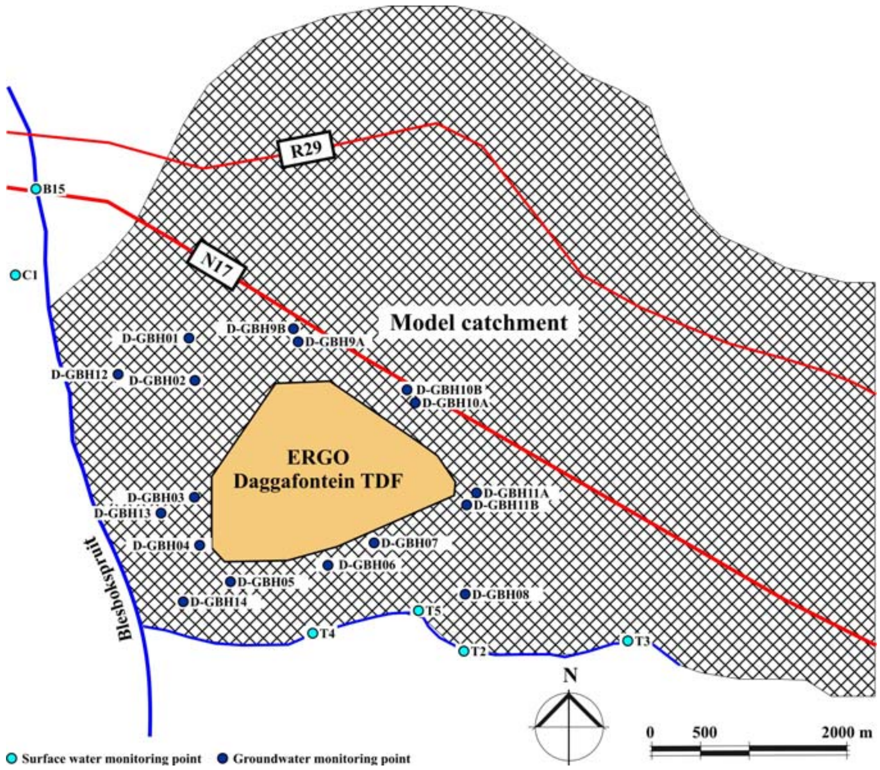


Figure 152: Modflow finite difference grid.

The numerical model has the advantage that it calculates dilution along the flow path which causes a smaller mass flux to the receiving water body (Figure 153, p. 258). This aspect would cause larger discrepancies between the two models the further the source is located away from the receiving water body. In this case, the dilution along the flow path must be taken into account. For this purpose, the analytical mass balance model was refined to take the steady-state dilution due to rainfall-recharge a one–dimensional section into account. A comparison between the numerical model (MT3D) and the analytical model shows that the results are comparable (Figure 154, p. 258).

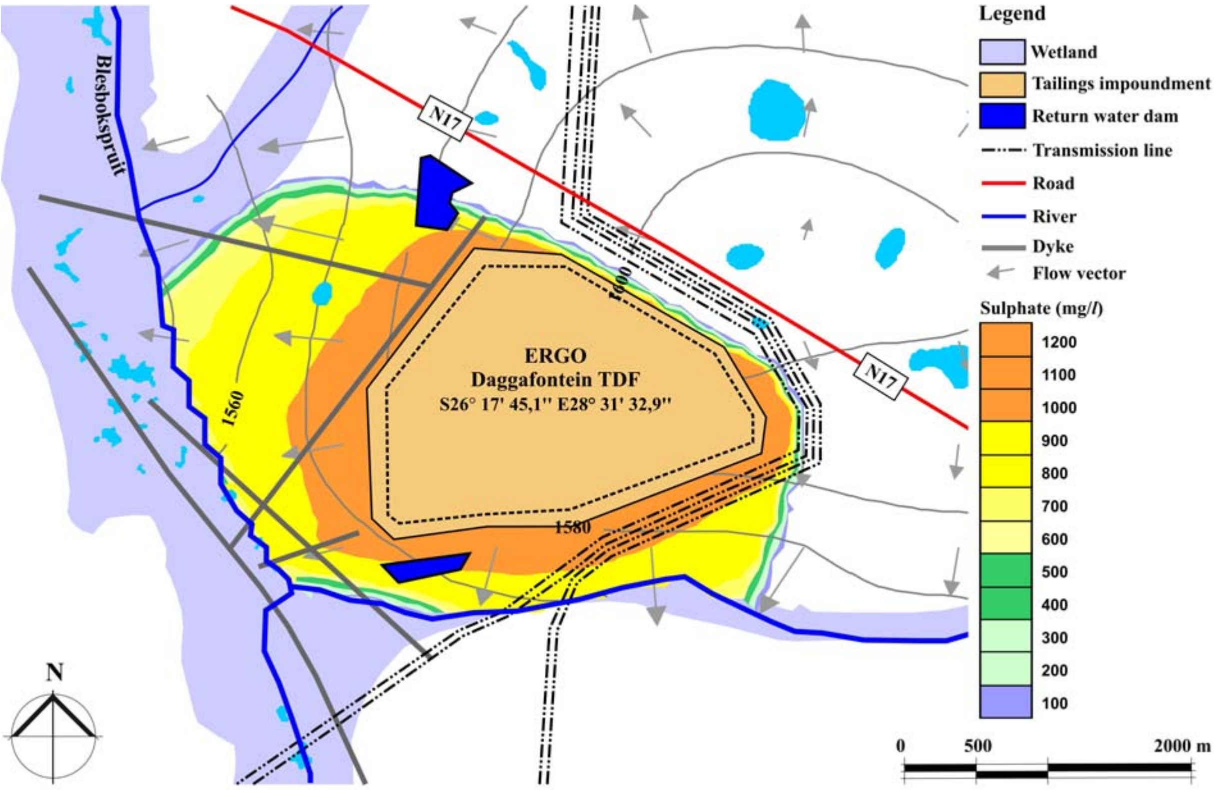


Figure 153: Simulated steady-state groundwater flow and sulphate transport.

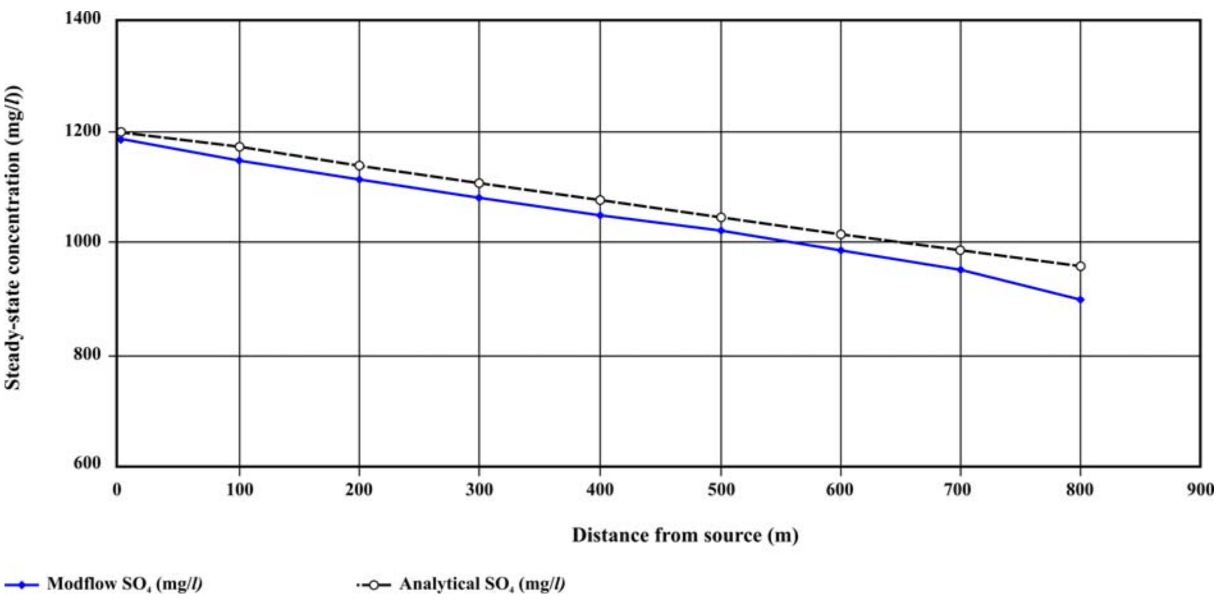


Figure 154: Comparing the dilution with distance from source results of the analytical model with Modflow.

4.6 Engineering costs

The engineering cost model can be used to determine the engineering costs for the design and construction (development), operation, decommissioning and closure, and post-closure maintenance and aftercare stages for tailings impoundments.

Engineering cost is a direct function of the impoundment shape and size (Figure 155). For example, the model can be used to compare the normalised cost per cubic metre tailings deposited of upstream spigotted ring-dyke impoundments. Modelling deposition rates between 990 000 tpm (large impoundment) and 50 000 tpm (small impoundment) with similar design parameters calculates normalised deposition costs varying between R5/m^3 and R16/m^3 tailings deposied. It is therefore more economical per cubic metre to deposit tailings for larger impoundments.

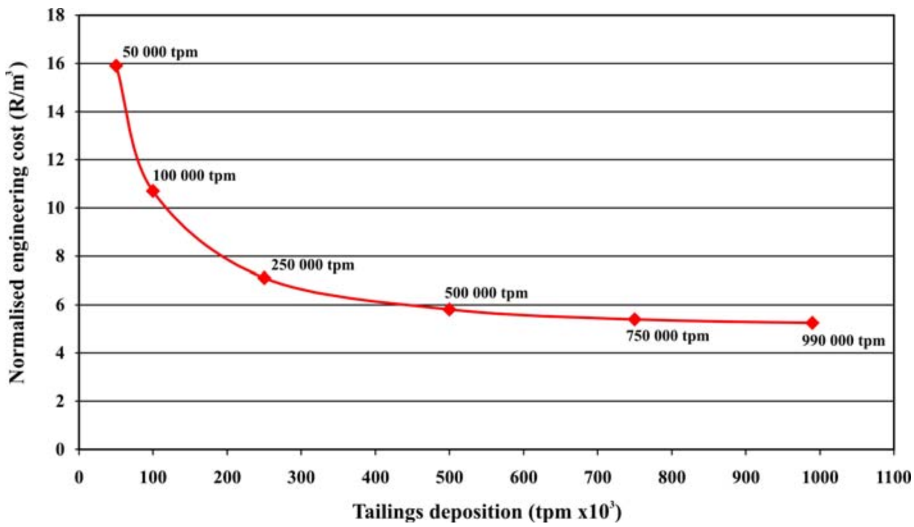


Figure 155: Normalised engineering costs to deposit tailings

The stacked bar chart (Figure 156) and the life-cycle scatter graph (Figure 157) on p. 260 plots the engineering cost results for the 28 tailings impoundment scenarios modelled as part of this study. The scenario codes for the configurations modelled are given in Table 20, p. 162. The deposition rate, final volume and height are constant for all the configurations modelled. Also, costs for a large impoundment with a deposition rate of 990 000 tpm and a final design capacity of 105 x10^6 m^3 are modelled.

The configuration results can be split into the two main groupings, namely:

- where the final embankment slopes are hydraulically deposited during the operation stage; and
- where the impoundments are constructed at a steep (1:1,5) overall embankment slope and flattened mechanically during the closure stage.

The configurations modelled are also arranged into sub-groups according to cover. For example, both scenario E16 and E28 allows for a 1:9 final overall embankment side slope and covered with 450 mm imported soil to support diverse vegetation. The difference between E16 and E28 is that the former's final embankment is constructed as part of the deposition of tailings during the operation stage and the latter's embankment slope is constructed through depositing the slope at a 1:1,5 side slope and then mechanically flattening it 1:9.

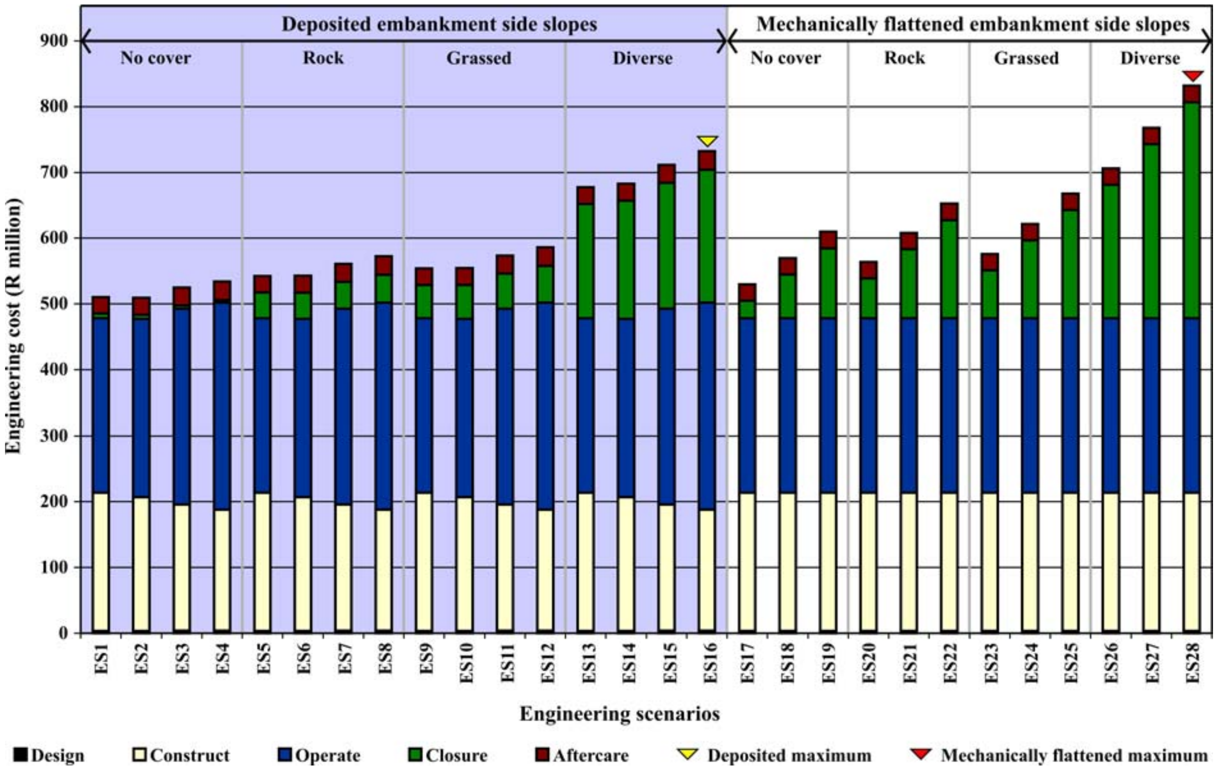


Figure 156: The total engineering costs for all the scenarios modelled indicating the relative costs for the different tailings impoundment construction stages.

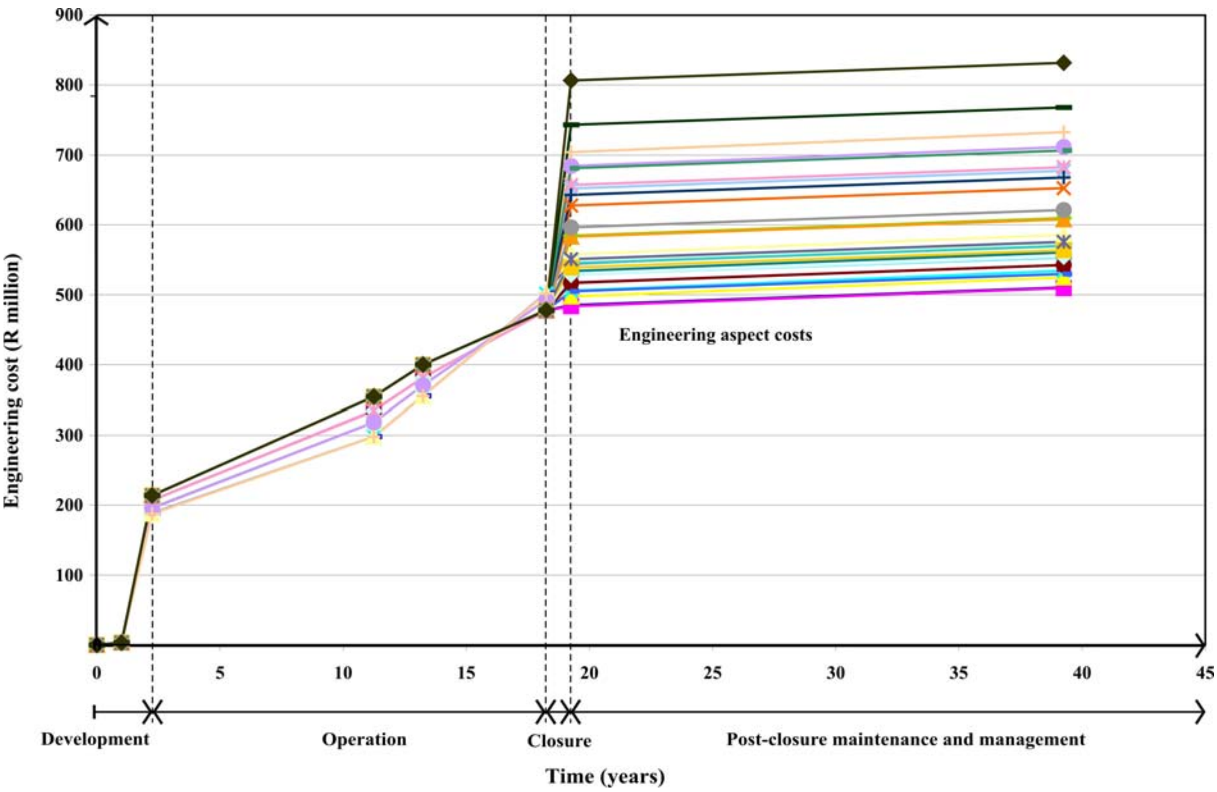


Figure 157: Cumulative engineering life-cycle costs for the 28 scenarios modelled.

The engineering costs for all the scenarios do not vary considerably up to the closure stage. It is at this point in the life-cycle that the tailings impoundment is rehabilitated. The difference in engineering costs at this point is approximately R25 million. On the other hand, the difference in costs at the point after closure and before the maintenance starts is more than R300 million.

Figure 157 plots the cumulative engineering costs over the life-cycle from initial planning through to the post-closure management and maintenance stage. The graph indicates the variance for all 28 scenarios modelled over the same period. Similar to Figure 156 it becomes apparent that variance in engineering costs occurs in the closure stage when comparing the different tailings impoundment configurations modelled.

The engineering cost model does not allow for the increase or decrease in maintenance costs resulting from for example measures required to combat erosion due to surface runoff. The maintenance and management costs for all of the options increase with the same amount annually irrespective of the final condition of the impoundment and include standard monitoring practice items such as:

- piezometer extensions;
- jet rodding of drain outlets;
- operator monitoring and inspections; and
- third party (external) monitoring and inspections.

4.7 Summary

This section presents the results of the various configurations, described in Section 3, for the:

- visual perception zones of influence for awareness, detection, and recognition zones;
- air quality zones of influence for total suspended particulates (TSP) and particulate concentration (PM_{10});
- water quality influence for sulphate flux; and
- engineering cost in Rands.

Where necessary the results are validated through additional experimental work or comparison with output results of accredited models. The environmental data is presented in such a form that it can now be combined, valuated and integrated with the engineering costs.

Zones of influence for both visual perception and air quality aspects are predicted and mapped, and the discharge in sulphate mass flux calculated. Although there is merit in evaluating the environmental aspects separately the true reflection of the possible impact on the environment can be best described by means of overlaying the separate aspects to form a sphere of influence. The sphere of influence is three-dimensional and represents on plan the total area upon which an impoundment will have an effect. This spatial representation is the overlay or sum of the different environmental aspect zones of influence of a particular configuration at a specific moment in time and is described in the following section, Section 5.

CHAPTER FIVE: COMBINING ENVIRONMENTAL IMPACTS WITH ENGINEERING COSTS

> "...the strongest argument of the detractors [of mining] is that the fields are devastated by mining operations...further, when the ores are washed, the water which has been used poisons the brooks and streams, and either destroys the fish or drives them away...thus it is said, it is clear to all that there is greater detriment from mining than the value of the metals which the mining produces."
>
> Agricola (1556)

> "According to the doctrine of objectivity, which is integral with traditional scientific method, what we like or do not like about *what we observe* [own words] has nothing to do with the correct thinking. We should not evaluate what we see. We should keep our mind a blank tablet which nature fills for us, and then reason disinterestedly from the facts we observe."
>
> Pirsig (1999:281)

5.1 Introduction

Chapter 4 presents the predictive modelling results for the various tailings impoundment configurations modelled in this study. It was observed that a change in impoundment slope and cover has a quantifiable effect on the visual and air environmental aspect influence zones as well as the sulphate mass flux. The following section combines the environmental impacts with engineering costs using an innovative technique. The three environmental aspects are described, the changes modelled and quantified, and the quantified results combined with engineering costs.

5.2 Engineering costs

Although the engineering costing system is relatively straightforward its development required considerable care to ensure that sufficient input data was obtained to provide a reliable result without overburdening the data acquisition process or the system itself with unnecessarily detailed information. In practice there is a strong tendency to over measure. The final results, however, for either a single cost item or a development stage give a clear indication of the major cost items. The initial input sheets show the sensitivity of these items to their input parameters hence indicates the required accuracy of measurement or estimation for these parameters.

The benefits of the engineering costing system have been found to be even more valuable than had been anticipated. Clearly the primary benefit is that decision makers tasked with the configuration of tailings impoundments can now reliably estimate engineering costs for proposed impoundments in good time so that stakeholders can readily assess the financial risks and liabilities associated with tailings impoundment construction.

The system is simple to operate, as most computer users are familiar with the spreadsheet programme, Microsoft EXCEL, used in this study to capture data and model outcomes. Additional items can be inserted or existing items can be deleted. Quantities and rates can easily be modified and escalating costs can be accommodated. The sensitivity of total costs to changes in individual rates or measurements can be tested, so that, for example a feasibility cost estimate can be updated as more reliable information becomes available.

Another benefit of the system is that it is transparent and can be used not only as an internal management tool but can also be reviewed by an independent assessor to determine the validity of say the costs provided for the rehabilitation and closure of an impoundment. These provisions can be updated on an annual basis with little effort to assess the liabilities and adjust the provision for these as required by legislation.

A further significant benefit of the system is that it is a practical tool for use by mining groups, managers, environmental practitioners, and others who are responsible for mine closure. It makes closure costs more readily available and tangible. It allows mine management to assess potential future costs which places them in a position to plan works to remedy environmental liabilities and reduce costs wherever possible.

Without modelling the engineering costs and environmental liabilities before tailings deposition commences a commitment may be made to rehabilitate to a higher standard than might be necessary. The amount of materials, such as soil and rock, required to undertake rehabilitation to a pre-determined post-closure land use can be easily and reliably calculated with the system. The system also informs reactive closure of abandoned tailings impoundments where shortfall of materials may exist and certain strategic decisions need to be made as to feasible rehabilitation alternatives and cost implications of each of these. It is, perhaps unrealistic to rehabilitate to a pre-mining land use for example, crop cultivation, if grazing is acceptable and in some cases may even be preferable. It would not be economical to rehabilitate by placing for example a 450 mm subsoil covered by 300 mm topsoil (typically required for reinstating to arable land use) compared with subsoil and topsoil depths of 150 mm and 100 mm respectively which are required as a minimum requirement for grazing land use. The difference in cost could easily be hundred millions for a mining group with no real benefit being achieved.

5.2.1 Flattening embankment slopes

The comparative column charts (Figure 158 and Figure 159) compare the engineering costs for deposited and mechanically flattened tailings impoundment embankment side slopes. The scenario codes for ES1 to ES29 were defined in Table 20 (p. 162) of which the engineering life-cycle costs are given in Figure 156 and Figure 157 on p. 260.

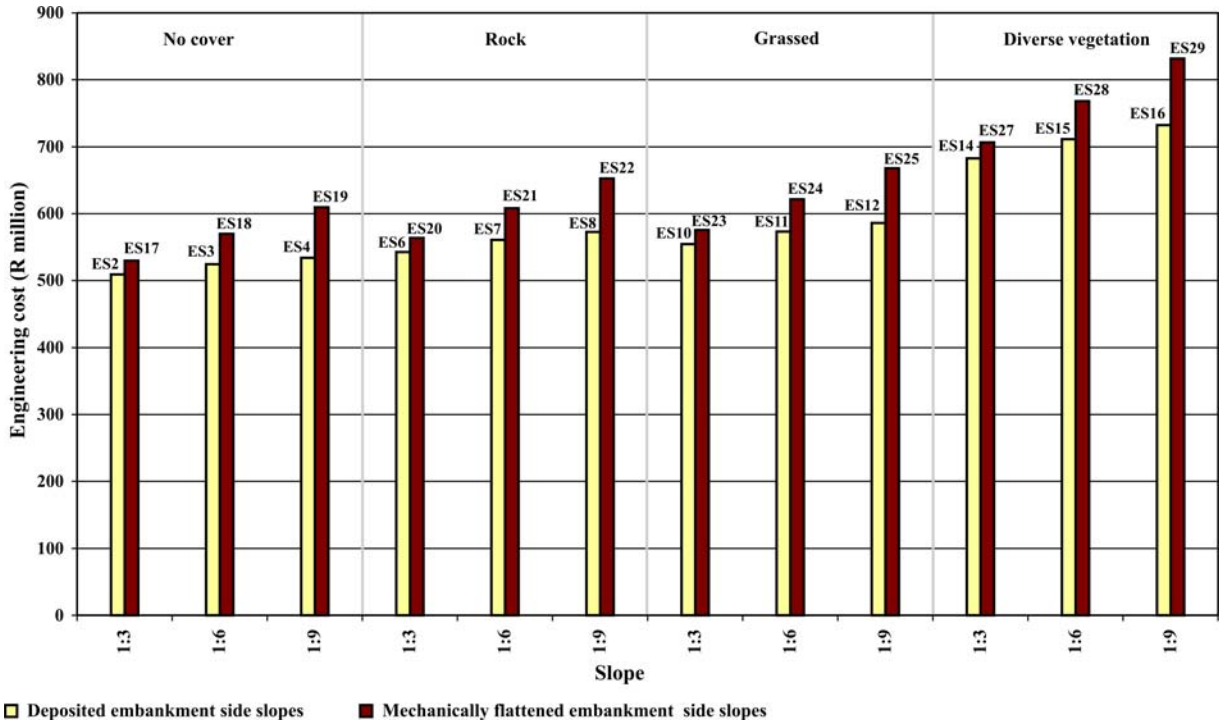


Figure 158: Comparing total cumulative costs for deposited and mechanically flattened slopes.

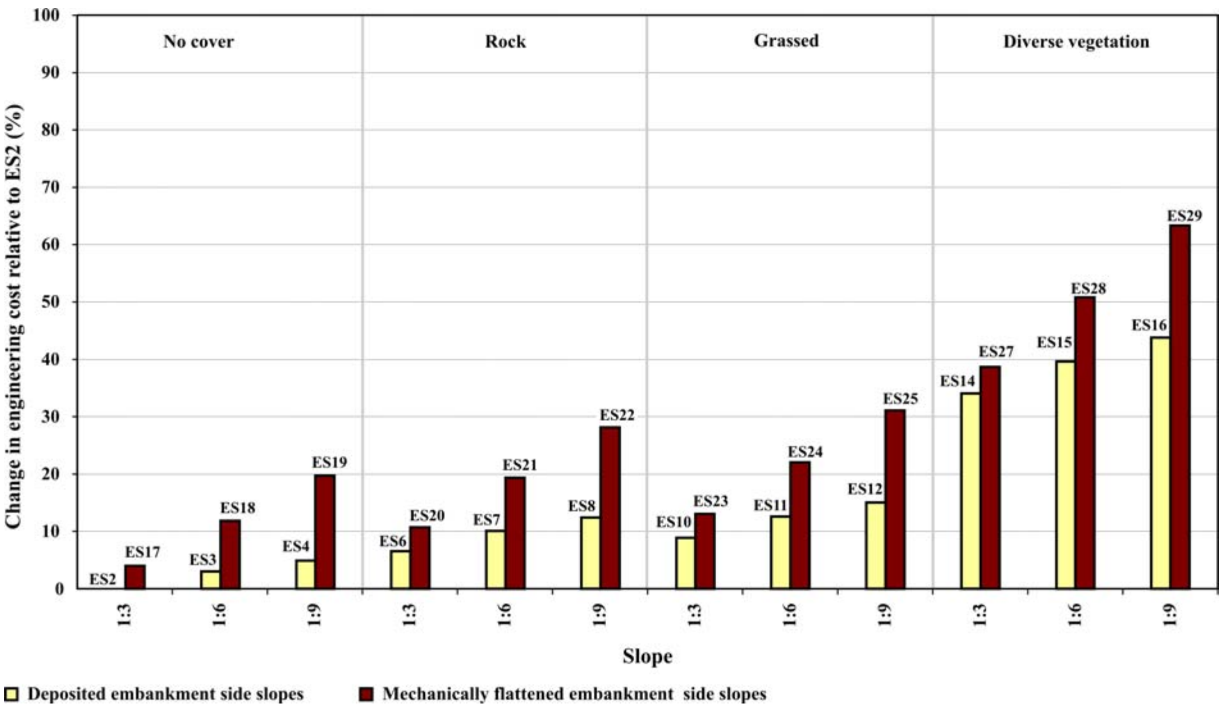


Figure 159: Comparing the costs of flattening embankment slopes for various covers to scenario ES2.

Many tailings impoundments were and in some instances are still constructed with steep embankment side slopes and when closure is sought, slopes are mechanically flattened to an embankment configuration acceptable to stakeholders. Impoundments can be designed and constructed with a final side slope configuration that does not require additional mechanical cut and fill of material during the closure stage in order to achieve an envisaged end embankment configuration. This can be accomplished by depositing the tailings at a predetermined flatter embankment configuration during the operation stage.

Cover systems significantly contribute to the overall costs of an impoundment and even more so than what may initially have been anticipated. The modelled results indicate that the cheapest option is not to cover the impoundment at all, followed by the rock cladding, grassed armoured cover and lastly and most costly the diverse vegetated cover. Constructing a vegetative cover with diversity in vegetation species costs the most. This is attributed to the 450 mm soil cover allowed for to sustain plant growth. It can be argued that even this is not sufficient and that even deeper soils may be required for sustainable root development and plant growth. The diverse vegetation covered impoundment scenario, whilst probably the best for all the adverse environmental aspects, is clearly the most expensive because it requires the most topsoil importation. The total cost depends on the presumption that 450 mm of topsoil is sufficient to sustain a diverse vegetation cover. The cost model can readily accommodate an increase or reduction in soil cover thickness if required.

It has been found that the addition of 300 mm of growth medium significantly affects the revegetation of non-acid tailings. Primary root growth occurs in the growth medium (Figure 95, p. 176), but roots can extend into the tailings to extract moisture during droughty conditions (Milczarek and Yao, 2004). At a gold tailings impoundment in Nevada a final cover thickness of 900 mm was selected to optimize evapotranspiration and minimize infiltration (Gorman, 2004). A natural soil deeper than 600 mm can be regarded as an arable soil on condition that the slope is not steeper than 1:14, whereas at least 250 mm of soil is needed to establish pastures (CM, 1981). If vegetation can be established in situ the cost of having to import soil to provide a suitable and sustainable growing medium will not be necessary and the cost therefore avoided.

Figure 159 compares various scenarios to configuration ES2. Configuration ES2 may be considered as the standard practice option in that it includes depositing tailings at an overall 1:3 embankment side slope, an allows for the planting of grass during operation to control erosion (rising green wall). However costs are not included for the construction of a final engineered cover.

This approach is standard practice in that it is at present the most common approach implemented by industry and approved by authorities. The figure compares the costs of flattening embankment slopes for various cover options to that of the scenario with an embankment slope of 1:3 and no cover (tailings in-situ). Scenario ES2 is estimated to cost R509,3 million. The most expensive option (ES29) is to construct the impoundment with an initial 1:1,5 embankment slope and then during the closure stage flatten the embankment to a 1:9 slope and cover the entire impoundment with diverse vegetation planted in 450 mm soil. This is estimated to cost R831,8 and is 63 % more than ES2.

Figure 160 uses scenario ES1 as the baseline configuration to compare scenarios ES4 and ES19 with. ES1 has a rate of rise of 2,5 m a year with an overall final embankment side slope of 1:1,5 with no cover. ES4 and ES19 both end with an overall embankment side slope of 1:9. The only difference between the these two configurations is that ES4's final embankment configuration is deposited during operation whereas ES19 is constructed at a steep slope (1:1,5) and then mechanically flattened during closure.

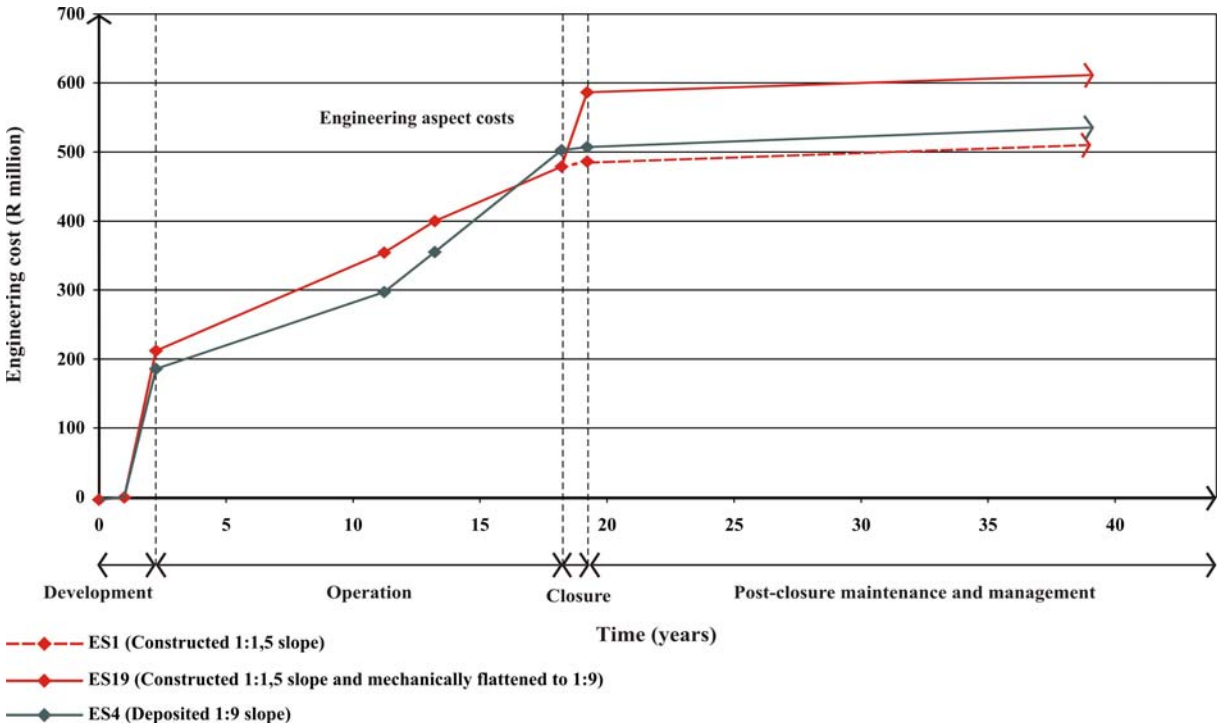


Figure 160: Comparing the engineering life cycle costs for an impoundment with no cover and a 1:9 deposited slope (ES4) and a 1:9 mechanically flattened slope (ES19). ES1 represents an impoundment with an overall side slope ratio of 1:1,5 with no cover.

Although configuration ES19's total life cycle cost is only 14% more than that of ES4, the closure cost of mechanical flattening the side slopes is almost twenty six times more than the closure cost for ES4. Minor routine activities are undertaken to close scenario ES4 whereas more than a R100 million will be spent to flatten scenario ES19's steep embankment side slopes mechanically to the same in situ deposited configuration as that of ES4. This example is used to illustrate the significant costs involved to mechanically flatten the embankment side slope for a tailings impoundment.

It is therefore cheaper to construct the final tailings embankment using deposited tailings as part of the operation stage compared to constructing an impoundment with a steep embankment and having to flatten such mechanically during the closure stage.

The initial total construction cost is higher for the steep (1:1,5) embankment slopes scenarios (ES1 and ES19) than that of the deposited flat (1:9) embankment slope scenario (ES4). Cost items which significantly influence the higher initial costs for the scenarios with steeper slopes during the construction state are:

- greater starter wall construction costs; and
- higher elevated chimney drain construction costs.

One would expect that the initial construction cost of impoundments with flatter embankment slopes must be more expensive than that of impoundments with steeper slopes because of:

- higher initial land acquisition costs to accommodate larger footprints; and
- additional initial construction costs resulting from the larger impoundment footprint.

These cost items are however far less than that of the starter wall and chimney drain costs which are more for impoundments constructed with steeper embankment side slopes.

5.2.2 Conclusion

This section demonstrates the use the engineering cost system by means of modelling different impoundment scenarios to test the effect on engineering costs when flattening tailings impoundment embankment side slopes.

The engineering costs for deposited and mechanically flattened slopes are also compared. The comparative cost analysis illustrates that the total costs for tailings impoundments are significantly influenced by the cost to mechanically flatten embankments during closure.

The choice in cover is one of the most important engineering cost items to consider for the impoundment life cycle. The variance in costs for the design, construction and operation stages are trivial especially when compared to the total tailings impoundment engineering costs and the potential costs that can be incurred during the closure stage. The final impoundment cover cost is also sensitive to the importing of materials required to construct such. For example, there is a significant difference between using a diverse vegetation cover (450 mm imported soil) and leaving it as is (no cover).

There is thus the opportunity to substantially reduce the engineering life-cycle costs by determining prior to deposition what the final impoundment embankment configuration must be and then use the tailings to deposit such during the operation stage.

The two main cost items during the closure stage are:

- the mechanical flattening of the slopes requiring the handling of large volumes of material; and
- the construction of a suitable cover that could require the importing of also large volumes of suitable material.

5.3 Combining environmental impacts with engineering costs

The combining of environmental impacts with engineering costs is demonstrated by using the practical examples of applying the results from the previous section in conjunction with the environmental data from the ERGO Daggafontein site for the purpose of illustrating these examples.

The two examples will elaborate on the typical standard practice approach where the overall impoundment embankment is constructed at a 1:3 side slope. The first example comprises using a constant 1:3 embankment slope with four different cover types which were previously defined, discussed and modelled, namely:

- not applying any cover (tailings in situ),
- rock cladding,
- grassed armouring, and
- diverse vegetative cover.

The second example focuses on using the same cover and flattening the overall tailings impoundment embankment side slope. The grassed armouring cover will be used for this application and the overall embankment side slopes will vary between what is considered to be steep (1:1,5) and flat (1:9), that is:

- 1:1,5;
- 1:3;
- 1:6; and
- 1:9.

5.3.1 Change in cover

Table 61 provides the codes for the scenarios modelled to calculate the engineering costs and quantify the environmental effects which result from the change in impoundment cover with an overall embankment slope of 1:3.

Table 61: Scenario codes used in the study for calculating the engineering costs and predicting the change in effect on key environmental aspects for an embankment slope of 1:3.

Covers	Engineering cost	Visual perception	Air quality	Water quality
Tailings in situ (no cover)	ES2	VS1	AS2	WS2
Rock cladding (300 mm)	ES6	VS3	AS6	WS6
Grassed soil-rock armouring	ES10	VS5	AS10	WS10
Diverse vegetation	ES14	VS7	AS14	WS14

The combination of the environmental impacts with the engineering costs requires the demonstration and discussion of the scenarios (Table 61) and will address:

- engineering costs;
- visual perception zone of influence;
- air quality zone of influence; and
- sulphate mass flux.

Engineering costs

The engineering costs for the modelled scenarios are summarised in Table 62, Figure 161 and Figure 162. Scenarios ES2, ES6, ES10 and ES14 share the same embankment slope configuration and differ only in the cover placed during rehabilitation as part of the closure stage which includes:

- doing nothing and leaving the impoundment uncovered;
- covering the impoundment surface with rock;
- covering the impoundment with a grassed armouring; and
- using a diverse vegetative cover.

The design and construction is scheduled to take a year each, operation is calculated over 16 years, closure is scheduled to take two years, and 20 years are allowed for the post-closure maintenance stage. The cumulative engineering life-cycle costs are indicated in Figure 161 for these stages over the tailings impoundment construction period.

Table 62: Engineering costs for covers ES2, ES6, ES10 and ES14.

	Engineering cost (R million)					
Engineering scenario	**Design**	**Construction**	**Operation**	**Closure**	**Maintenance**	**Total**
ES2 (No cover)	3,4	203,5	270,4	6,4	25,7	509,4
ES6 (Rock cladding)	3,4	203,5	270,4	39,8	25,7	542,8
ES10 (Grassed armouring)	3,4	203,5	270,4	51,7	25,7	554,7
ES14 (Diverse vegetation)	3,4	203,5	270,4	179,8	25,7	682,8

The closure cost for the four configurations are R6,4 million, R40 million, R52 million and R180 million respectively. There is more than a R170 million difference in the closure costs when comparing the no cover scenario, i.e. leaving the impoundment as is after deposition, and rehabilitating the impoundment with a diverse vegetation cover (the most expensive cover modelled). It will cost about R33 million more to cover the impoundment with a 300 mm rock cladding and approximately R45 million more to rehabilitate the impoundment with a grassed armouring than it is to do nothing. The armouring is 300 mm deep and is made up of 67% rock and 33% soil. It is astonishing to realise how much covers can cost. Although it is expensive to construct an engineered cover, the cost of this item is in most cases still less than the total initial construction cost or the total cost to operate the facility.

The closure costs represent the money to be spent at closure on rehabilitation and may be regarded by regulators as a liability during the life of the facility in terms of cost to be incurred in order to meet some sort of acceptable post-closure end state. Legislation requires proponents to provide financially for liabilities setting the said amount aside during the life of the facility and in the event that the rehabilitation is not undertaken by the responsible party, government has the financial means to undertake such rehabilitation instead.

Design, construction and operation costs are the same for the four scenarios. The amount of tailings disposed is the same and the geometry remains the same. Similarly the overall embankment side slope configuration is constant. However, the covers are varied and it is evident that the choice of final cover has a significant impact on the overall impoundment construction cost. Closure costs vary between R6,4 million and R180 million. This presents a significant variance in costs.

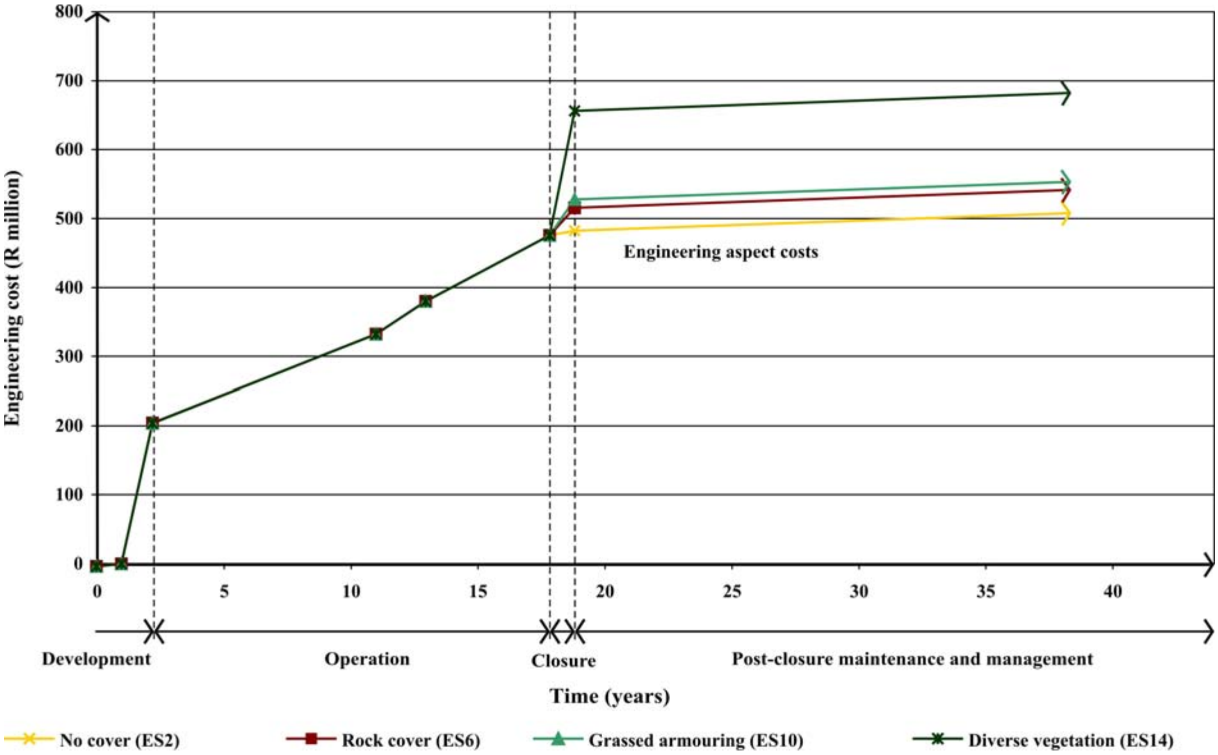


Figure 161: Cumulative engineering impoundment life-cycle costs indicated for ES2, ES6, ES10 and ES14.

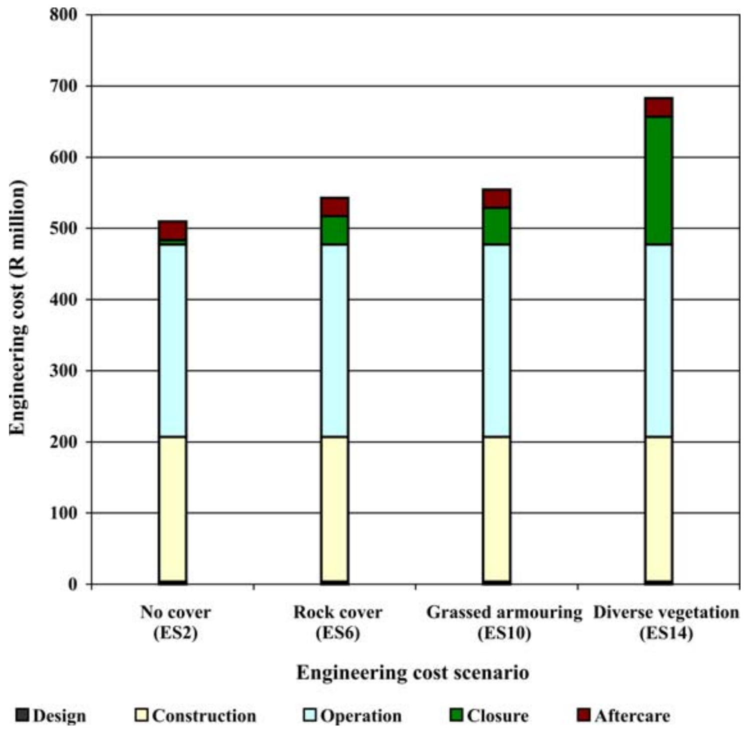


Figure 162: Influence of change in cover types on engineering stage costs.

When comparing the closure stage cost items to that of the construction stage it becomes apparent that the total closure stage cost are still less than the total initial construction stage costs. The perception is that it is expensive to close and rehabilitate a tailings impoundment. Indeed, it can be expensive to rehabilitate an impoundment, but relative to other impoundment stage costs it is not orders of magnitude more.

The slopes of the lines in Figure 161 for the post-closure maintenance and management stage are identical. In practice this will not be so as different cover types will result in varying maintenance requirements. Presently the engineering cost system allows for the following standard post-closure maintenance and management (aftercare) cost items:

- access road maintenance;
- external storm water controls maintenance;
- fence line maintenance;
- paddock maintenance; and
- third party (external) monitoring and inspections.

Visual

The visual perception influence zone results presented in Figure 148 (p. 252) are used in Figure 163 to compare the critical visual perception zones of influence for the visual scenarios VS1, VS3, VS5 and VS7. There is a marked change in the various perception zones of influence resulting from the change in cover.

Surface areas of the detection perception zones for the scenarios are VS1 (21 800 ha), VS3 (16 000 ha), VS5 (7 400 ha), and VS7 (1 200 ha). A remarkable change in the detection visual perception zone of influence is achieved by changing the impoundment cover. The detection visual perception zone of influence is reduced from more than 21 000 ha to 1 200 ha when comparing the best performing diverse vegetative cover with poorest alternative of doing nothing and leaving the impoundment uncovered.

Covering the impoundment with rock will cost R 33,4 million more than doing nothing. This is an increase of 7 % in cost (ES6 compared to ES2). However, by spending 7 % more a reduction of 26 % in the detection visual perception zone of influence is achieved. Furthermore, by spending an additional R 12 million to cover the impoundment with a grassed armouring cover, a 66 % reduction in area can be achieved. The most expensive cover (diverse vegetation) will cost R128 million more than leaving the impoundment without any cover. However, by spending this additional amount (34 % more than doing nothing) the detection visual perception zone of influence area is reduced by almost 95 % (Figure 164, p. 272).

The option to cover an impoundment with a grassed armouring at an additional cost of about R45 million has the highest cost to reduction in surface area factor. For every additional R1 million spent, compared to the do nothing option, a reduction in 320 ha is achieved whereas rock cladding and diverse vegetation have a 170 ha and a 120 ha reduction respectively. A similar trend in reduction of the recognition visual perception zone of influence is observed although not as dramatic as with the detection visual perception zone of influence. Selecting the appropriate cover can significantly reduce the detection visual perception zone of influence. This additional cost, especially when compared with the total impoundment construction cost, and the reduction in zone of influence may justify the additional expense.

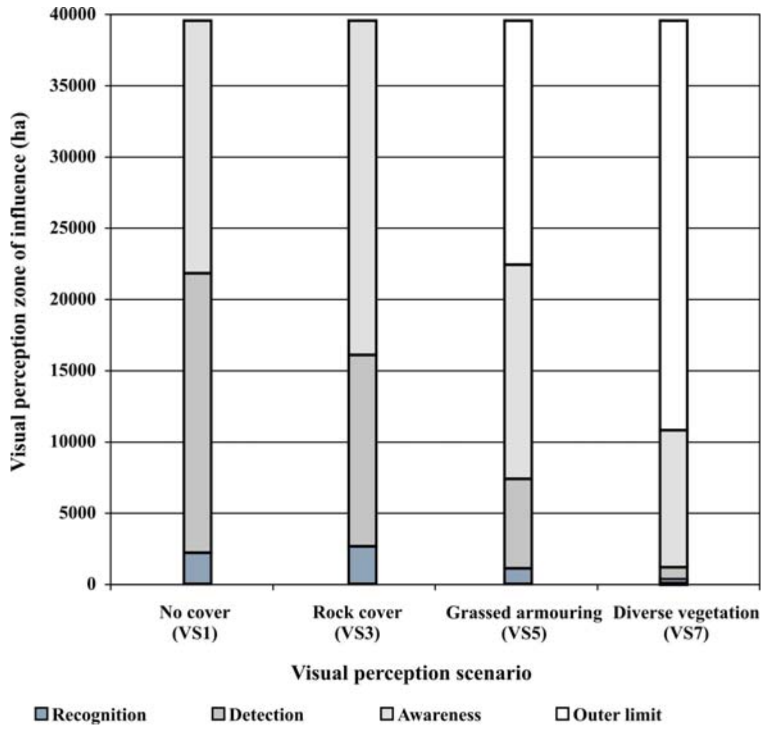


Figure 163: Comparing the various covers modelled shows a marked reduction in the critical visual perception zones of influence.

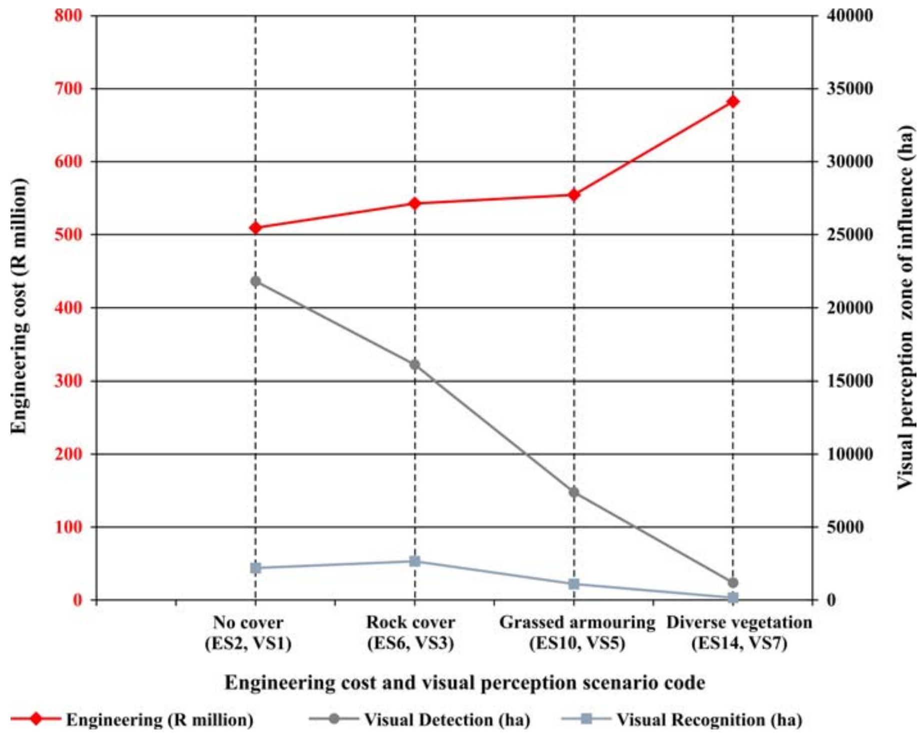


Figure 164: Combining visual perception zone of influence and engineering costs for different cover types.

Air

Figure 165 compares the 25 µg/m^3 PM_{10} concentration and the dustfall (TDS) air quality zones of influence for scenarios AS2, AS6, AS10 and AS14.

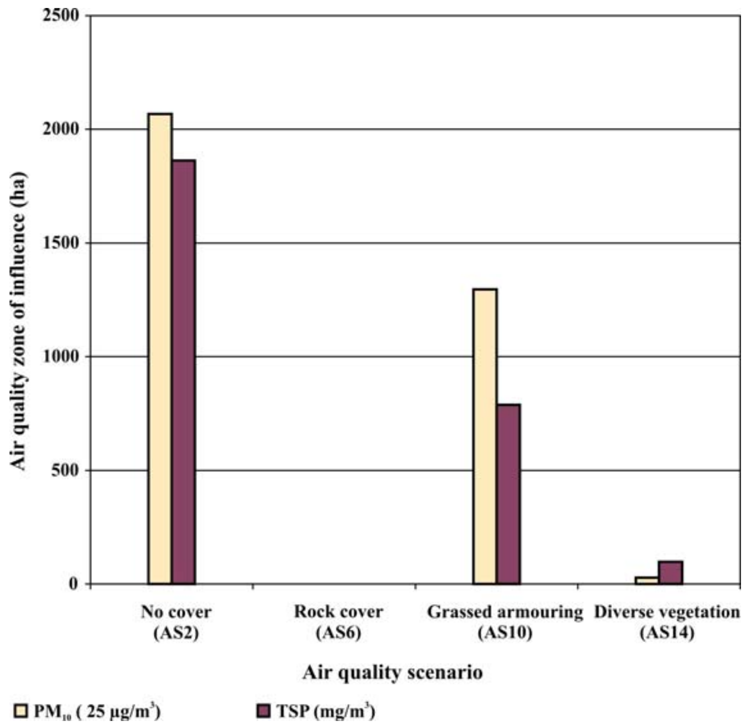


Figure 165: Influence of change of cover on air quality zone of influence.

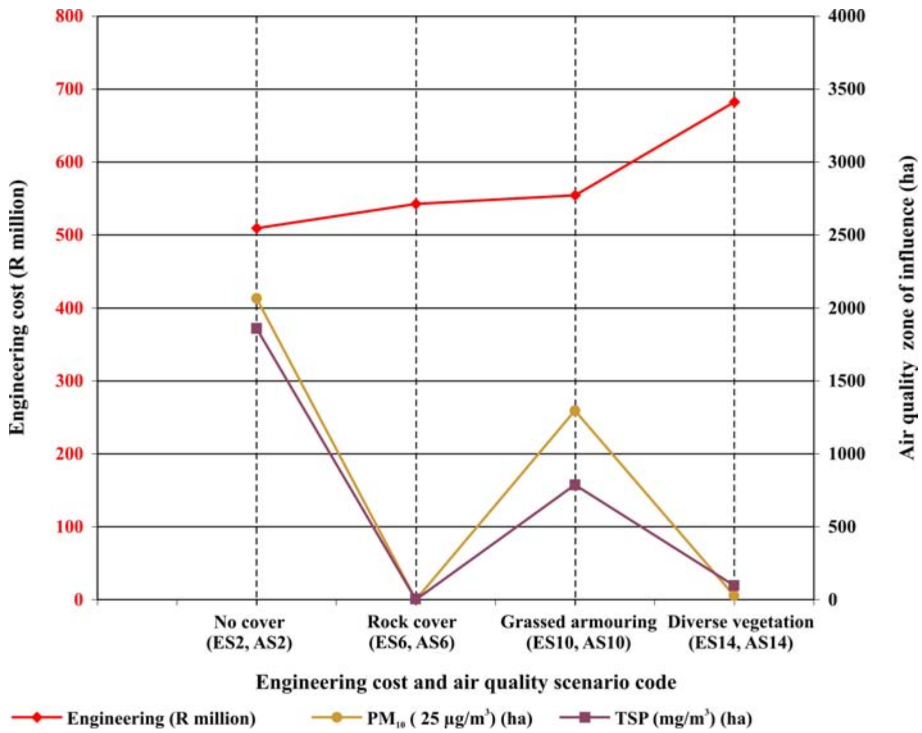


Figure 166: Combining air quality zone of influence and engineering costs for different cover types.

The covers (control efficiencies) are applied to the entire impoundment surface, which is the embankment slopes and top of impoundment. At the time of the modelling of the air quality impacts it was assumed that using a rock cover will reduce the emissions off the impoundment by 100 % which is maybe over conservative as an imported rock cover is likely to contain some fines. Also, a mitigation efficiency of 50 % is attributed to the grassed armouring cover and 80 % to the diverse vegetation cover. It is possible that both the afore-mentioned covers will be more effective in reducing the potential impact on air quality.

A pronounced change in the air quality zone of influence results from the change in cover. The approximate air quality influence zones are AS2 (2 070 ha), AS6 (0 ha), AS10 (1 300 ha), and AS14 (30 ha) for the 25 µg/m^3 PM_{10} concentration and AS2 (1 850 ha) AS6 (0 ha) AS10 (790 ha) and AS14 (100 ha) for dustfall. The air quality influence zone is reduced from 2 070 ha to 30 ha when comparing the doing nothing option with using a diverse vegetative cover.

By spending R34 million more in covering the impoundment with rock than the no cover option a reduction of 2 070 ha is achieved. At an additional cost of R45 million the grassed armouring reduces the 25 µg/m^3 PM_{10} concentration air quality influence zone by 770 ha to 1 300 ha. Using a grassed armouring reduces the emission influence zone by 37 %. Furthermore, the diverse vegetation cover achieves a 99 % reduction in influence area at an additional cost of R173 million (comparing VS14 to VS2).

The option to cover an impoundment with rock at an additional cost of about R34 million has the highest cost to reduction in influence area ratio. For every additional R1 million spent, compared to the no cover (tailings in situ) option, a reduction in 60 ha is achieved whereas the grassed armouring and diverse vegetation have a 17 ha and a 12 ha reduction for every additional R1 million spent respectively.

Water

Figure 167 compares the change in mass load for the water modelling scenarios WS2, WS6, WS10 and WS14 representing an impoundment with an overall embankment side slope of 1:3 and no, rock, grassed armouring and diverse vegetation covers respectively. A change in the mass load results from a change in cover. The mass load sulphates measured in tonnes for the various water modelling scenarios are WS1 (1 800 t), WS6 (2 200 t), WS10 (1 600 t), and WS14 (1 200 t). The mass load is reduced from 2 200 t to 1 200 t when comparing a rock covered impoundment and an impoundment covered with diverse vegetation.

WS6 indicates that the rock cover will result in less runoff, less evaporation, and more infiltration and discharge with the potential for slightly more sulphates to be released into the system. Scenario WS14 indicates the lowest mass load of 1 200 t when comparing the four covers. This can be achieved by spending an additional R 173 million than the no cover option. Similarly for an additional R 45 million the mass load sulphates released into the system can be reduced to 1 600 t. This is a 15 % reduction in sulphates compared to scenario WS2 (no cover). Although the diverse vegetation cover can reduce the mass load by 34 % the cost to reduction in mass load ratio is lower than that for the grassed armouring option. The cost to reduction in mass load ratio for the grassed armouring and diverse vegetation cover options are about 6 and 4 respectively. In other words, for every additional R1 million spent a reduction in 6 and 4 t sulphates can be accomplished.

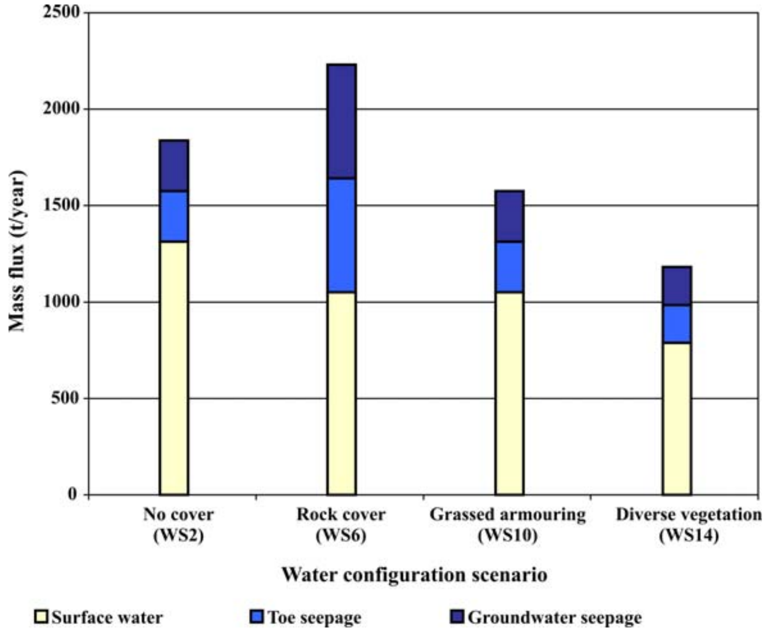


Figure 167: The comparative bar chart illustrates the influence of change in cover on mass flux.

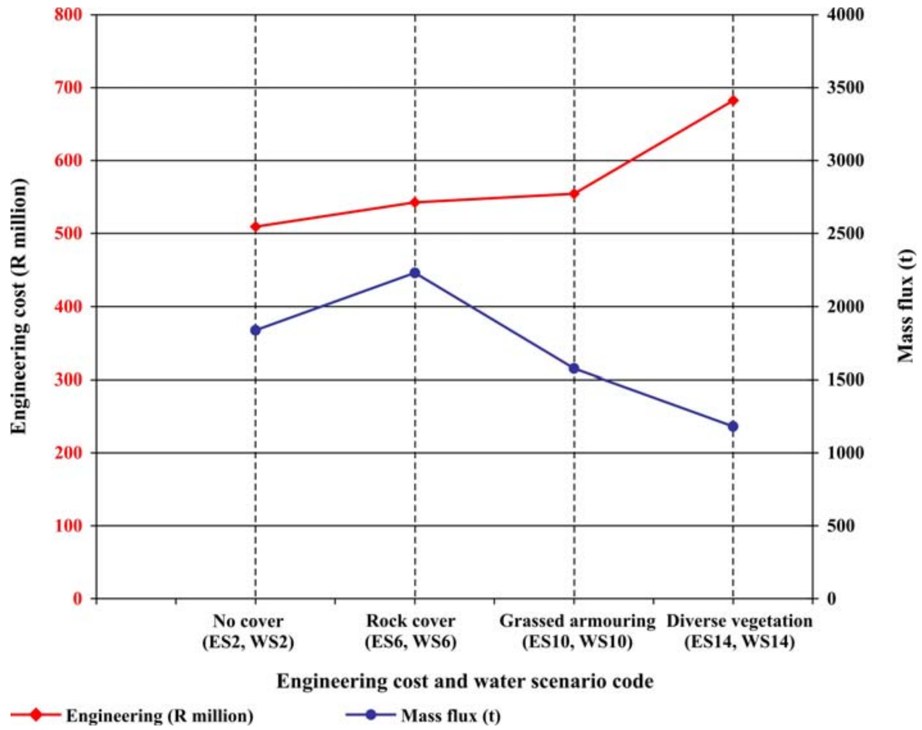


Figure 168: The combination of mass flux and engineering costs for changes in cover types.

Combined results

Figure 169 is a plot of the total engineering life-cycle costs combined with the environmental aspects for the scenarios modelled in the previous section to illustrate the influence of cover type.

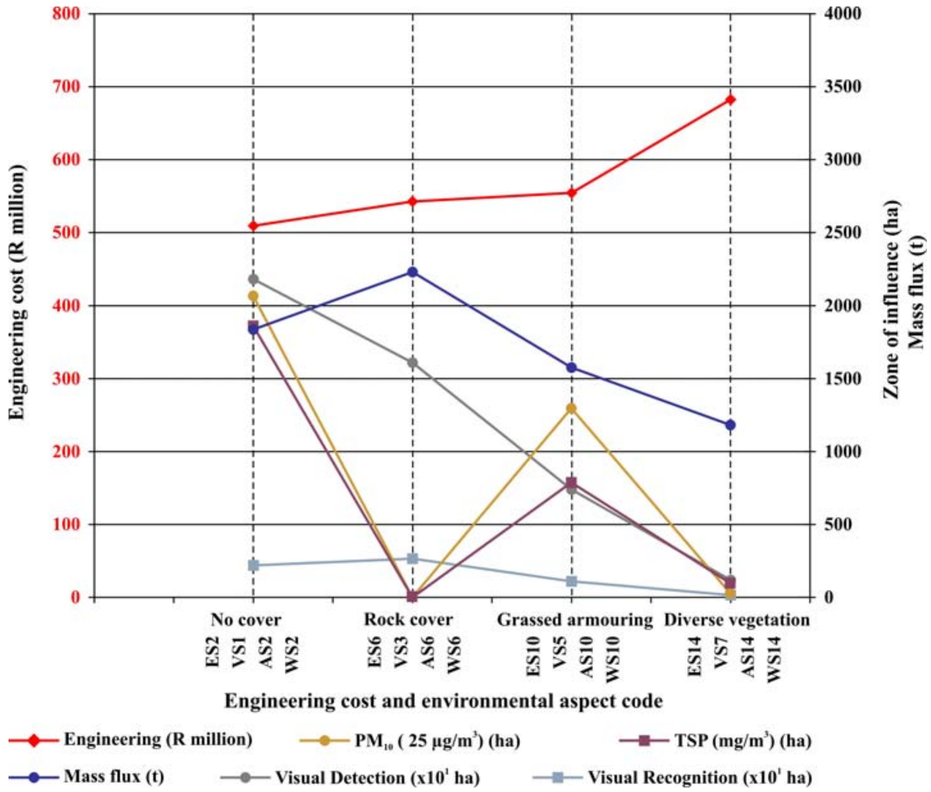


Figure 169: Combined environmental aspect influences and engineering costs for changes in tailings impoundment cover types.

This figure visually illustrates the combination of visual and air quality influence zones, sulphate flux mass flux, and engineering costs resulting from the change in cover type. Environmental lobbyists' may insist that the impact on the environment ought to be minimised at whatever expense and hence the engineering design with the diverse vegetation cover may be preferred. At an additional cost of R173 million (the option is 34 % more expensive than the total engineering cost of ES2) a decrease in 95 % visual detection perception influence zone, 99 % PM10 air quality influence zone, and 36 % sulphate mass load can be achieved. Using rock cover results in a 7 % increase in engineering costs and a 21 % increase in the sulphate mass load. However the visual detection perception influence zone is reduced by almost 26 % and decrease the PM10 air quality influence zone reduced significantly. On the other hand at an additional cost of R45 million to applying no cover, a grassed armouring cover (scenario ES10) results in a reduction of 66 %, 37 % and 14 % for the visual detection perception influence zone, PM10 air quality influence zone, and sulphate mass load respectively.

Engineering cover costs can be determined and compared to the expected change in both influence zones and water pollutant as mass loads. Graphs, such as Figure 169, can be used to communicate the relative change in environmental aspect influences for different engineering decisions made when considering the rehabilitation alternatives during closure.

5.3.2 Flattening embankment slopes

The previous section evaluated the influence of change in cover type on the environment and combined these aspects with engineering costs. The following section models and describes the effect of slope change on the environment and will combine these influences with engineering costs. Table 63 provides the codes for the scenarios modelled to demonstrate the effect that can be expected if the overall embankment side slope is changed while keeping the cover the same. A grassed armouring cover was used as this represents what is currently accepted as best practice. The overall embankment side slopes vary between what is considered to be steep (1:1,5) and flat (1:9):

- 1:1,5;
- 1:3;
- 1:6; and
- 1:9.

Table 63: Scenario codes used to illustrate the influence of change resulting from a change in slope. A grassed armouring cover is used in the scenarios.

	Grassed armouring cover			
Slope	**Engineering cost**	**Visual perception**	**Air quality**	**Water quality**
1:1,5	ES9	VS5	AS9	WS9
1:3	ES10	VS5	AS10	WS10
1:6	ES11	VS5	AS11	WS11
1:9	ES12	VS5	AS12	WS12

The following environmental aspects are modelled and combined with engineering costs:

- visual perception zone of influence;
- air quality zone of influence; and
- sulphates mass flux;

Engineering costs

It is more expensive to reactively flatten embankment slopes mechanically than it is to construct slopes during the operation stage using deposited tailings. For this reason, the following section investigates the influence for deposited slopes and not mechanically flattened slopes.

The engineering costs for scenarios ES9, ES10, ES11 and ES12 are presented in Table 64.

Table 64: Engineering life-cycle costs for scenarios ES9, ES10, ES11 and ES12 indicate the change in costs relative to the change in embankment slope.

	Cost (R million)					
Engineering scenario	**Design**	**Construction**	**Operation**	**Closure**	**Maintenance**	**Total**
ES9 (1:1,5)	3,2	210,7	264,1	50,9	25,0	553,9
ES10 (1:3)	3,4	203,4	270,4	51,7	25,7	554,6
ES11 (1:6)	3,7	191,9	296,9	53,8	27,0	573,3
ES12 (1:9)	4,1	183,7	314,0	55,9	28,2	586,0

The results indicate the overall engineering costs varying between R554 million for the 1:1,5 slope and R586 million for the 1:9 embankment slope configurations covered in grassed armouring. When comparing the total engineering costs of scenarios ES10 with an embankment slope of 1:3, ES11 with an embankment slope of 1:6 and ES12 with an embankment slope of 1:9 to the scenario with the steepest embankment slope of 1:1,5 (ES9), the increase in costs varies between R0,7 million (0,1 %) and R33 million (6 %).

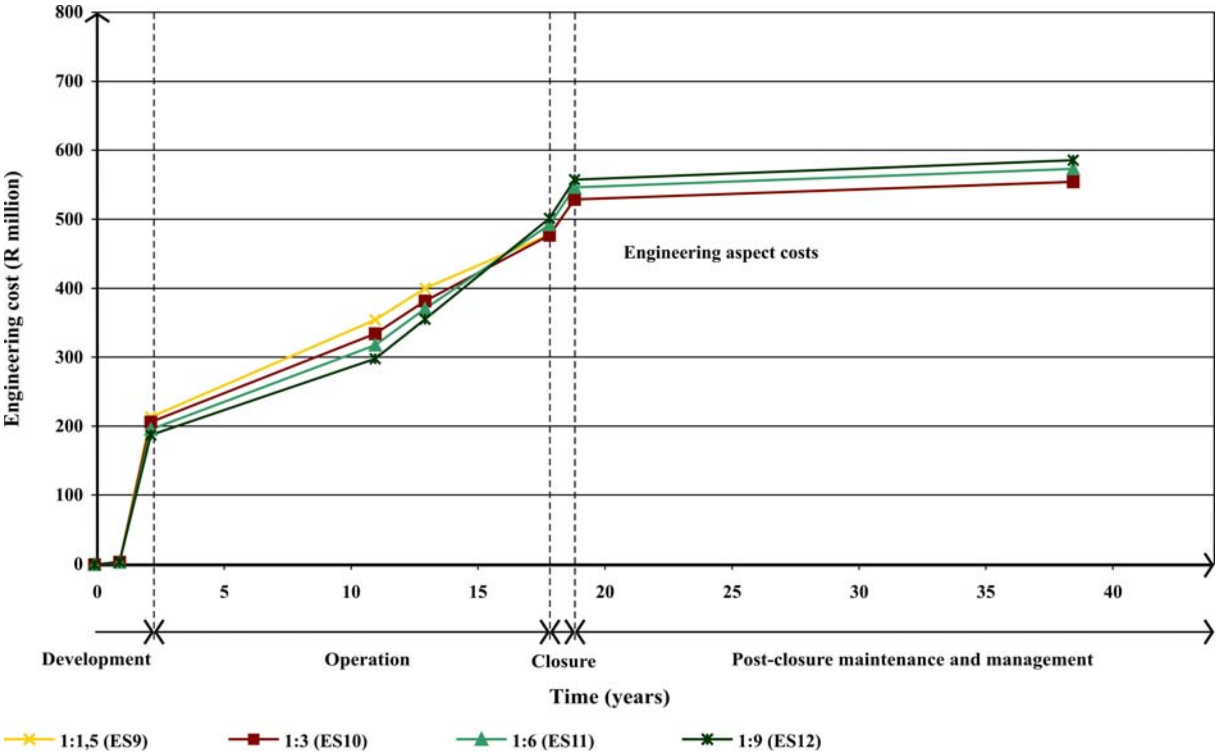


Figure 170: Cumulative engineering impoundment life-cycle costs indicated for scenarios ES9, ES10, ES11 and ES12.

The difference in total engineering costs of 6 % is negligible when compared to the total impoundment life-cycle costs of between R554 million and R586 million. This is an important observation as vegetation establishment may in certain instances favour flatter step-in side slopes which in turn will require the flattening of the overall impoundment embankment side slope.

Engineering cost items that significantly influence the impoundment life-cycle costs are the:

- starter wall, paddock wall, blanket drain, and elevated drain chimney construction costs;
- wall building and pipe work relocation, catwalk and platforms lifting, the increase in outer surface area which is grassed as the impoundment rises, elevated drain construction operation costs; and
- basin profiling, rehabilitation of the basin, and rehabilitation of the outer slopes closure costs as a result in changed impoundment configuration.

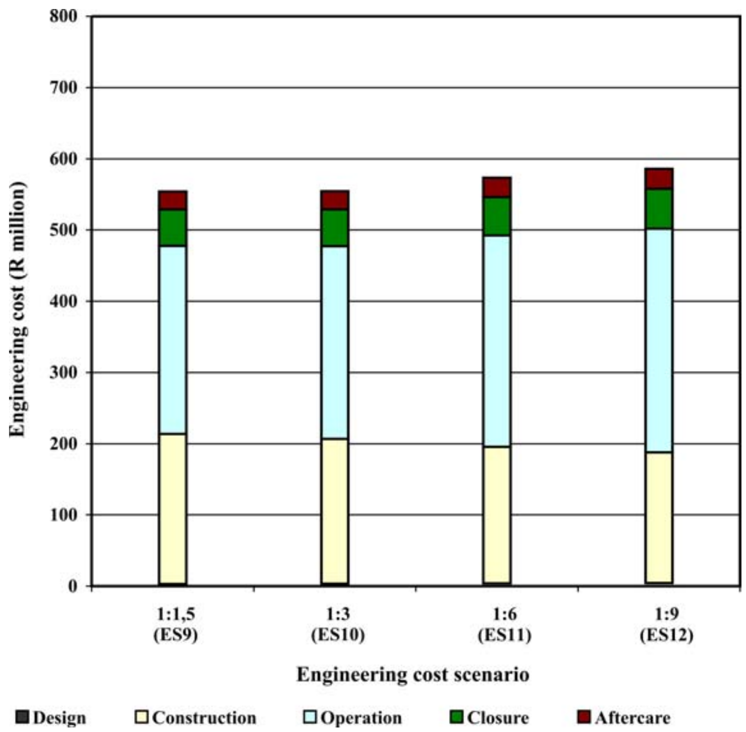


Figure 171: Comparative bar chart results for the engineering scenarios costs ES9, ES10, ES11 and ES12. The development cost is split into design and construction cost items.

There is a variance of about 30 % in the design, 15 % in the construction, 20 % in the operation, 10 % in the closure, and 13 % in the maintenance stage costs when comparing the flattest embankment slope option (1:9) to the steepest embankment slope option (1:1,5) modelled. The total cost of the 1:9 configuration is about R30 million more expensive that the 1:1,5 configuration. It is therefore cheaper to construct an impoundment with a steeper embankment side slope than to construct an impoundment with a flatter embankment side slope (Table 65). Engineering construction cost items that significantly influence the total construction cost are:

- starter wall construction;
- elevated drain chimneys construction; and
- return water dam (RWD) construction

Table 65: Significant construction cost items for scenarios ES9, ES10, ES11 and ES12.

	Engineering costs (R million)			
Description	**ES9 (1:1,5)**	**ES10 (1:3)**	**ES11 (1:6)**	**ES12 (1:9)**
Starter wall construction	92,5	88,1	80,7	75,0
Elevated drain chimneys construction	25,0	22,7	19,0	16,4
RWD embankment construction	12,3	12,4	13,0	13,5
Toe wall construction	1,1	1,2	1,5	1,7
Blanket drain construction	2,8	2,9	3,1	3,2
Delivery and distribution piping installation	14,6	14,7	14,8	14,9

The rehabilitation costs (Table 66) to cover just the side slopes with a grassed armouring is about R7 million for an impoundment with an overall embankment side slope of 1:1,5, approximately R11 million for slope of 1:3, R18 million for a 1:6 slope and R26 million for an embankment overall slope of 1:9. If for argument sake an overall embankment slope of 1:6 is required to sustain grass, the additional engineering cost compared to the slope of 1:3 will be about R20 million.

Table 66: Comparison of closure stage cost items for the various embankment side slopes modelled.

	Grassed armouring costs (R million)			
Closure stage cost items	**ES9 (1:1,5)**	**ES10 (1:3)**	**ES11 (1:6)**	**ES12 (1:9)**
Basin profiling	5,2	4,2	2,7	1,7
Tailings impoundment basin cover	37,2	34,4	29,0	23,8
Tailings impoundment embankment slope cover	6,4	10,9	19,7	28,0
Total	48,8	49,5	51,5	53,4

Figure 172 illustrates an important observation in that the embankment slope does not have the same significant impact on engineering cost as change in cover has. It can however be expected that an impoundment with a very flat embankment slope will increase in costs whereas an impoundment with a steep embankment slope will not vary significantly in engineering cost from an impoundment with a 1:1,5 embankment slope.

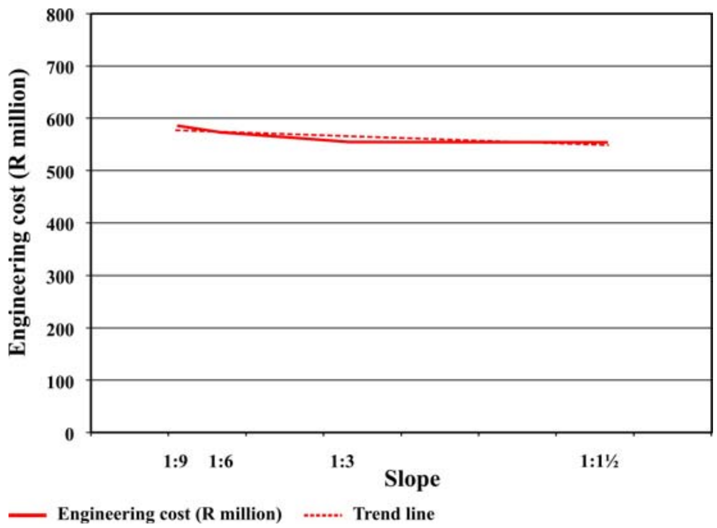


Figure 172: Change in engineering cost for changes in slope for a grassed armouring covered impoundment.

Visual

The mean visual perception comparative bar chart results in Figure 141 (p. 245) illustrates that there is no definitive relation between overall embankment side slope and its effect on visual perception distance as there is no apparent trend from these results. This may well be because only two overall embankment side slope configurations were tested in the experiment namely 1:3 and 1:6. It was however observed that cover type significantly influences the visual perception distances.

It was therefore decided to use the 1:3 embankment visualisation results presented in Table 56 (p. 249) for combination with engineering costs in Figure 173. The detection perception zone influence surface areas for the scenario VS5 (1:3 slope and grassed armouring cover) is 7 400 ha and for the purpose of this example this number will be used for the scenarios being compared.

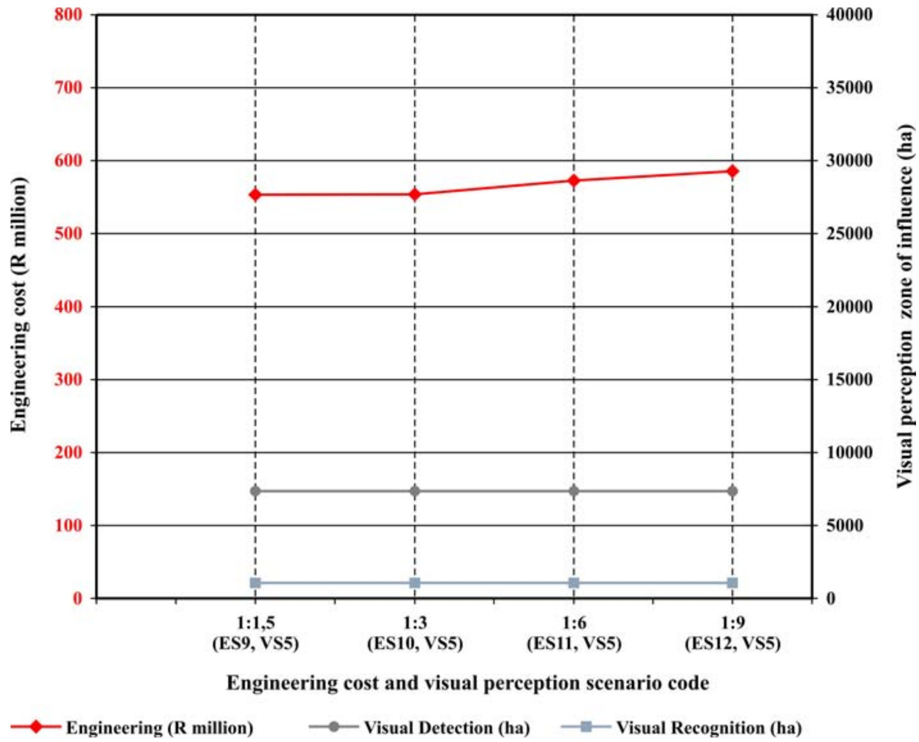


Figure 173: Combining visual perception zone of influence and engineering costs for change in slope.

Air

Figure 174 shows an increase in air quality zone of influence surface area with a decrease in embankment slope. The air quality influence areas for the 25 µg/m^3 PM10 isopleths are 1200 ha (AS9), 1300 ha (AS10), 1500 ha (AS11) and 1750 ha (AS12). This represents an increase of 0,1 %, 3,5 %, and 6 % for AS10 (1:3), AS11 (1:6) and AS12 (1:9) respectively when compared AS9 (1:1,5). The increase in air quality influence area is attributed to the change in impoundment surface area exposed to wind erosion.

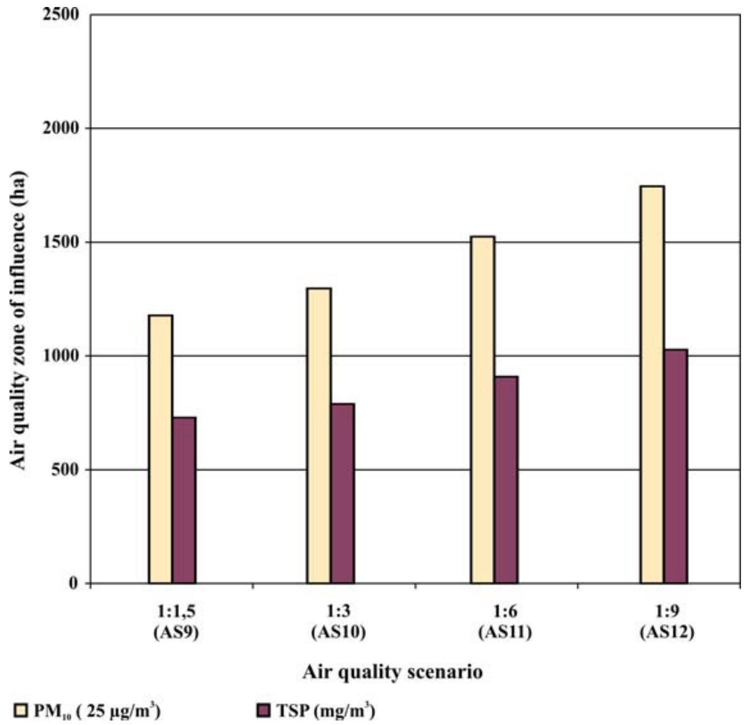


Figure 174: Influence of change in slope on air quality zone of influence.

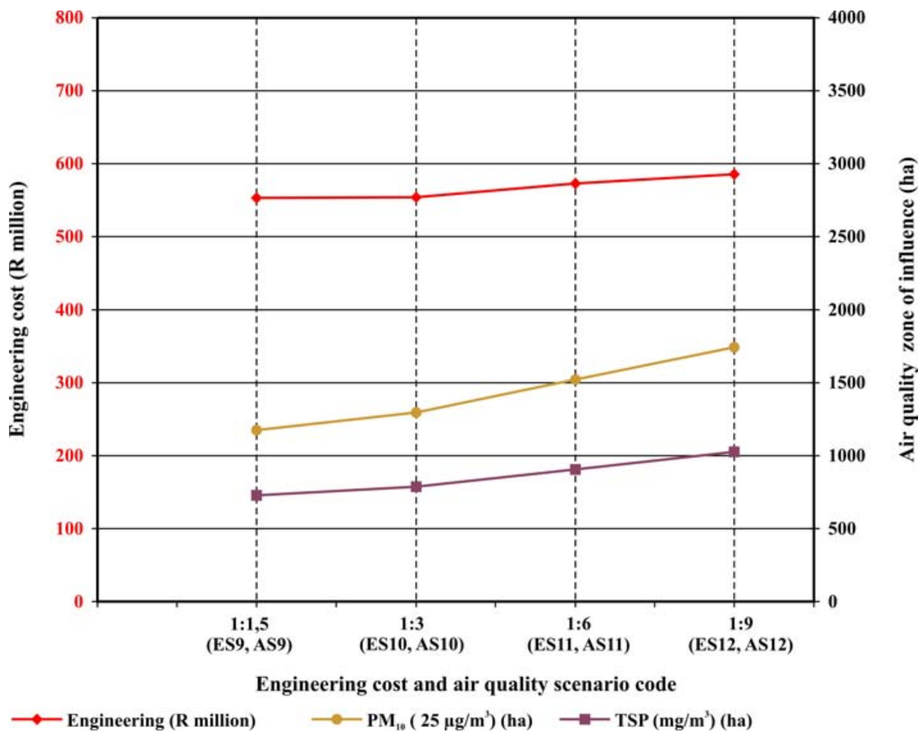


Figure 175: The combination of air quality zone of influence and engineering costs for changes in embankment slopes.

The modelling of the change in slope scenarios for the same grassed armouring cover indicates that there is an increase in the air quality influence surface by flattening the embankment slope and as mentioned previously is likely the result of an increase in impoundment exposed surface area. It may well be that by flattening the embankment slope configuration that a reduction in air quality influence areas will be achieved as flatter step-in slopes are likely to be more resistant to surface runoff erosion and be less draughty which create a better environment for vegetation establishment and the sustaining thereof. It can also be expected that an improved grass cover will increase the management control efficiency in terms of wind erosion which will result in a reduction in emissions off the impoundment.

The air quality models used did not allow for an increase in emission control efficiency with the decrease in overall embankment side slope with regard to improved grass coverage. The results do however indicate a possible increase of between 10 % and 50 % in the air quality influence zone surface area and lead to the conclusion that flattening impoundment embankment side slope may well not be better in terms of the potential increased influence on the surrounding environment. In other words, the objective for flattening embankment slopes must be clearly defined as this could exacerbate and not alleviate issues relating to air quality related impacts.

Water

The mass load sulphates measured in tonnes for the various water modelling scenarios are WS9 (1 480 t), WS10 (1 575 t), WS11 (1 760 t), and WS12 (2 260 t). The flattening of embankment slope results in the increase in engineering costs as well as the increase in sulphate discharge calculated as mass load.

Comparing the two extreme slopes modelled, i.e. the 1:1,5 and the 1:9 slope configuration, a difference in R32 million (6 %) in the total engineering life-cycle costs and 780 t (50 %) in sulphate discharge per annum is observed.

For the purpose of this example the 1:1,5 (steepest embankment slope modelled) is the best case scenario and the 1:9 (flattest embankment slope modelled) is the worst case scenario as it is not only the most expensive but potentially discharges the most sulphates into the environment.

The results presented in Figure 151 (p. 255) indicate that cover as well as slope influences the sulphates released into the environment (calculated as mass flux). The previous discussion focussed on the influence of change in slope to illustrate the effect that an engineering design decision, in terms of impoundment embankment slope, could potentially have on the receiving environment. Similarly, Section 5.3.1 illustrates how a change in cover can have an effect on the mass flux. Both slope and cover influence the potential impact on the environment. Also, both these attributes have a direct bearing on the post-closure land use of an impoundment.

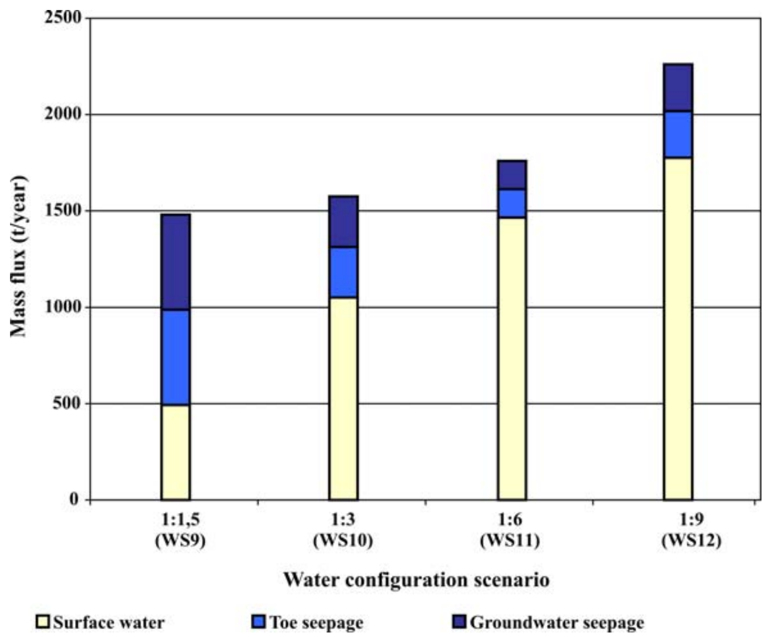


Table 67: Influence of changes in slope on mass flux.

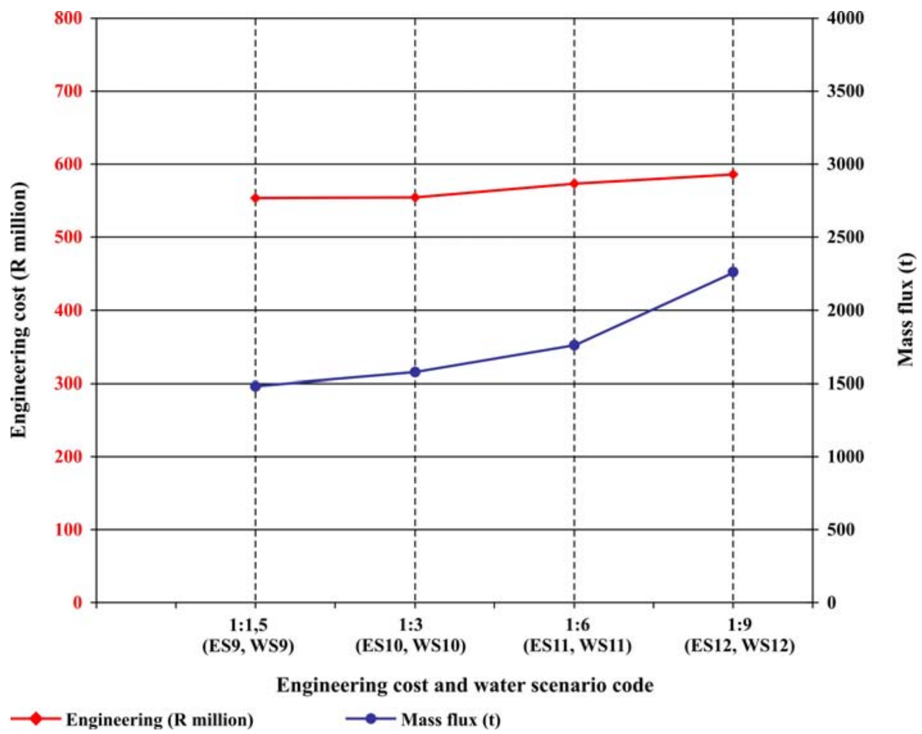


Figure 176: The combination of sulphates expressed as mass flux and engineering costs for different slopes.

Combination of results

It may well be that the post-closure land use objective is to reinstate some form of grass cover that can sustain grazing. However, land use is both a function of cover and access (slope). The change in slope will directly influence access to the top of the impoundment. If one assumes that access has to be unrestricted the overall embankment slope should be less than 1:3 and the step-in slopes less than 1:3,5.

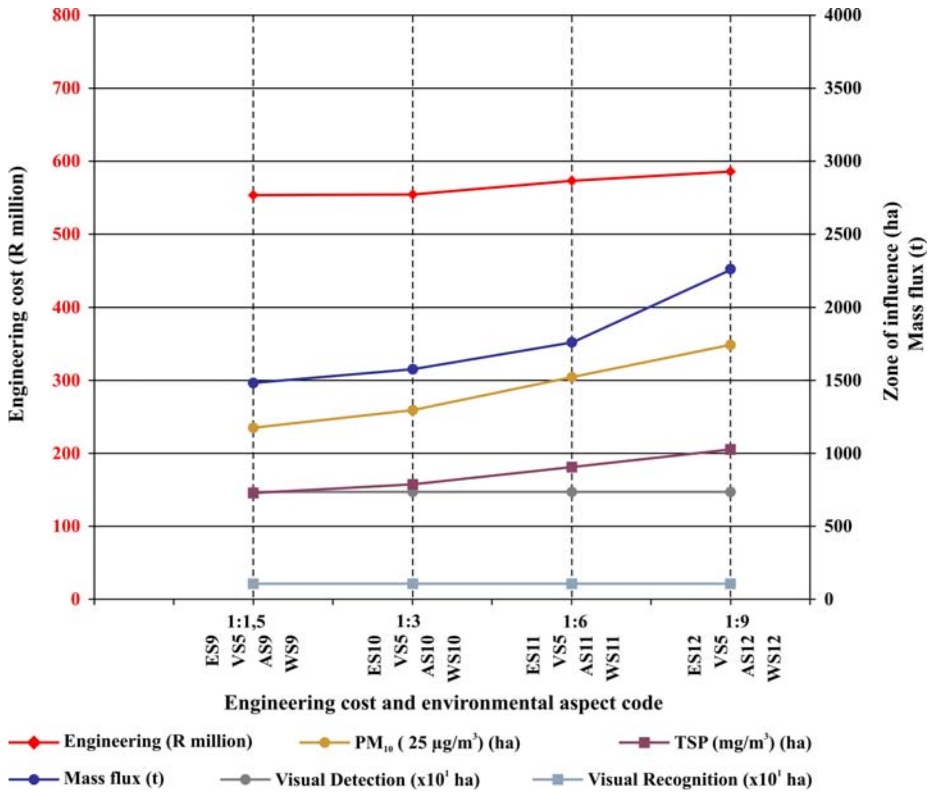


Figure 177: The combination of environmental aspect influences and engineering scenario costs for changes in embankment slopes.

Land use is determined collectively by a host of intrinsic attributes (El-Swaify and Yakowitz, 1998:11). These attributes, whether physical, chemical, or biological, can favour, limit, or completely inhibit certain activities and include attributes such as climate, soils, and landform characteristics which are discussed in Section 2.13.5.

Slope characteristics may favour or restrict land use; as they determine:

- accessibility,
- trafficability,
- stability against surface erosion and mass movement of material,
- potential runoff and flooding, and
- exposure to climatic influences, particularly wind, rain and solar radiation.

Slope can have a limiting effect on the use of land. Figure 77 (p. 152) shows slope requirements for various land uses. Level or gently sloping sites are usually necessary for industrial and commercial buildings and sports fields. Grazing land is generally limited to slopes of less than 1:3 with a preferred slope of about 1:5 for impoundment embankments because of the performance and safety restrictions posed by the operation of machinery such as tractors. The criteria, regarding soil depth and slope as summarised from the Chamber of Mines Rehabilitation Guidelines (CM, 1981) for the following land capability classes are:

- Arable land: soil depth will not be less than 0,6 m and the slope will not exceed 7 % (1:14).
- Grazing land: soil depth will be at least 0,25 m an the slope will not exceed 30 % (1:3).
- Wilderness land: soil depth is less than 0,25 m but more than 0,15 m.

Theoretically the top of the impoundment, depending on the final engineered cover, will not pose any restrictions in terms of land capability. It is however the embankment configuration that could limit the use as a result of slope steepness. When keeping the geometric volume and height of the impoundment constant at 105 600 000 m^3 and 37,3 m respectively, the impoundment embankment configurations of the scenarios modelled can be summarized as:

Overall embankment slope ratio	**1:1,5**	**1:3**	**1:6**	**1:9**
Overall embankment slope angle	33,7 °	18,4 °	9,5 °	6,3 °
Step-in slope ratio (rounded)	1:1	1:2,5	1:5,5	1:8,5
Step-in slope angle	45 °	21,8 °	10,3 °	6,7 °

It is also not the overall embankment slope that is important but the step-in slope angle. Thus to reinstate a slope of a minimum of 1:3,5 and preferable 1:5, which is required for grazing, an overall embankment slope of 1:6 will be necessary. A post-closure impoundment configuration consisting of an overall embankment slope angle of 1:6 and 300 mm armouring will cost about R570 million, have a potential detection perception zone of influence area of about 7 400 ha, an 25 µg/m^3 PM_{10} air quality influence area of about 1 500 ha, and a sulphate mass load of 1760 t. There is an increase of about R19 million (3,5 %) in engineering costs when comparing the 1:6 and 1:3 embankment slope scenarios. This additional cost will be required in order to configure the embankment slope suitable to sustain grazing. It does however come at a cost – a cost to the environment in that the air quality influence area may increase by 230 ha and the sulphate mass load increase by 185 t. The detection visual perception influence area is estimated to be about 7 400 ha. However, this may be justified if it can be demonstrated that the impoundment embankment configuration can sustain the intended post-closure use.

5.3.3 Summary

The previous two sections in this chapter describe the influence that change in tailings impoundment cover types and slopes has on the environment. The quantified environmental aspects are combined with engineering costs and summarised in Figure 169 (p. 276) for the change in cover type and Figure 177 (p. 285) for the change in slope. Visual and air quality influence zones and water pollutant as mass loads are compared to engineering costs. The graphical representation of the combination of environmental aspects and engineering costs effectively communicates the relative change in environmental aspect influences for different closure alternatives. This can be used to inform rational decision making. The trends may have been expected but the question still remains how to use the environmental aspects and take the process to the next stage of ascribing costs and benefits to the environmental improvements. In other words, describing changes in absolute terms and not only relative terms. Once this can be done, the environmental aspects can be integrated with engineering costs. The following section integrates the environmental impacts with engineering costs.

CHAPTER SIX: INTEGRATING ENVIRONMENTAL IMPACT COSTS WITH ENGINEERING COSTS

"God does not care about our mathematical difficulties.
He integrates empirically."
Albert Einstein (Quotations, 2007)

6.1 Introduction

From the onset of the study the aim was to develop a rational and transparent system that can be used to quantify some of the key environmental aspects and also scale and weight the impacts so that the optimum long term design of a tailings impoundment can be achieved.

Planning a tailings impoundment site focuses on the engineering, biophysical, economic and social-cultural issues. It is often the economic and social factors, and not necessarily the practical matters, that hold the most sway when undertaking the planning and design of an impoundment. Although the main interest of the proponent is to meet certain financial targets. Despite the increased awareness of the importance of the environment, factors such as the fear of wasting money or not making enough money to please shareholders are likely to determine a proponent's final decision about a scheme more readily than environmental concerns. Proponents and regulators need to realize that economic disadvantage to individuals and society can result from failure to take proper account of all aspects of the environment.

Figure 169 (p. 276) and Figure 177 (p. 285) illustrate the combined engineering costs and environment aspect influences for a change in impoundment cover and change in embankment slope. Although altering the embankment slope of an impoundment influences engineering costs and change environmental aspect influences, it is not quite as dramatic as that resulting from changing impoundment covers. The change in slopes considered, which cover the full range of practical slopes, leads to a change in cost of about 6 % whereas the change in covers, which also encompass the full range of cover types, leads to a change in cost of about 30 %. Therefore the following section demonstrates the costing of impacts as a result of change in impoundment cover type.

Table 61 (p. 268) provides the unique codes for the scenarios modelled used to calculate the engineering costs and quantify the environmental effects. These scenarios are used to illustrate the influence of cover change for an impoundment with an overall embankment side slope of 1:3. Figure 169 (p. 276) presents the combined results and plots the environmental aspect influences and engineering costs for changes in tailings impoundment cover types.

Based on the assumption that depositing tailings is to take place; the specific planning problem can further be formulated as:

- the need to minimise costs, and
- the requirement to maintain a certain visual, water, air, and land use quality.

Visual and air quality deterioration and water pollution can lead to serious negative impacts on value of land, health, and services. The physical evidence is compelling.

The costing of these impacts is frequently ignored because it is:

- considered too difficult to establish direct cause-effect relationships; and
- not always feasible to place monetary values on effects.

Regardless, the following section in this thesis demonstrates how valuating environmental impacts can be used as a tool to facilitate decision making.

6.2 Valuating environmental impacts

Calculating the engineering as well as the environmental impact costs is an important part of the tailings impoundment planning process both in terms of actual cost to the proponent and the costs to society as a result of a scheme.

General conclusions reached by Georgiou, Whittington, Pearce and Moran (1997) are that economic valuation is:

- extremely useful in raising the profile of the environmental aspects of development projects;
- widespread in terms of its applications in developing countries; and
- generally successful in its application.

Costs to society can be incurred through for instance the:

- potential conflict in land use because of degradation to visual resources within the impoundment's visual zone of influence;
- increase in ill-health effects of people who live within the impoundment air quality zone of influence;
- mitigation or treatment cost incurred to treat polluted discharge to meet regulatory water quality standards;
- provision for new or additional infrastructure;
- extra work required to protect natural resources impacted on by the tailings impoundment; and
- loss of cultural resources with heritage value either as a direct result of the displacement caused by the physical footprint of the impoundment or as a result of the impoundment's sphere of influence.

The following section uses the ERGO Daggafontein site and practical examples to demonstrate this. The section on the valuation of impact change, Section 2.9.2 states that the following two key elements are required when valuating environmental impacts:

- measuring the environmental impacts; and
- placing monetary values on the measurements.

The measuring of the visual, air and water impacts are described in Chapter 3 and the results provided in Chapter 4. Placing monetary values on the measurements or valuation is now demonstrated. Two distinctive approaches to valuate impacts are described in detail in Section 2.9.2. Either objective valuation approaches (OVA) or subjective valuation approaches (SVA) can be used to cost impacts on the environment. Valuation of impacts can be difficult in instances such as the:

- valuation of changes in ecosystems;
- impact on sites of heritage importance; and
- loss of recreational benefits of game reserves.

It is possible although difficult to estimate the economic values of the impact of an impoundment on a nature reserve by using the travel cost approach or conducting contingent valuation studies.

Several impacts can also be related to a specific environmental aspect. For example, the increase in particulate concentrations in air can cause:

- ecological alterations especially when emissions include toxic elements;
- the reduction in visibility which in turn can have an adverse effect on transport safety;
- property values to change; and
- ill-health effects.

It is important to choose one or more of the effects in order to quantify and cost these. It is proposed that the:

- visual impact will be valuated by using property pricing and land value;
- air quality impact will be valuated by costing the increase in respiratory hospital admissions; and
- water quality impact will be valuated by using water treatment costs.

It is possible that, depending on the locality, that the construction of an impoundment will only be allowed if the proponent can demonstrate that the environmental impacts can be managed and in certain instances prevented. If an impact is entirely prevented, the cost of prevention can be taken into account when doing the economic and financial analysis of the scheme. If an impoundment is covered with rock at a cost of R40 million to eliminate air pollution, there is no impact on the air quality. On the other hand, if a grassed armouring is placed at a cost of R50 million, the cost of mitigation action is a direct and identifiable cost of the scheme, but the value of the residual impact on air quality, i.e. the possible increase in respiratory hospital admissions as a result from the increase in particulate concentrations, also needs to be included in the cost of the scheme.

The following environmental aspects are valuated in the next section as part of this study:

- visual perception;
- air quality; and
- water quality.

6.2.1 Visual

Valuating visual impacts typically make use of subjective valuation approaches (SVA) such as the hedonic valuation method of which the pricing theory holds that because people select a good for its characteristics, the value of the characteristics is reflected in the price of the good (Table 5, p. 67 and Figure 39, p. 69). The good in question is property, and the attribute of interest is aesthetics. A major problem with hedonic pricing arises from the extent to which the focus variable (in this case, aesthetics) can be correctly identified, accurately measured and reliably distinguished from related factors (Bateman, 1994, p. 31). The examination of property and land values will be used to calculate the cost of the tailings impoundment visual influence.

A desktop survey was undertaken to determine the way in which property prices and land values, especially that of residential property and land with the potential for game farming with a tourism component can be affected by its proximity to tailings impoundments. A process can be followed to elicit expert views of property valuator and estate agents as regards changes in property prices due to its locality within the different visual perception zones of influence. (It is recommended that this could be a topic for further research.) However, the premise is that land use and property values could differ depending on its locality relative to the tailings impoundment. Also, there can be incompatibilities between the post-closure tailings impoundment and the land use of the surrounding area.

Compatible and incompatible land uses for this study are proposed in Table 68. The impoundment configurations defined and used in the experimental work and modelling section will again be used and where, in the section on combing environmental impacts and engineering costs, the change was measured and described in visual detection and recognition zones of influence and expressed in surface area, the change will now be presented in monetary terms.

Table 68: Proposed compatible and incompatible land uses within the recognition and detection visual perception zones of influence.

		Visual perception zone	
Zoning	**Land use**	**Recognition**	**Detection**
Wilderness	**Wilderness**	Compatible	Compatible
Agriculture	**Grazing**	Compatible	Compatible
	Crop cultivation	Compatible	Compatible
Residential	**Low cost**	Compatible	Compatible
	Medium cost	Likely incompatibility	Compatible
	High cost	Incompatible	Likely incompatibility
Light industry	**Light industry**	Compatible	Compatible
Game farming	**Farming**	Compatible	Compatible
	Tourism	Incompatible	Likely incompatibility

Current and future land uses are discussed by comparing the ERGO Daggafontein study area's land use with the specific long-term impoundment configuration alternatives. Long-term post-deposition land use of an impoundment is likely to be completely different as the use and level of use on the site prior to the construction of the impoundment. The definition of level of land use is subjective. It is perhaps more appropriate to consider levels of post-deposition long-term uses to be that which are acceptable in terms of present and future planning initiatives and land use.

The land around the ERGO Daggafontein tailings impoundment is typically zoned for:

- agriculture;
- small holdings;
- residential; and
- light industrial.

Open space although indicated as agricultural land can be used for wildlife habitat and recreation. Using information on property transfers and applying recent house price indexes it is possible to calculate approximate 2006 prices for properties in the ERGO Daggafontein area (Table 69).

Table 69: Property values in the area of the ERGO Daggafontein tailings impoundment.

Erv no	Transaction date	Property value (R)	2006 value (R)	Property size (ha)	Value (R/ha)
Daggafontein Ext. 7A					
110	2005/03/29	250 000	305 279	0,74	413 490
158	2004/05/27	110 000	177 528	0,21	833 466
185	2005/12/20	120 000	146 534	0,18	798 986
				Average value	681 980
Daggafontein Ext. 1					
25	2004/08/16	220 000	355 056	0,12	2 927 093
42	2003/04/01	120 000	235 167	0,24	971 364
49	2004/02/06	275 000	538 925	0,14	3 816 748
62	2005/04/23	800 000	976 894	0,26	3 751 513
				Average value	2 866 679
Daggafontein Ext. 2					
441	1994/04/08	150 000	570 247	1,09	525 090
413	2002/02/28	92 000	211 846	0,30	714 732
344	2005/05/12	350 000	366 335	0,32	1 129 618
378	1995/08/24	109 000	398 442	0,20	1 944 568
360	1996/09/02	75 000	263 613	0,14	1 915 791
				Average value	1 245 960
Daggafontein Ext. 5					
610	1998/11/26	600 000	1 931 229	1,09	1 778 296
591	1996/09/12	100 000	351 484	0,30	1 185 843
535	1999/07/28	100 000	300 815	0,32	927 581
555	1998/10/20	170 000	547 182	0,20	2 670 482
570	1994/03/29	30 000	114 049	0,14	828 848
622	2002/08/19	1 200 000	2 763 214	0,50	5 526 429
				Average value	2 152 913
Daggafontein Ext. 7B					
194	1994/08/17	181 000	688 098	0,75	921 396
333	2006/06/03	161 000	161 000	0,40	398 022
212	2004/07/06	30 000	48 417	0,17	284 303
325	2005/10/13	1 400 000	2 259 449	7,14	316 472
313	2005/11/18	316 000	3 85 873	0,14	2 804 310
				Average value	944 901

The agricultural land use value for grazing is about R8 000/ha whereas land which is irrigated and used for crop cultivation can be as much as R42 000/ha. Small holdings sell for about R110 000/ha and residential property varies between R680 000 and R2,9 million/ha. Land used for light industry in the area sells for about R2,2 million/ha. Property values in Table 69 for the ERGO Daggafontein area is spatially represented in Figure 178.

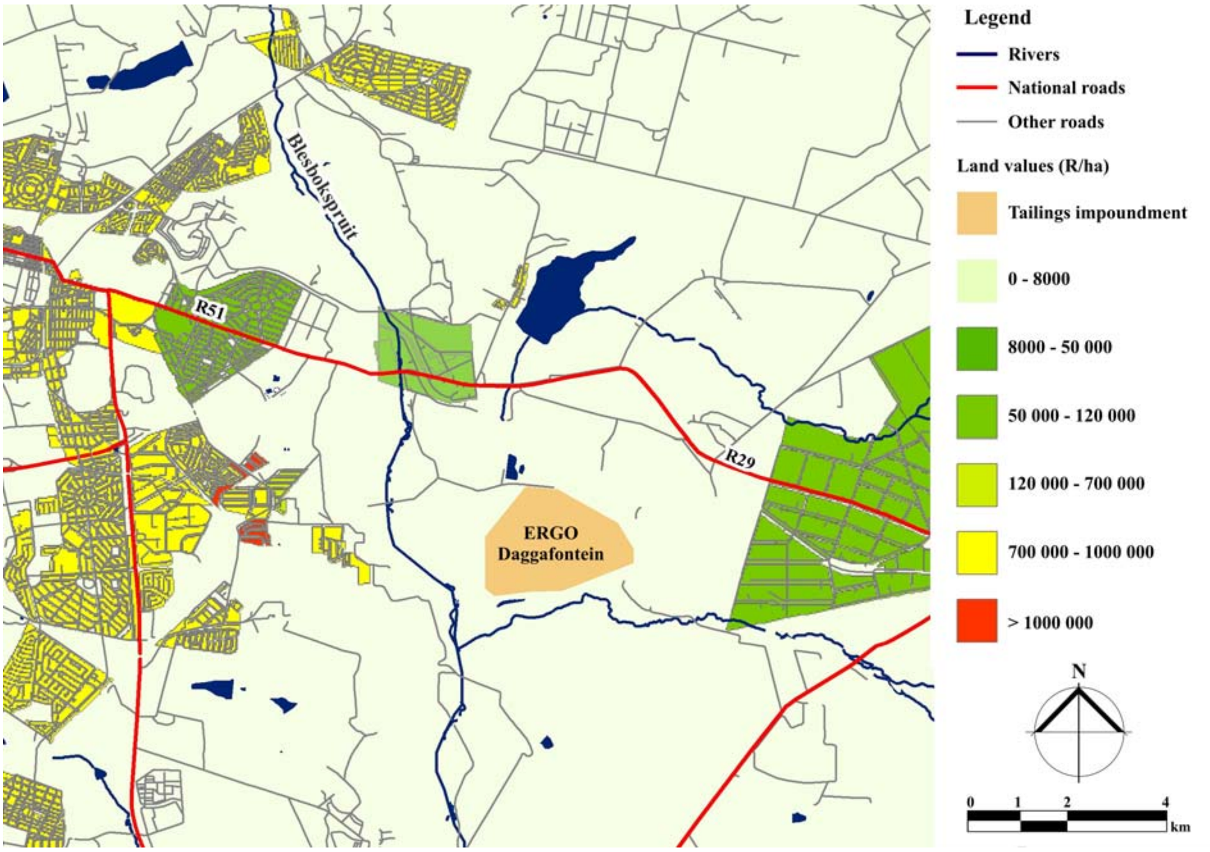


Figure 178: Land value map (R/ha) around the ERGO Daggafontein tailings impoundment.

It may be possible to decide on a post-closure impoundment configuration and use that are least in conflict with these surrounding uses. Simplistically there are five general levels of use that can be committed to for future use.

These are, in ascending order of level of involvement:
- wilderness;
- limited agriculture or recreation with little development, such as grazing and game farming;
- developed agriculture such as the cultivation of crops;
- residential, light commercial and light industry; and
- residential, heavy commercial and heavy industry.

Visual perception zone of influence for scenarios VS1, VS3, VS5 and VS7 are included in Appendix A4. If the recognition and detection zones are superimposed on the land value map (Figure 178) and applying the land values (Table 70) a bar chart can be used to compare the existing value of land within the area of influence (Figure 179).

Table 70: Land values used in the quantification of land use incompatibilities.

Zoning	Land use	Land value (R/ha)
Wilderness	**Wilderness**	8 000
Agriculture	**Grazing**	8 000
	Crop cultivation	42 000
Residential	**Low cost**	680 000
	Medium cost	1 430 000
	High cost	2 870 000
Light industry	**Light industry**	2 150 000
Game farming	**Farming**	25 000
	Tourism	120 000

The existing total value of land in the recognition visual perception zone of influence for the cover types modelled are approximately R17,5 million (VS1), R21 million (VS2), R8,7 million (VS5) and R1,3 million (VS7). Similarly the total value of land in the detection zone is R1 200 million (VS1), R738 million (VS2), R168 million (VS5) and R8,2 million (VS7) (Figure 179).

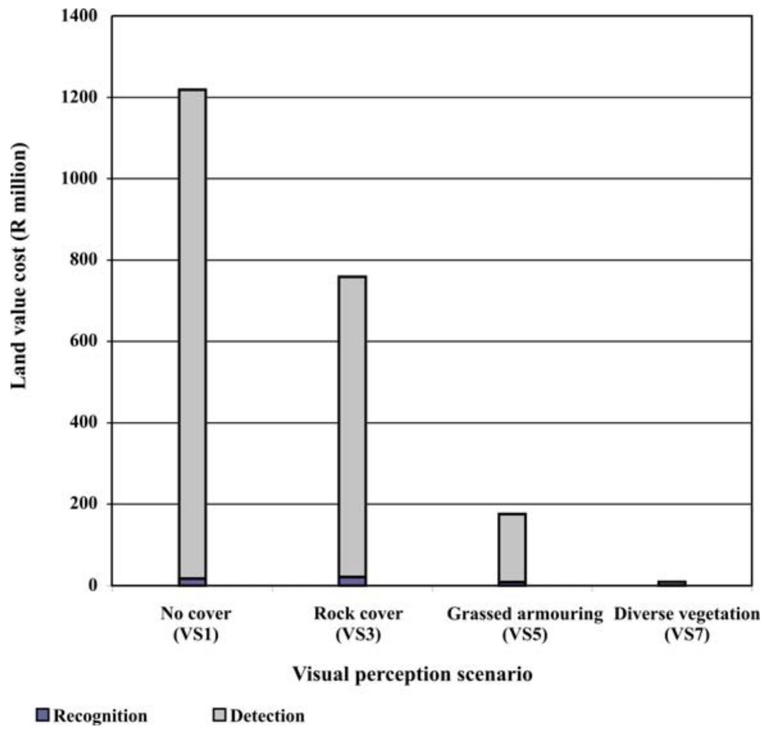


Figure 179: Total existing value of land within the visual perception zones of influence.

The size of the detection zone results in a total land value within the influence zone of up to R1 200 million. The existing value of land in the recognition zone is much less (R18 million) because the area of influence is much smaller. The value of land in the impoundment with no cover detection zone (VS1) is almost seventy times more than the value of land in the recognition zone. Similarly the no cover detection influence zone is more than three orders of magnitude greater than that of the impoundment covered in diverse vegetation (VS7). The value of land in VS7's recognition zone is just over R1,25 million whereas the land value in VS1's recognition influence zone is about R18 million.

In order to valuate the potential visual impact that could result from the tailings impoundment it is necessary to consider the potential land use incompatibilities and conflicts between different land uses. Potential incompatible land uses are proposed in Table 68, p. 290.

There are many examples, such as those illustrated in Figure 180, where low cost residential development has been constructed in the recognition visual perception zone of influence. It is however unlikely that high cost residential development will be compatible in the same zone. Similarly it may in certain instances be that there will be a conflict in developing high cost residences in the detection zone. There could also be conflict between game farming land with a tourism potential and the recognition and detection visual perception zones of influence.

Looking towards one of the Grootvlei Proprietary Mines tailings impoundment's with low cost residential land in the foreground.
2 A view towards existing Krugersdorp West Mine residue deposits with a new residential development adjacent.

Figure 180: Residential development in the visual perception zone of influence.

The following sections consider ascribing values for land for high cost housing and land for tourism (game farming) and the potential loss in land value resulting from conflict with land used for impounding tailings.

Sterilising land for high cost residential property development

There is the potential that land in close proximity to a tailings impoundment, and more specifically land which lies within the visual recognition perception zone of influence, could be sterilised for future high cost residential development.

For the purposes of illustrating the potential sterilisation of high cost residential development within the tailings impoundment visual perception zone of influence it is best to focus on the recognition zone. The reasons are two-fold.

Firstly, the detection zone surface area is orders larger than the recognition zone and the valuation of the visual impact is sensitive to the area influenced by the impoundment.

Secondly, as mentioned before, research has to be undertaken to determine conflicting land uses and incompatibilities that will arise when constructing an impoundment in proximity to different land uses or vice versa. The costs for potential sterilisation for high cost residential developments within the detection visual perception zone of influence run into the thousands of millions of Rands.

The possible visual impact cost in the visual perception visual zone of influence is the difference in high and medium cost residential development property value (Figure 181). The impact is the potential change brought about by the tailings impoundment. The potential visual impact costs for loss in land value (high cost housing minus medium cost housing) are R30 billion (VS1), R20 billion (VS3), R9 billion (VS5) and R1,5 billion for the no cover, rock, grassed armouring and diverse vegetation covers.

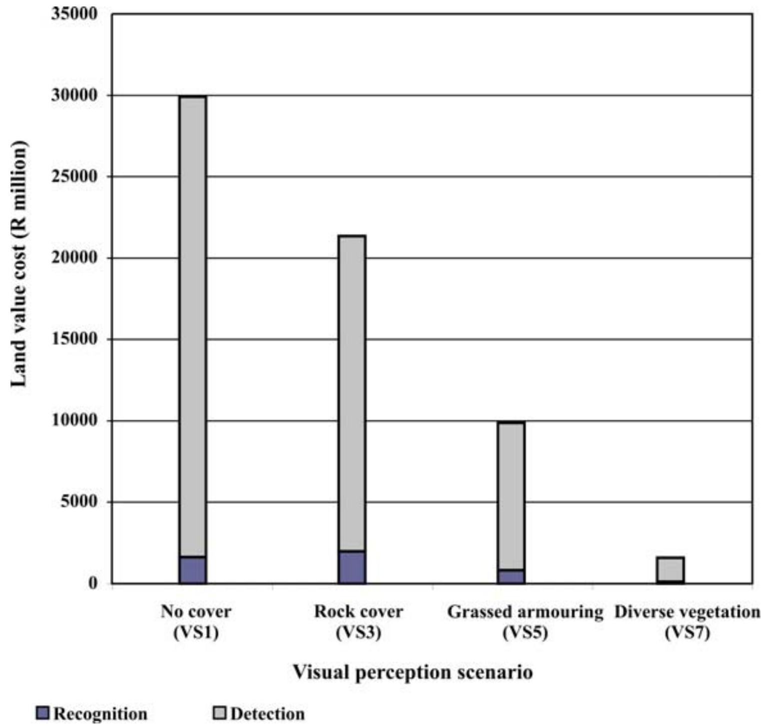


Figure 181: The potential total loss of property development value. The loss is the difference between high and medium cost residential property values within the visual impact zone.

The visual impact cost is indicative of the total change in land value over the entire area of visual influence. It is likely that the total cost will only be incurred over time as development is constrained as a result of the influence of the impoundment. The total visual impact cost has therefore been spread over a 20 year post-closure period which is the same as the time allowed in the engineering cost model for post-closure maintenance and management (Figure 182).

The development stage (design and construction) and the operation stage engineering costs are the same for the scenarios modelled and illustrated in this figure. The line between points A and C, which plots the costs, are therefore the same. There is a change in the engineering closure stage costs (lines between points C and D) depending on the type of cover. The lines between points D and E represent the integrated visual impact costs and engineering post-closure maintenance and management costs for the various cover types.

The high cost housing value in the visual perception recognition zone that will not be actualised are:

- R1,6 billion for the impoundment scenario without any cover (VS1);
- R1,9 billion for the rock cladding scenario;
- R800 million for the grassed armouring option; and
- R117 million for the impoundment scenario covered in diverse vegetation.

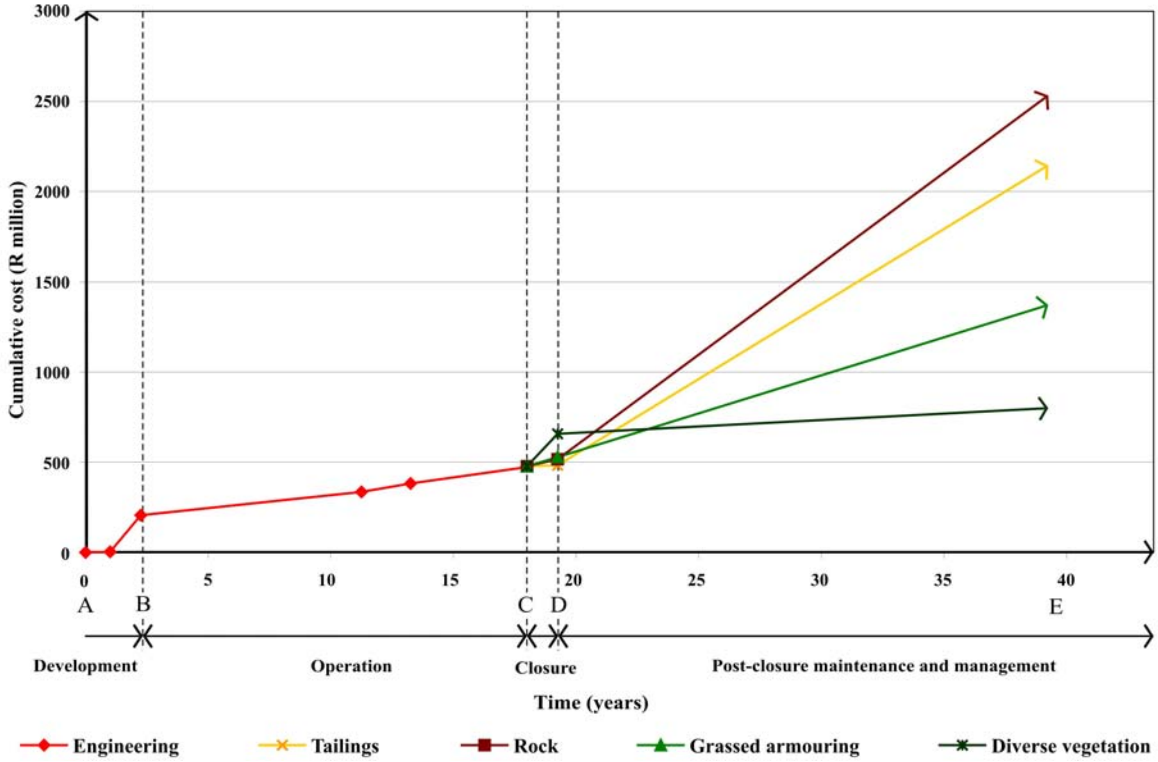


Figure 182: Potential visual impact life-cycle cost, spread over 20 years, resulting from the conflict in land use between the development of high cost residential property and the tailings impoundment within the visual perception impact zone.

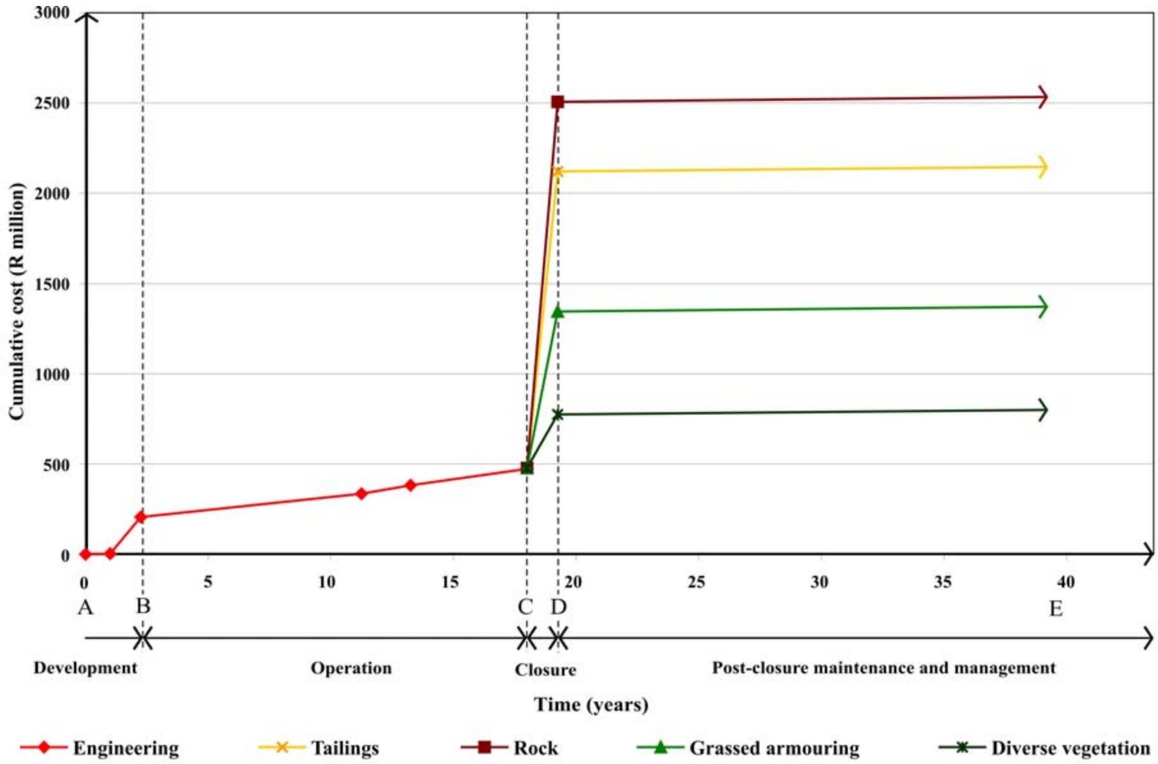


Figure 183: Potential visual impact life-cycle cost indicated as an event during closure resulting from the conflict in land use between the development of high cost residential property and the tailings impoundment within the visual perception impact zone.

The visual impact cost (loss of property value) can also be indicated as a once off event which may be the case where there is an immediate and total loss in land value resulting from the impoundment (Figure 182, p. 296).

Irrespective of the visual impact indicated as a once off event or spread over 20 years the potential sterilisation of high cost property development in the no cover recognition zone is fourteen times more than that of the diverse vegetation zone. The high cost property development sterilisation in the grassed armouring recognition zone is about half of that of the no cover scenario. A 50 % reduction on land value sterilised can therefore be achieved by covering the impoundment with a grassed armouring as apposed to doing nothing.

Sterilising land for game farming tourism potential

The following case study will illustrate the possible effect on the costing of property values if the ERGO Daggafontein impoundment was surrounded by game farms with tourism potential. The site is in the North West Province located immediately North of the Pilanesberg National Park (PNP). Mining North of the PNP could impact on several tourism initiatives one of which includes the establishment of a corridor linking the PNP and Madikwe Game Reserve. Figure 184 illustrates the proposed corridor initiative which has the potential to act as a catalyst for future investment.

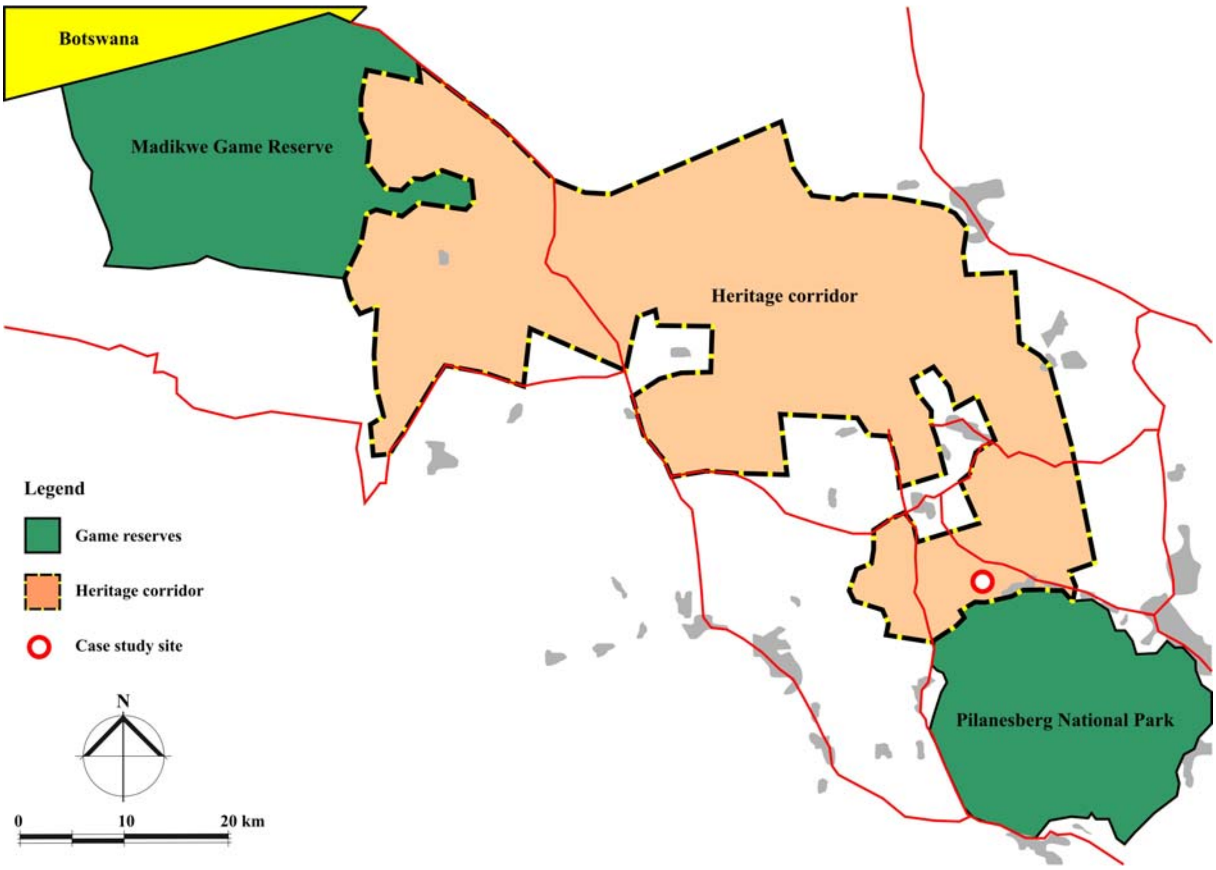


Figure 184: Proposed heritage corridor linking the Pilanesberg National Park with the Madikwe Game Reserve (SEF, 2002).

The potential for conflict between mining and conservation land use exists. After decommissioning and closure of a mine the tailings impoundment and rock dumps will remain which could result in a continued negative visual impact. The terrain is flat and depending on the impoundment configuration it could result in a significant visual zone of influence, comparable to that of the ERGO Daggafontein study site.

Because of the impoundment's locality in terms of tourism initiatives, it can be expected that the long term post-closure visual impact may be of greater concern than for example the potential impact on water. The reasons are that platinum tailings' chemical properties is less toxic than that of gold tailings, the site is underlain by soils which inhibit seepage, and water runoff can be effectively controlled by implementing standard practice engineering design principles.

Typical platinum tailings contain a mixed blend of approximately two thirds UG2 and one third Merensky ore. Extensive chemical analysis of various individual or mixed platinum tailings streams indicate that metal concentrations are generally low in the solid phase indicating that seepage pose a minor to insignificant risk to the environment. The liquid phase of the tailings slurry also generally show that metal concentrations to be low. However, salinity can impact on the soils, surface water and the groundwater. Platinum tailings generally classify as general waste material (SRK, 2003).

The conceptual design for the proposed tailings impoundment will need to:

- keep the post-closure visual detection perception zone of influence as small as possible, especially if the Pilanesberg National Park is to expand;
- allow for embankment slopes that can be ploughed, vegetated and mechanically maintained;
- keep the air quality zone of influence as small as possible; and
- integrate the impoundment, through proper slope and cover design, into the anticipated post-closure surrounding land use.

Potential sterilisation of land for use as game farming with tourism potential within the recognition and detection visual perception zones of influence are compared in Figure 185 and the costs in the recognition zone plotted in Figure 186. The cost is the difference in land value and is determined by subtracting the average value of agricultural grazing land (R8000) from the lowest value of land used for game farming with tourism potential (R25 000) (Table 71).

Table 71: Typical land values for agricultural and game farming land in the North West and Limpopo Provinces.

Province	District	Use	Area (ha)	Selling price (R)	Land value (R/ha)
North West	**Koster**	Agricultural grazing	216	1 480 000	6 852
	Bloemhof	Agricultural grazing	604	5 500 000	9 106
	Rustenburg	Game farming	200	5 000 000	25 000
	Zeerust	Game farming	30	1 500 000	50 000
Limpopo	**Naboomspruit**	Game farming	55	2 600 000	47 273
	Bela-Bela	Game farming	45	3 200 000	71 111
	Mabula	Game farming	340	40 000 000	117 647

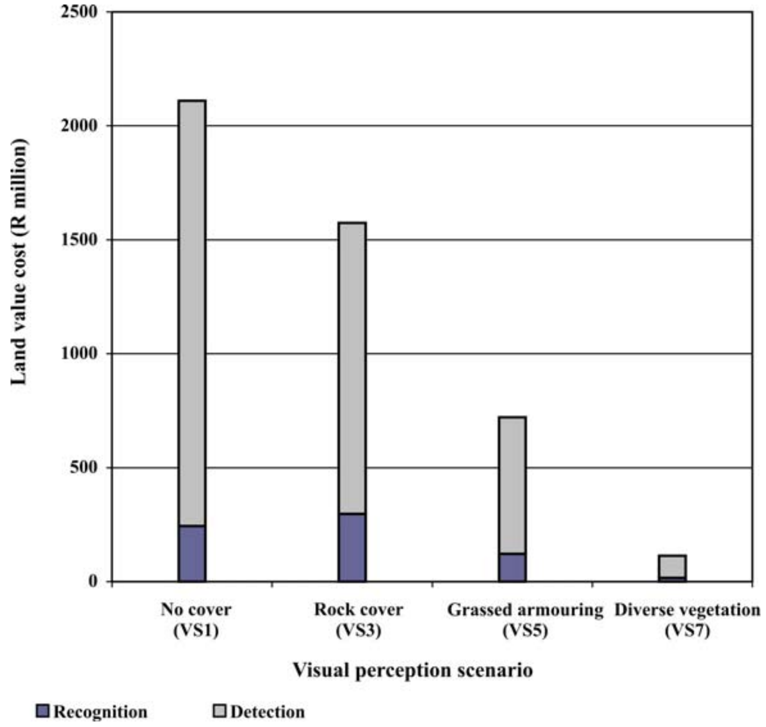


Figure 185: The potential total loss in game farming land value. The impact is the difference in values between game farming and typical farmland used for grazing within the tailings impoundment visual impact zone.

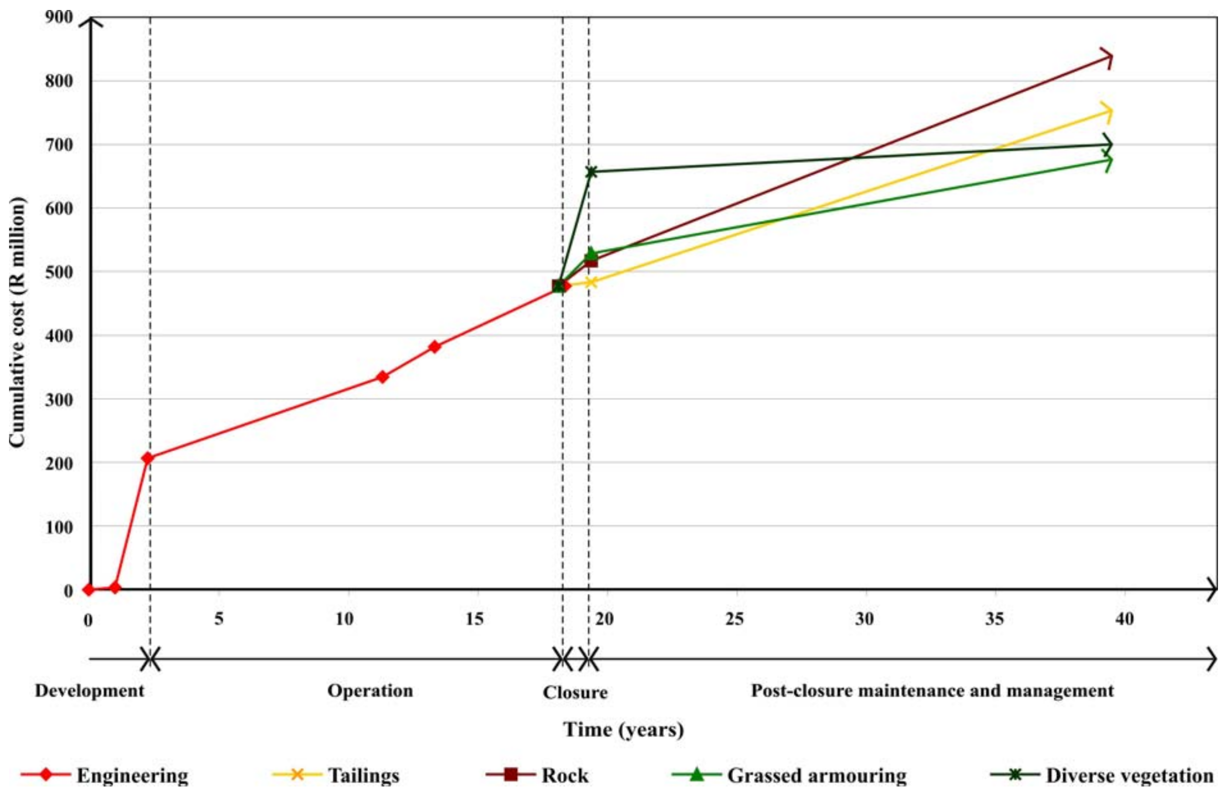


Figure 186: Potential visual impact life-cycle cost, spread over 20 years, resulting from the conflict in land use between the use of land for game farming with tourism potential and the tailings impoundment within the visual perception impact zone.

Similar to the previous discussion on high cost residential development, if the value of land had to be valuated for both the recognition and detection zones of influence the total cost will run into billions of Rands (Figure 185). Research will have to be undertaken to confirm the sensitivity of game farming land with a tourism potential within the detection zone of influence. However, for the purposes of this study it is assumed that there will be an incompatibility in the impoundment recognition visual perception zone of influence (Table 68, p. 290).

The difference in property value as agricultural grazing land and game farming with tourism potential is indicated in Figure 186. The figure divides the total cumulative cost of the visual impact post-closure over 20 years. By covering the impoundment with diverse vegetation (VS7) similar to that of the natural surroundings reduces the land value by R17 million whereas not covering the impoundment and leaving the tailings bare will result in a cost of R245 million. Grassed armouring (VS5) will reduce the value of land by R122 million and rock (VS3) by R297 million (VS3). Camouflaging the impoundment by using a diverse vegetative cover as the advantage that it can reduce the potential cost by up to seventeen times when compare to using rock and by fourteen times when compared to doing nothing. These are significant improvements in any terms.

6.2.2 Air

Until recently there has been little guidance about the calculation of the costs of air pollution and using these costs to evaluate alternative air pollution control strategies. Rational decision making requires quantification of impacts. Valuation of impacts is but one approach to quantify impacts. It does have certain advantages in that control technologies can be compared in monetary terms. This study describes a method to quantify costs and benefits as a result of changing the design of an impoundment.

The costs of implementing for argument a more expensive and rigorous cover which are aimed at reducing emissions can be offset by the reduction in health risk. The health risk cost must be factored into the total impoundment cost. The difference in the intervention cost and the subsequent health risk cost provides an indication of the true total cost related to the impoundment configuration choice. Valuating the air quality impact provides decision makers with the opportunity to test and compare different closure options in Rand terms using engineering costs and air quality costs.

Health impacts, as discussed in Section 2.11.5, will be used to cost the impact of impoundments on air quality as there is a clear cause and effect link. The causal sequence of air quality impacts is important. There must be a clear link between the source, emission, ambient levels, exposure, health outcomes, and finally the costing of the ill-health effects.

The following were determined and used to estimate the value associated with changes in air pollution as a result of the release of particulates released from an impoundment:

- Estimation of change in PM_{10} concentration. Emissions were estimated, dispersion modelled, and spatially mapped to determine the 25 $\mu g/m^3$ PM_{10} air quality influence zone.
- Determining the susceptible population.
- Applying dose-response relationships (respiratory hospital admissions dose-response relationship was used). Refer Section 2.11.5 for information on the valuation approach.
- Economic valuation of the health endpoint (costs associated with respiratory hospital admissions).

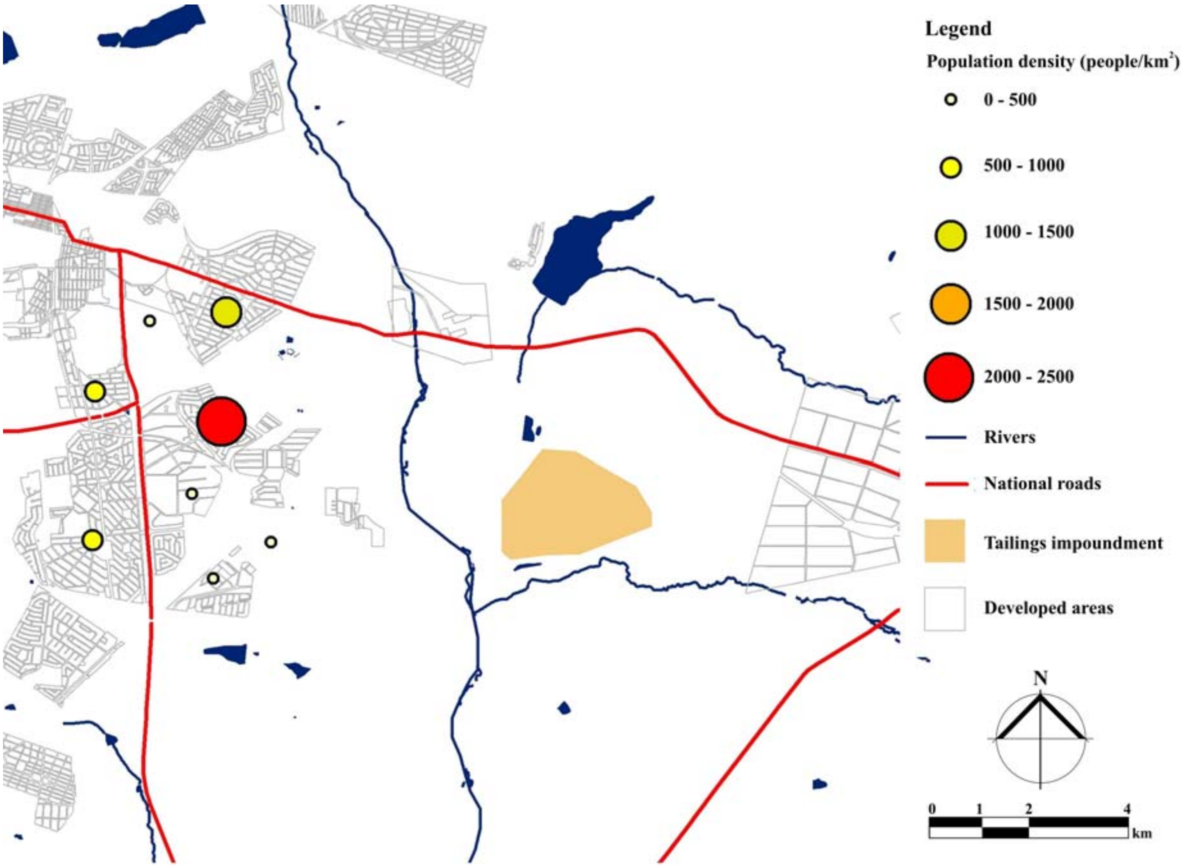


Figure 187: Population densities in the vicinity of the ERGO Daggafontein case study site.

The 25 µg/m³ PM_{10} and TSP air quality influence zones for the no cover (AS2), rock cladding (AS6), grassed armouring (AS10), and diverse vegetation cover (AS14) configurations are provided in Appendix B.1. One of the factors used in the dose-response relationship is information on the population at risk of health effect in the air quality influence zone. Applying the respiratory health effect costs (Table 12, p. 104) to different population densities for the covers modelled, annual costs can be estimated and are provided in Table 72 and Figure 188

Table 72: Potential health risk costs as a result of a 25 µg/m³ increase in PM_{10}. The costs reflect the change in population density within the influence zone.

	(R million/annum)					
Densities	**250 people/ha**	**80 people/ha**	**25 people/ha**	**15 people/ha**	**10 people/ha**	**5 people/ha**
AS2	163,0	52,2	16,3	9,8	6,5	3,3
AS6	0,0	0,0	0,0	0,0	0,0	0,0
AS10	102,2	32,7	10,2	6,1	4,1	2,0
AS14	2,2	0,7	0,2	0,1	0,1	0,0

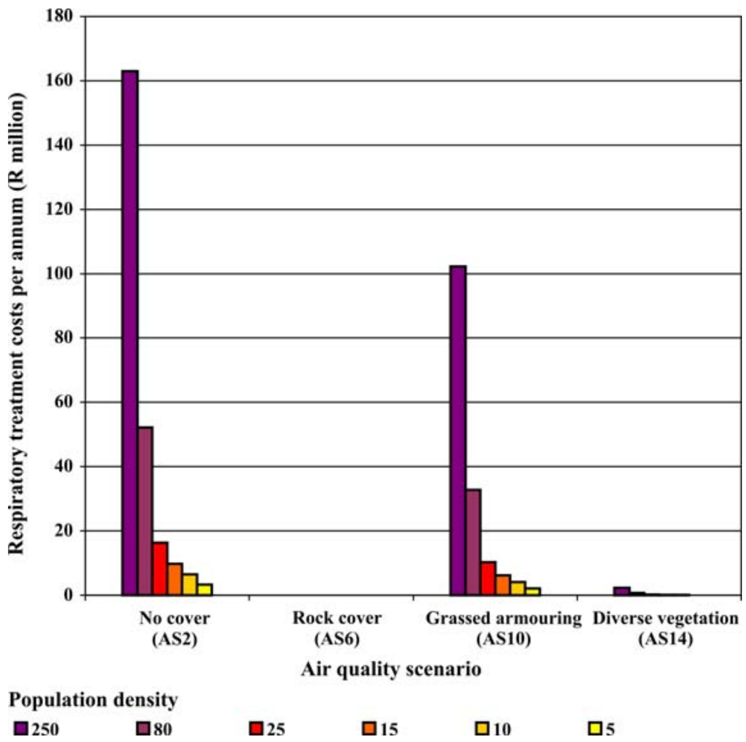


Figure 188: Indication of annual respiratory treatment costs for different population densities.

Figure 188 provides the costs per annum to treat patients suffering from respiratory ill-health effects and Figure 189 uses the same costs to indicate the cumulative effect over a period of 20 years after closure. Population density and area of influence significantly impact on the increase of air quality costs.

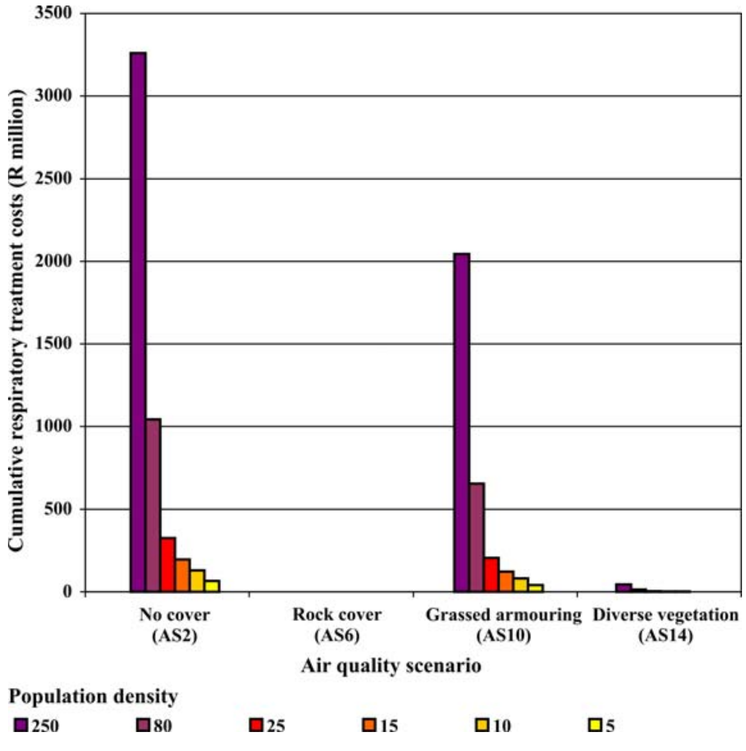


Figure 189: Total cumulative respiratory treatment costs over a 20 year post-closure period for various exposures.

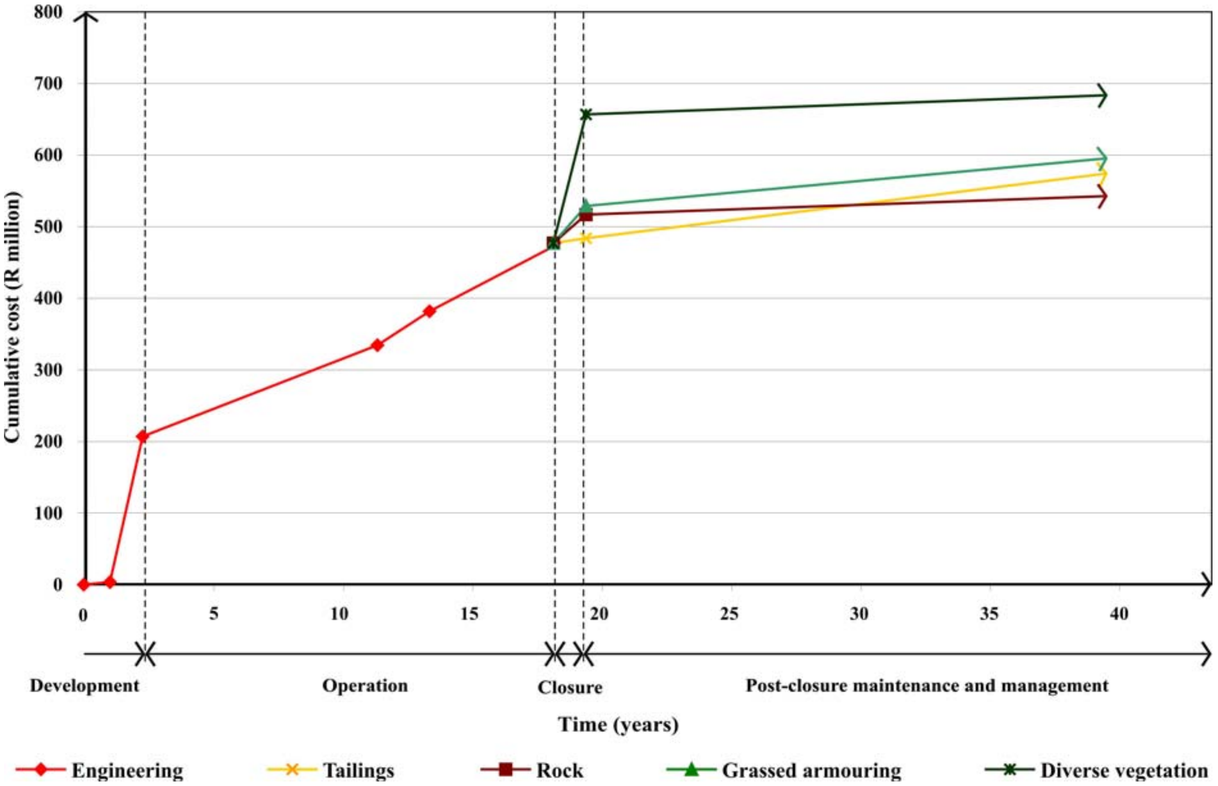


Figure 190: Integrating air quality life-cycle costs for 5 people/ha in the air quality zone of influence with the engineering costs.

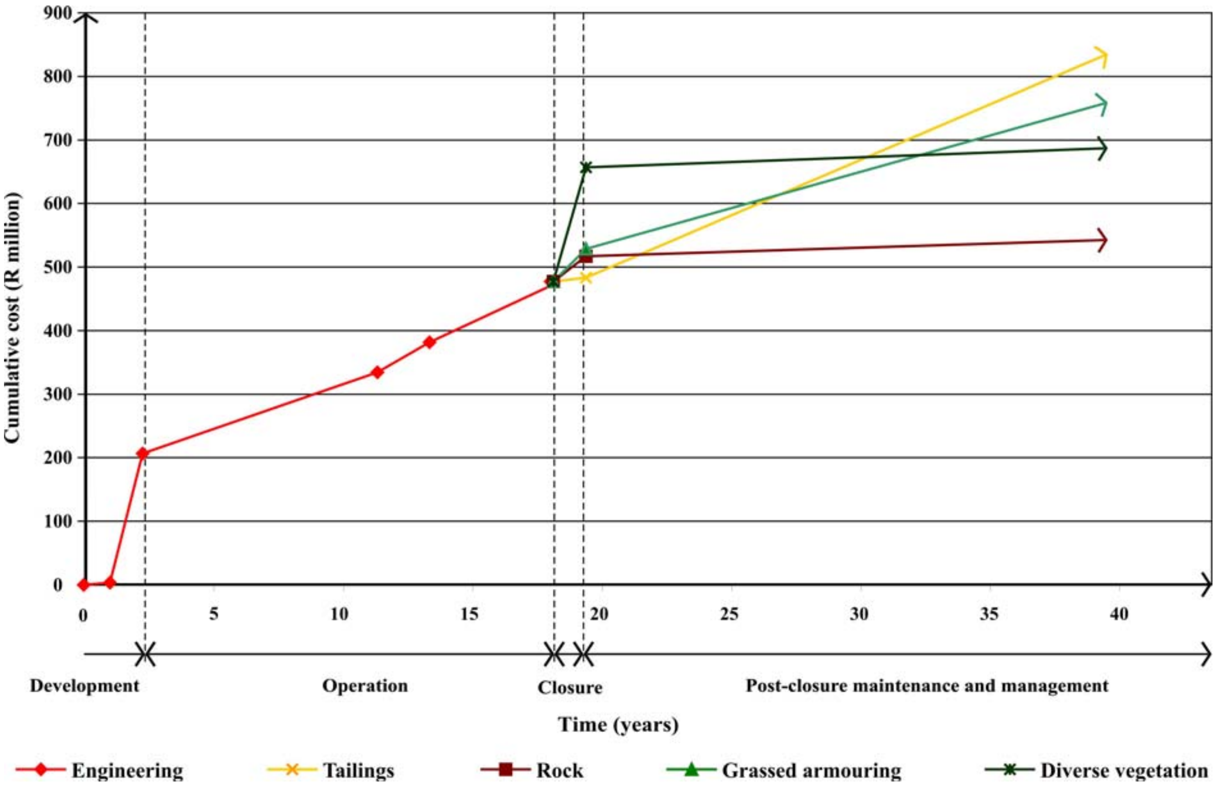


Figure 191: Integrating air quality life-cycle costs for 25 people/ha in the air quality zone of influence with the engineering costs.

The development stage (design and construction) and the operation stage engineering costs are the same for the scenarios modelled and illustrated in Figure 190 and Figure 191. Depending on the choice in cover the engineering closure stage costs change accordingly. The lines representing the post-closure stage include the air quality impact costs and engineering post-closure maintenance and management costs.

The current estimates of costs and benefits for changing an impoundment's configuration are based on broad averages and fairly simple assumptions. However, the examples used illustrate how engineering design decisions can change the 25 $\mu g/m^3$ PM_{10} influence zone which in turn translate into respiratory hospital admissions used to valuate the impact. These estimates provide the basis for comparing the various impoundment scenarios modelled.

When comparing the plots of cost over time for the 5 and 25 people per hectare densities it demonstrates to what extent the system is sensitive to the change in population density. It is therefore important to try and keep the exposure in the influence zone as low as possible or reduce the zone of influence. The zone of influence is important and can be readily dealt with by looking at the additional engineering costs for the cover types and choosing a cover type which, depending on the exposure, presents the best option.

There is still a great deal of uncertainty and controversy over valuating air quality costs. Recognizing this uncertainty the costs provided indicate a likely estimate of what would probably fall within a range with a lower and upper bound. In addition, the use of costs related to respiratory health admissions is only one of many health effects suspected of being associated with PM_{10}. Particulates blown from an impoundment is likely to be associated with non-health effects such as materials damage, soiling, vegetation losses and visibility degradation. These costs have not been included in this estimation and are therefore considered to be an underestimation of actual costs associated with exposure to PM_{10} for the impoundment scenarios modelled. The valuation does however provide an initial basis for assessing the potential which exists for offsetting the costs of implementing management measures aimed at reducing air pollution concentrations.

6.2.3 Water

Section 2.12.15 discusses various sulphate removal technologies and Section 2.12.16 provides information on the costs to treat water using the different technologies. The decision to use a specific technology will depend on cost and the need to meet some sort of water quality objective. Table 73 and Figure 192 compare the costs for the configurations modelled to remove sulphates using different technologies. It was assumed for this study that the slaked lime process will suffice. The total cumulative cost during the post-closure stage is illustrated in Figure 193.

The cost to treat the discharge for the various configurations are R34 million (WS2), R42 million (WS6), R30 million (WS10), and R22 million (WS14) for the no cover, rock, grassed armouring, and diverse vegetation covers respectively. The membrane desalination process is the most expensive and costs almost four times that of the slaked lime process to remove the sulphates released by the tailings impoundment. The biological process is about 3,4 times more expensive than that of the slaked lime process.

Table 73: Comparison of annual sulphate removal costs of various treatment technologies.

		Scenario cost (R million)			
Treatment process	**Cost item**	**WS2**	**WS6**	**WS10**	**WS14**
Limestone	Capital cost	0,45	0,55	0,39	0,29
	Running cost	16,91	20,53	14,49	10,87
	Total cumulative cost	17,36	21,08	14,88	11,16
Slaked lime	Capital cost	4,34	5,27	3,72	2,79
	Running cost	30,14	36,60	25,84	19,38
	Total cumulative cost	34,48	41,87	29,56	22,17
Biological	Capital cost	23,48	28,52	20,13	15,10
	Running cost	110,28	133,91	94,52	70,89
	Total cumulative cost	133,76	162,42	114,65	85,99
Membrane based	Capital cost	25,53	31,00	21,88	16,41
	Running cost	91,90	111,59	78,77	59,08
	Total cumulative cost	117,42	142,59	100,65	75,49

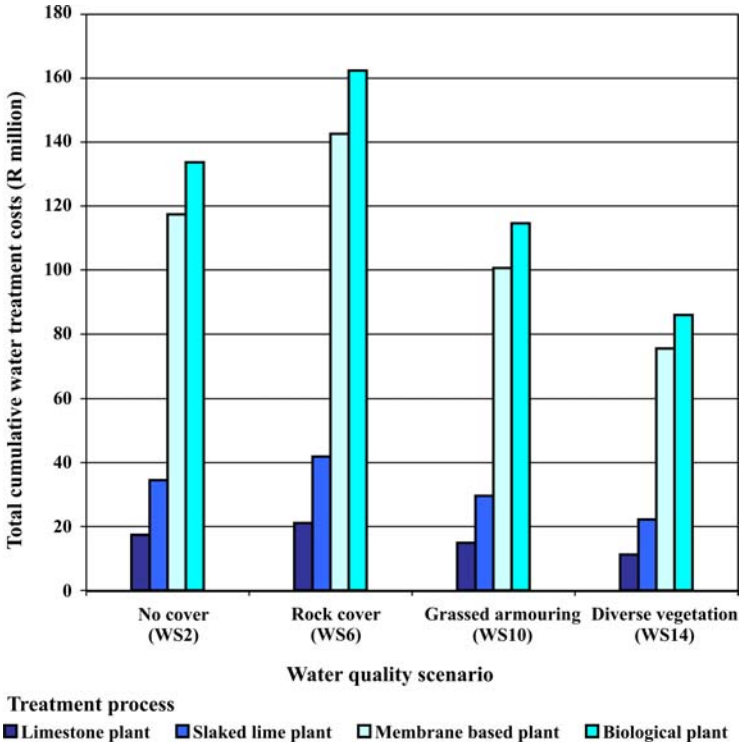


Figure 192: The column chart compares the cumulative water treatment costs for different treatment technologies.

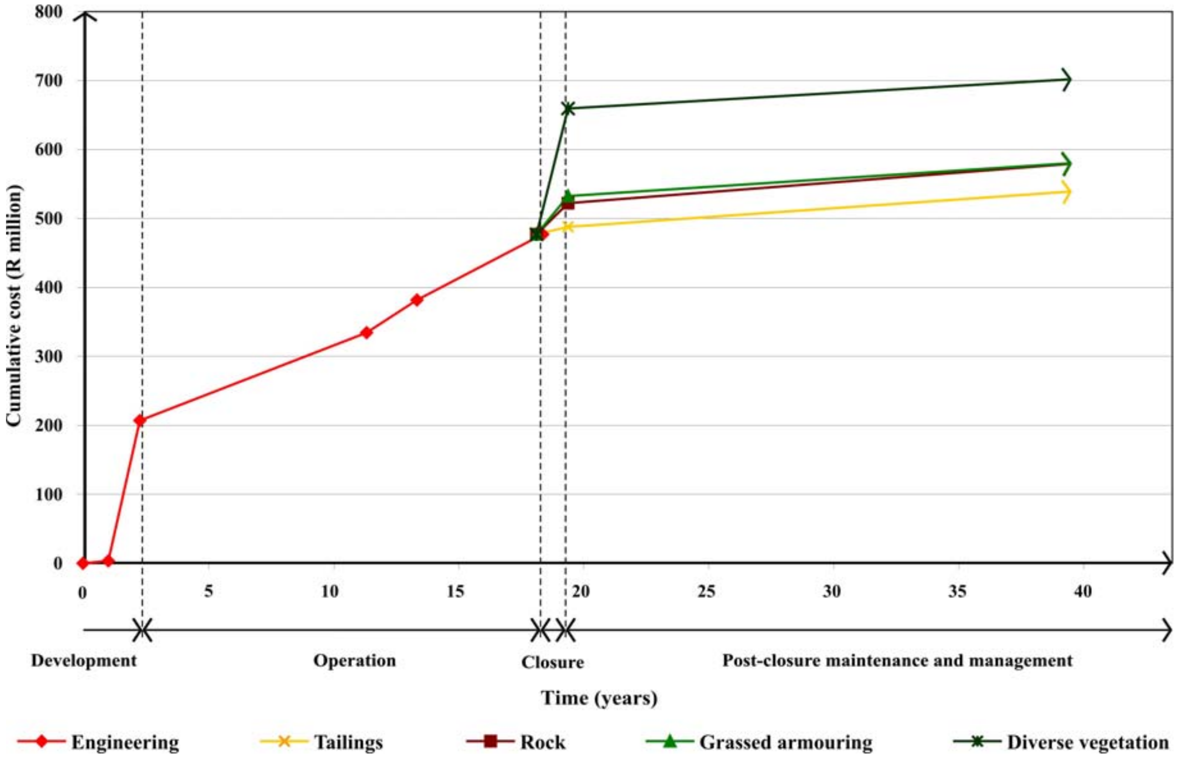


Figure 193: Impoundment life-cycle costs for various covers integrating the engineering and water treatment costs using the slaked lime process.

The development stage (design and construction) and the operation stage engineering costs are the same for the scenarios modelled in this part of the study (Figure 193). Depending on the choice in cover and the water treatment technology the closure stage costs change accordingly. The closure stage cost is the sum of the engineering cover construction cost and the water treatment plant capital (construction) cost. The lines representing the post-closure stage include the costs to treat and remove the sulphate load and the engineering post-closure maintenance and management costs.

6.3 Integrating environmental impact costs and engineering costs

Chapter 5 describes how environmental aspects can be combined with engineering costs. This section on the other hand has undertaken to integrate environmental impacts and engineering costs by ascribing costs to the environmental impacts.

The costing of environmental impacts has been accomplished through valuating quantifiable changes brought about by the influence of tailings impoundments on the environment. The preceding section of this chapter illustrates the valuation process for various tailings impoundment covers. Although this is in itself useful, the following section presents the integrated environmental aspect costs for the different cover types:

- no cover (tailings in situ);
- rock cladding;
- grassed armouring; and
- diverse vegetation

This study demonstrates how environmental impacts can be integrated with engineering design. At the onset of the research it was stated that the research will develop and describe a system which will integrate environmental impact costs and engineering costs using the same measure for comparison. The means of doing this is to quantify the environmental aspect impacts and evaluating their costs.

The cumulative life-cycle costs for the environmental impact costs and engineering cost of each scenario with an accompanying map presenting the spatial sphere of influence follows from page 308 to page 311. The environmental aspect influence zones are overlaid and synthesise spatial data graphically. Each cover can be compared and presented to decision makers communicating the costs and benefits associated with each impoundment configuration.

The last section of Chapter 6 sums the environmental aspects costs to provide a total environmental impact cost. The total environmental impacts costs can then be added to the engineering costs to provide the total integrated environmental impact and engineering cost for each cover type modelled. Comparisons can then be made between the total costs for the covers:

- no cover (tailings in situ);
- rock cladding;
- grassed armouring; and
- diverse vegetation.

No cover (tailings in situ)

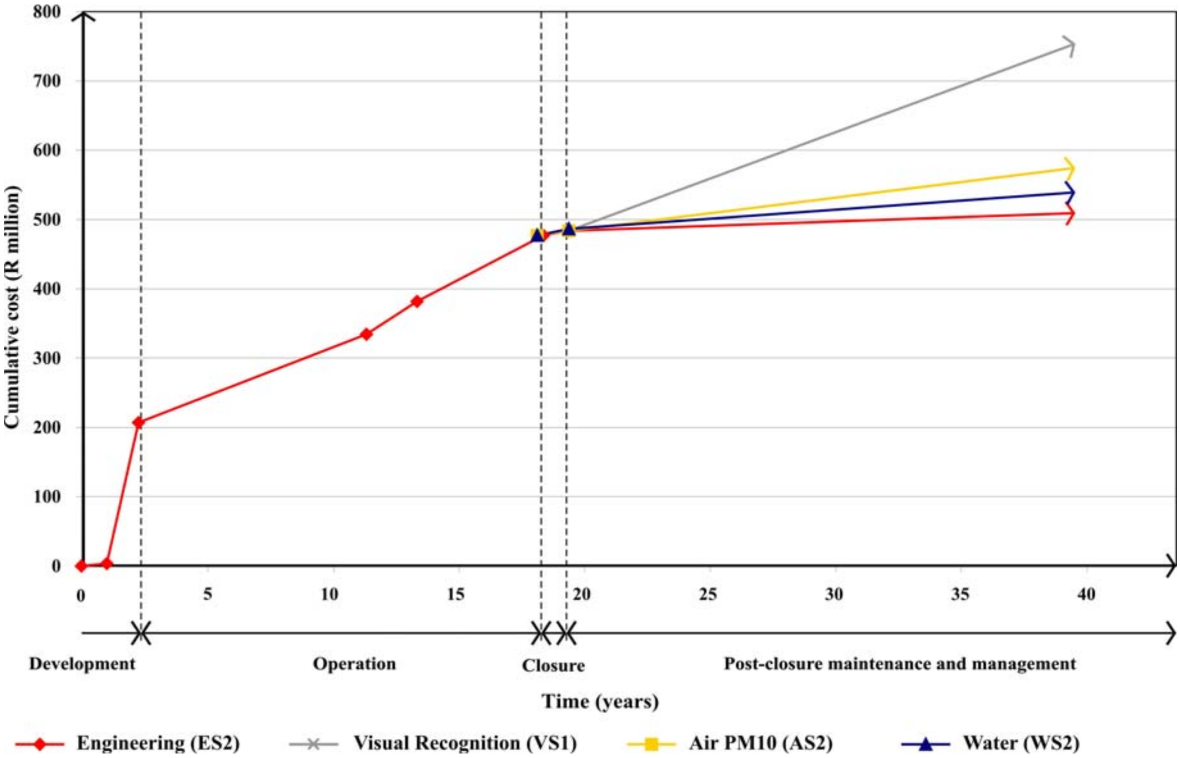


Figure 194: Total environmental and engineering costs for scenario without any cover.

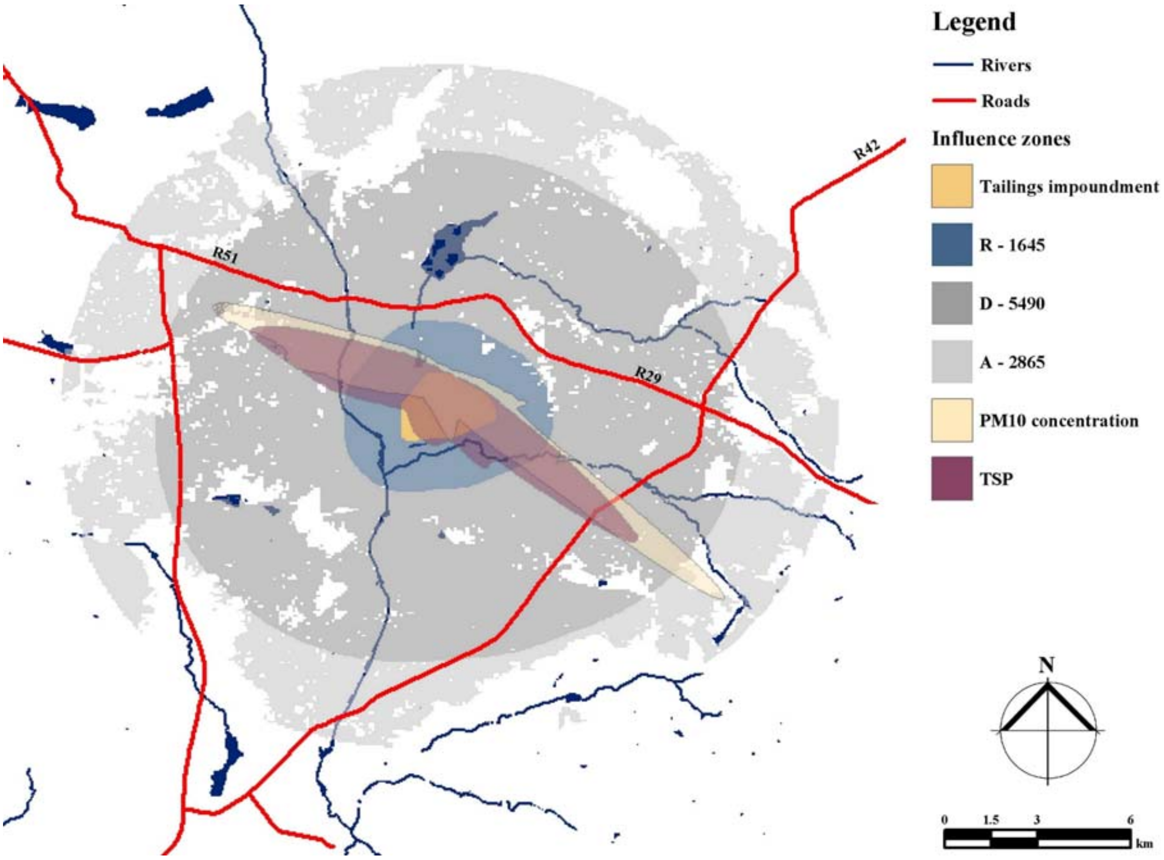


Figure 195: Sphere of influence for the impoundment scenario without any cover.

Rock cladding

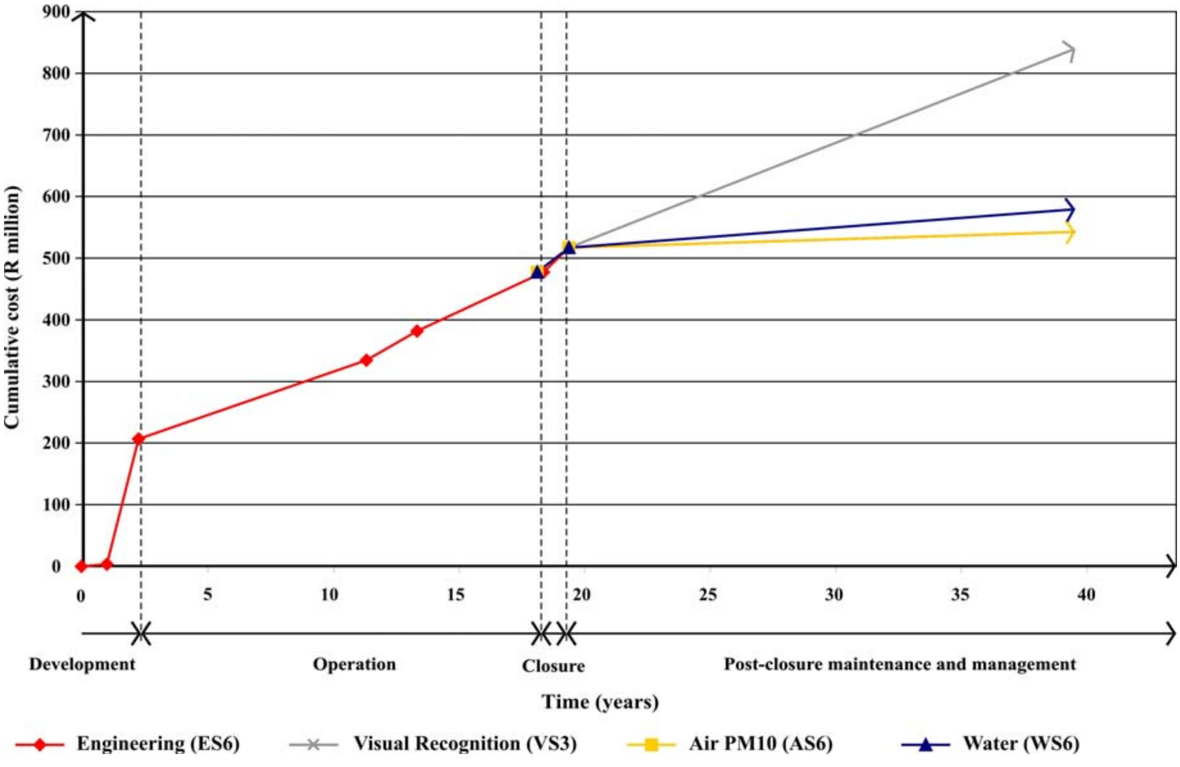


Figure 196: Total environmental and engineering costs for rock covered impoundment scenario.

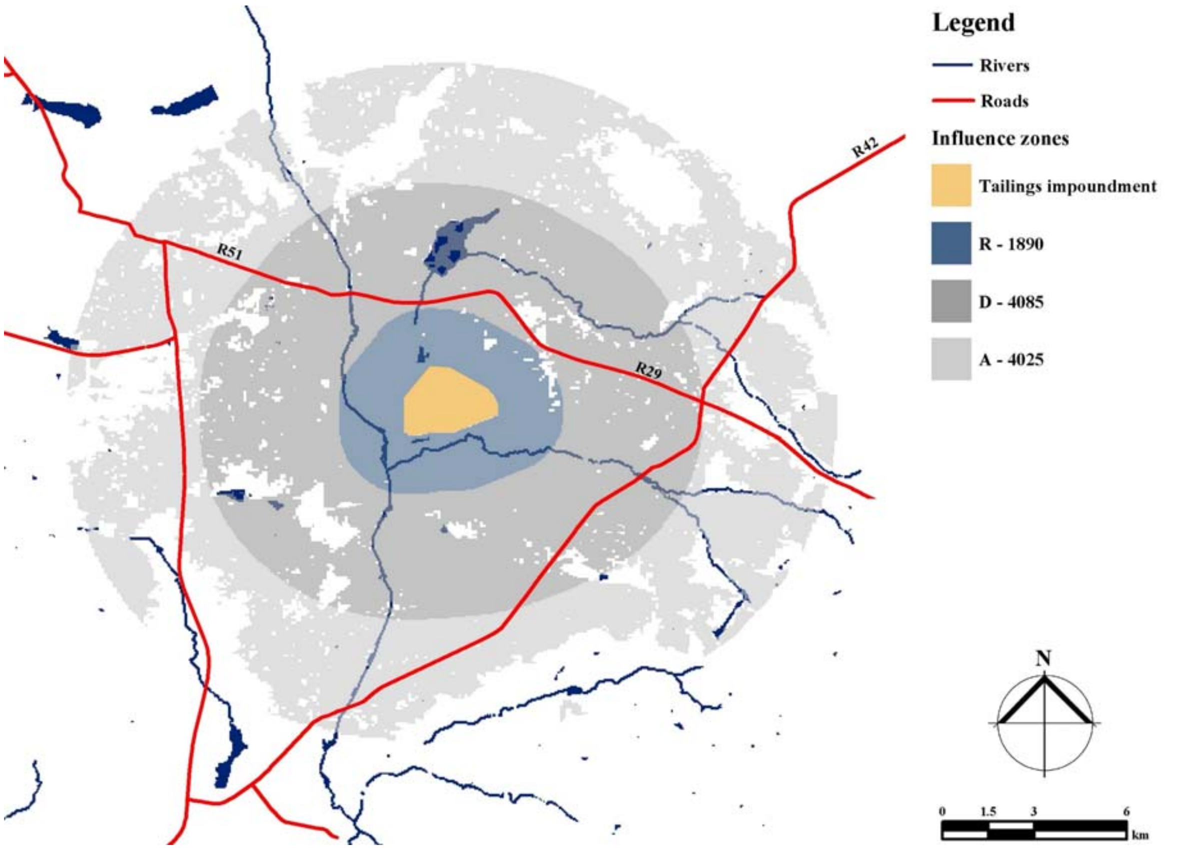


Figure 197: Sphere of influence for the impoundment scenario covered in rock.

Grassed armouring

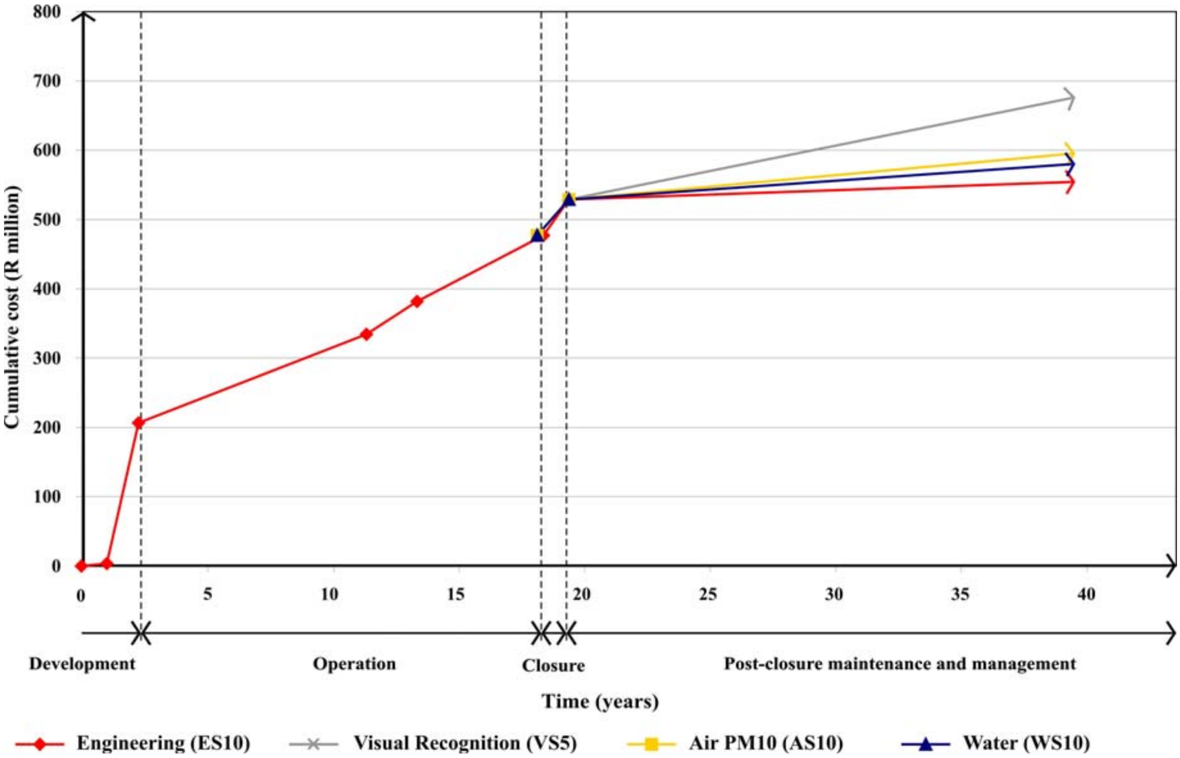


Figure 198: Total environmental and engineering costs for a grassed armouring.

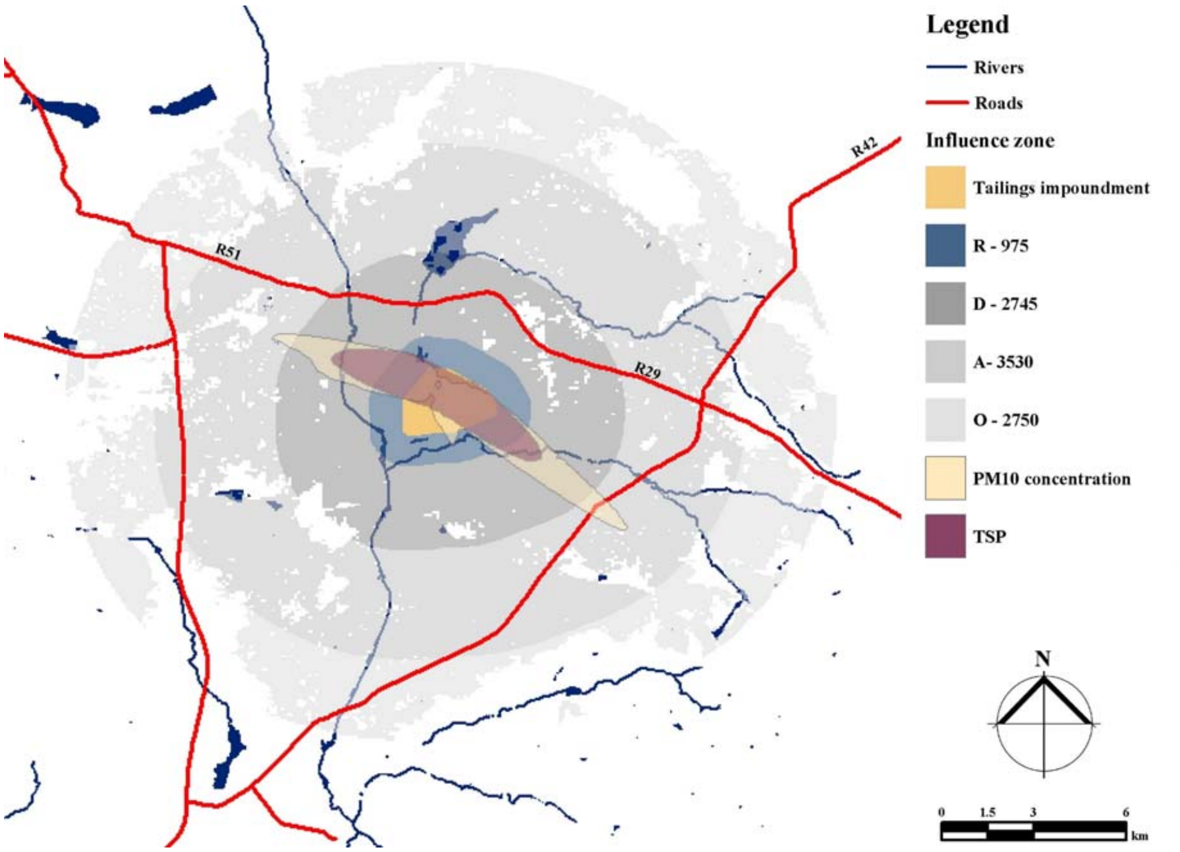


Figure 199: Sphere of influence for the impoundment scenario with a grassed armouring cover.

Diverse vegetative cover

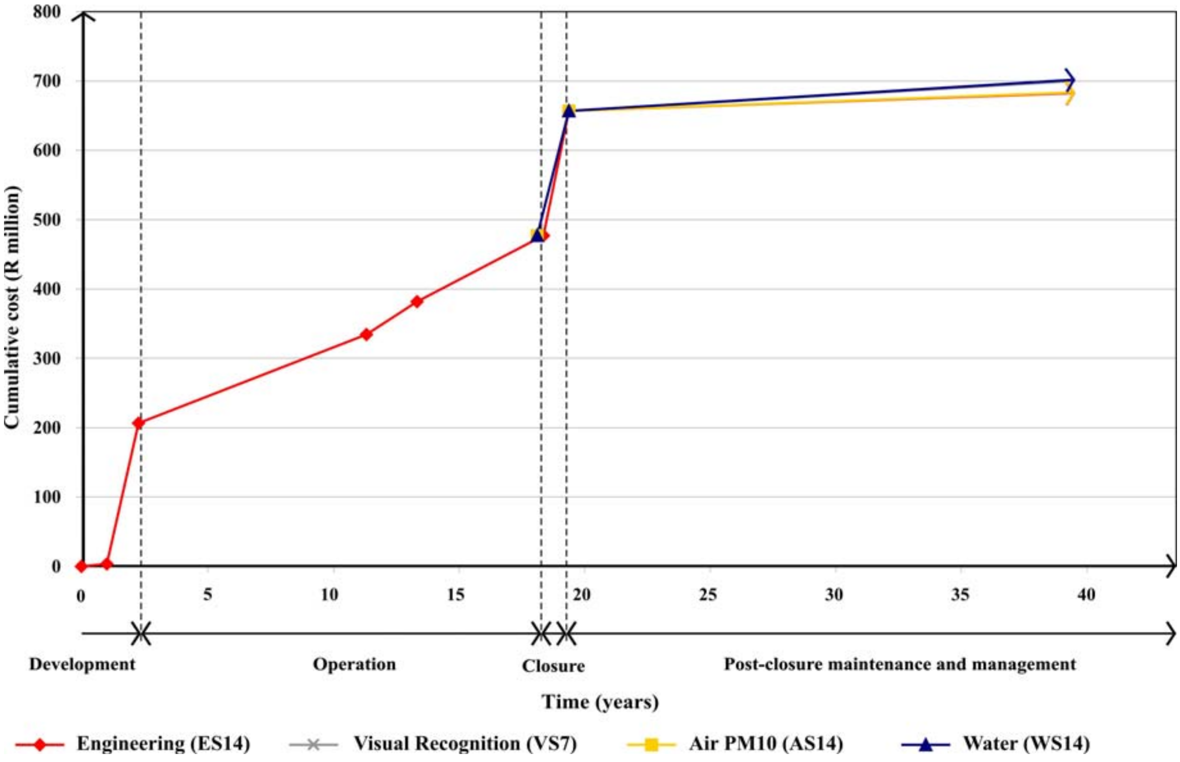


Figure 200: Total environmental and engineering costs for a diverse vegetative cover.

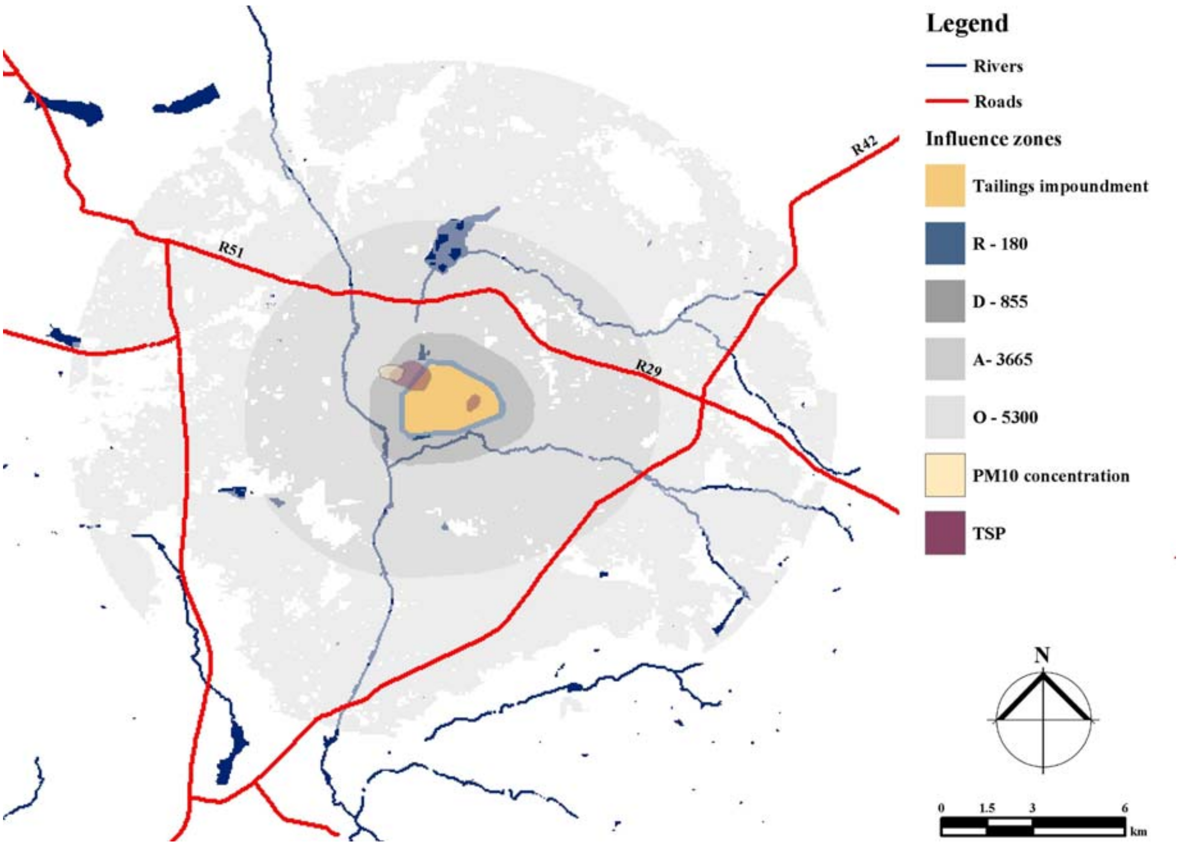


Figure 201: Sphere of influence for the impoundment scenario with a diverse vegetative cover.

6.4 Total integrated environmental impact costs and engineering costs

The total integrated cumulative environmental costs and engineering aspect costs for the configurations modelled are given in Table 74, Figure 202 and Figure 203 (p. 313). Figure 203 graphically illustrates the life-cycle integrated environmental and engineering costs for the different tailings impoundment cover types.

Table 74: Total integrated cumulative environmental and engineering aspect costs.

	Impoundment cover costs (R million)			
Cost item	**No cover**	**Rock**	**Grassed armouring**	**Diverse vegetation**
Total engineering cost	**509**	**543**	**555**	**683**
Construction and operation	477	477	477	477
Closure	6	40	52	180
Aftercare and maintenance	26	26	26	26
Total environmental cost	**344**	**339**	**193**	**40**
Visual recognition	245	297	122	17
Air PM_{10}	65	0	41	1
Water treatment SO_4	34	42	30	22
Total cost	**853**	**882**	**748**	**723**

The total engineering costs for the impoundment cover scenarios are R510 million (no cover), R545 million (rock), R555 million (grassed armouring), and R680 million (diverse vegetation). The engineering cost includes the costs for closure and standard practice maintenance. The total environmental costs for the same scenarios are R345 million (no cover), R340 million (rock), R190 million (grassed armouring), and R40 million (diverse vegetation) over the 20 year aftercare and maintenance period. It is interesting that although the initial diverse vegetation engineering cost is about R175 million more expensive than that of doing nothing, the total cumulative environmental cost after 20 years is almost R300 million less. The total environmental cost and engineering cost for this scenario over the life of the tailings impoundment is R130 million less than that of doing nothing. Similarly the grassed armouring may initially cost R45 million more than doing nothing at closure, but at the end of 39 years the total cost would be R110 million less than that of an impoundment with no cover.

By integrating the environmental aspect costs with the engineering aspect costs it is possible to make rational decisions as to the costs and benefits pertaining to post-closure land use and how the impoundment configuration is likely to impact on the environment over the life of the facility.

The comparative data for the various covers can be used to inform decision making pertaining to the configuration of tailings impoundments. Depending on the impoundment locality and the sensitivity of the receiving environment resources, decision makers can decide as to what alternative would least impact the environment and at what cost. It is not a given that the lowest total cost option may be the preferred option as a site may be located in a declared air quality management area which requires that no additional particulates can be released into the air as a result of the existing high ambient PM_{10} concentrations.

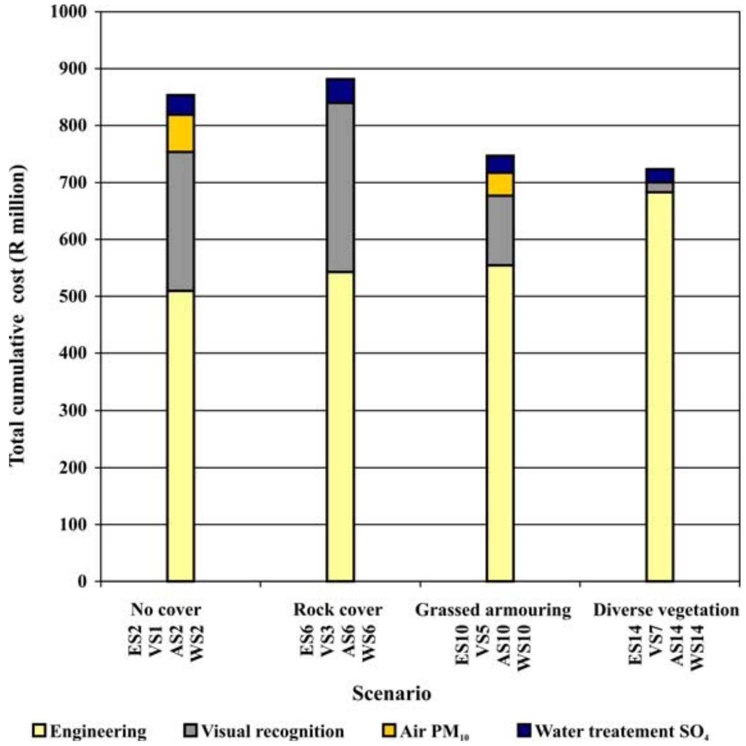


Figure 202: Total integrated cumulative costs for the various impoundment covers modelled.

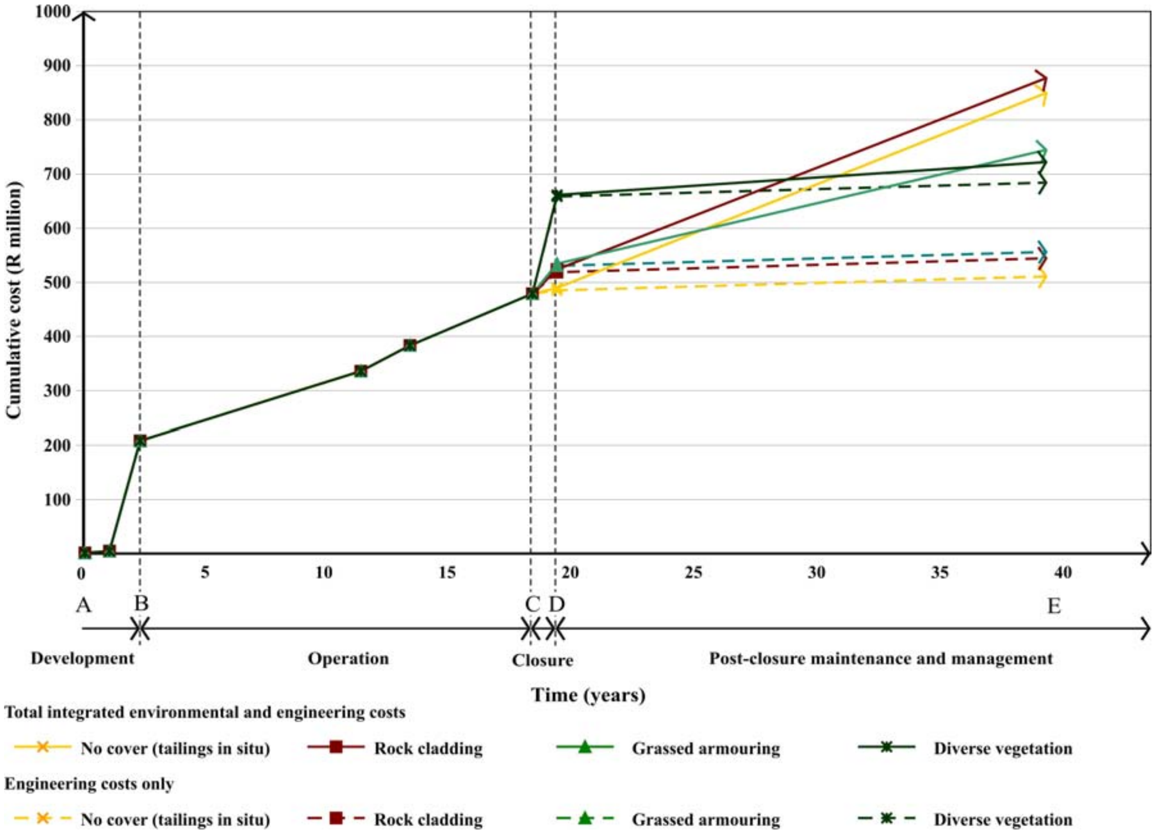


Figure 203: Total integrated environmental and engineering life-cycle costs for the different cover types modelled. The dashed lines indicate only the engineering costs whereas the solid lines are the total integrated environmental and engineering costs.

By covering the impoundment with rock it could probably be argued that post-closure dust will be effectively eliminated. This however comes at the highest total cost of R880 million. Similarly if an impoundment is in proximity to sensitive viewers such as discussed in the previous case study, it may be required to cover the impoundment with a diverse vegetation cover at an initial additional closure cost of R175 million but surprisingly at the lowest total cost of R720 million. The end result is that real environmental impact costs are added to the engineering costs for the closure and post-closure stages of the tailings dam development. This is illustrated by the following environmental and engineering cost model equation.

	Stage of tailings impoundment construction			
	Development[1]	**Deposition**	**Closure**	**Post-closure**
Engineering cost =	Eng cost AB +	Eng cost BC +	Eng cost CD +	Eng cost DE
Visual perception impact cost =	Eng cost AB +	Eng cost BC +	**VPI CD +**	**VPI DE**
Air quality impact cost =	Eng cost AB +	Eng cost BC +	**AQI cost CD +**	**AQI cost DE**
Water quality impact cost =	Eng cost AB +	Eng cost BC +	**WQI cost CD +**	**WQI cost DE**
Total cost AE =	Eng cost AB +	Eng cost BC +	**Total cost CD +**	**Total cost DE**

[1] Development is the term used for the design and initial construction.

The total costs associated with the tailings impoundment can be used in the overall financial feasibility of a new mine by using the costs in a parallel equation which evaluates all other impacts, both negative and positive.

The graphical nature of the spatial representation of the environmental aspects provides a useful tool to communicate the possible extent of the environmental sphere of influence. This can be used to inform future strategic land development objectives and it can be used to pre-empt possible areas of land use conflicts (Figure 204).

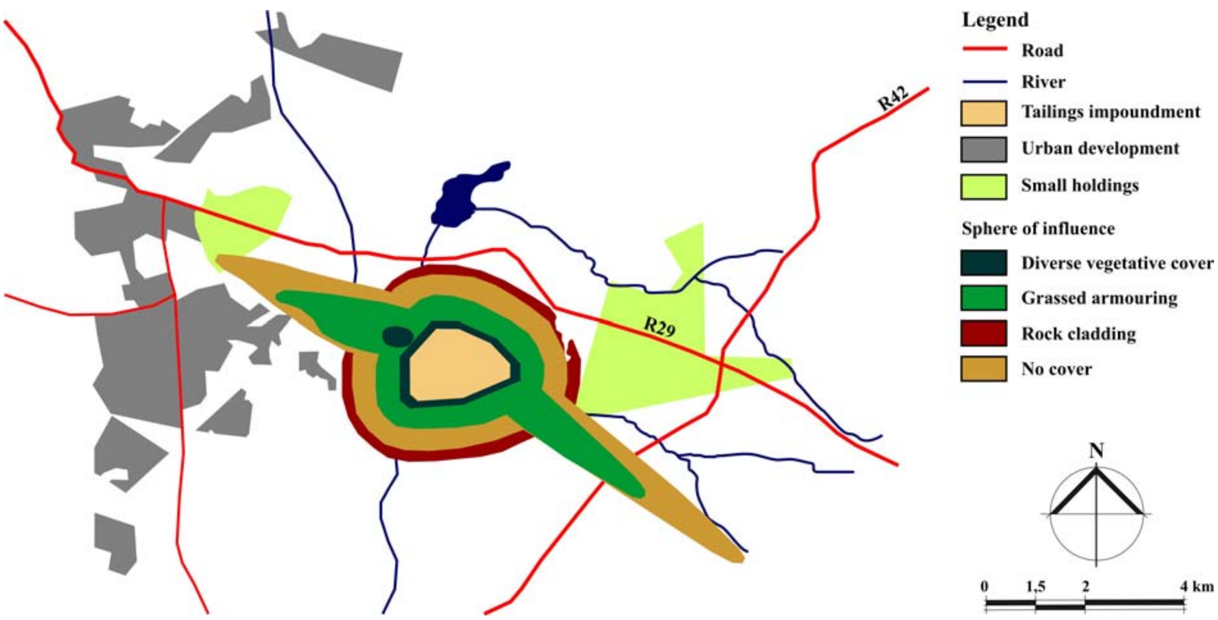


Figure 204: Combined visual perception and air quality environmental influence zones for the various impoundment covers modelled illustrating the change in possible impact zone as a result of change in impoundment design.

CHAPTER SEVEN: INFLUENCE OF ENVIRONMENTAL IMPACTS ON TAILINGS IMPOUNDMENT DESIGN - DISCUSSION

Tailings impoundment configuration requires you not to respond to immediate emotional impulses without considering the big rational picture. Stakeholders are told, "This tailings impoundment may cause water and air pollution even with the best controls [immediate emotions], but without it the economy of the whole region will collapse [big picture]." In terms of the old dichotomy, what is being said is, "Don't base your decisions on romantic surface appeal without considering the classical underlying form."

Inspired by Robert Prisig (Pirsig, 1999:235)

7.1 Introduction

The total environmental and engineering aspect costs for different tailings impoundment cover types are integrated in Chapter 6. The costs for the two main impoundment stage categories are summarised in Table 75 and graphically represented in Figure 205.

Table 75: Simplified total environmental and engineering costs for different impoundment cover types. The costs are grouped into two categories namely development and operation cost, and closure and post-closure costs.

	Stage of tailings impoundment construction		
Total environmental and engineering cost	**Development[1] and operation cost[2] (R million)**	**Closure and post-closure cost[3] (R million)**	**Total (R million)**
No cover cost	**477 +**	**376 =**	**853**
Rock cladding cost	**477 +**	**405 =**	**882**
Grassed armouring	**477 +**	**271 =**	**748**
Diverse vegetation	**477 +**	**246 =**	**723**

[1] Development is the term used for the design and initial construction.

[2] Development and operation cost is the term used for all the engineering cost prior to closure.

[3] Closure and post-closure cost is the term used for the environmental and engineering costs during and after closure.

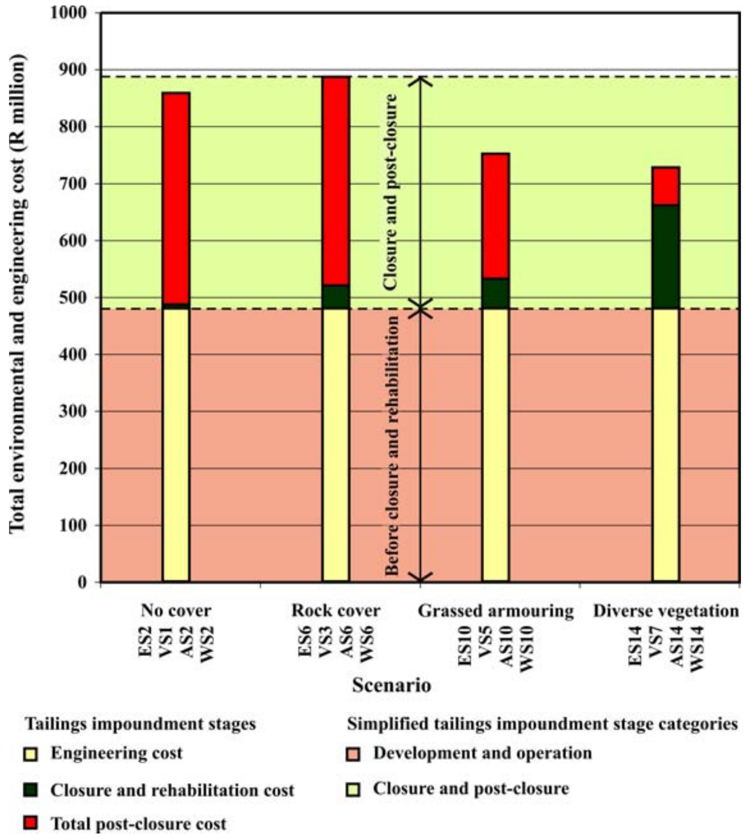


Figure 205: Simplified integrated environmental and engineering costs for different cover types.

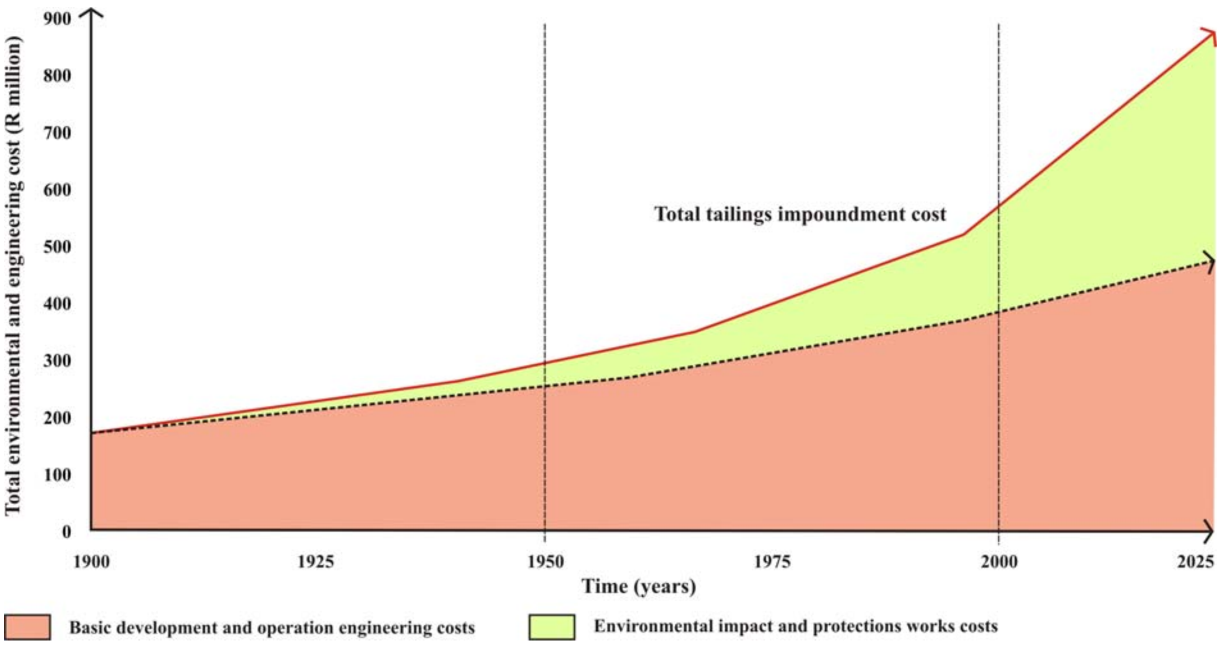


Figure 206: Schematic illustration of simplified environmental impact and basic engineering costs.

The total environmental and engineering costs for the cover types are:

- no cover (R850 million);
- rock cladding (R880 million);
- grassed armouring (R750 million); and
- diverse vegetation (R720 million).

The costs are grouped into the two categories to illustrate the potential change in total costs brought about by change in covers (Figure 205). The initial development and operation engineering costs are the same for the different covers since the volume, height and configuration of the impoundment remains constant.

By including the environmental costs in the cost estimation the closure and post-closure category costs are 45 % (No cover), 40 % (Rock cladding), 30 % (Grassed armouring), and 10 % (Diverse vegetation) of the total environmental and engineering costs.

Depending on the choice in cover (constructed during rehabilitation as part of the closure stage) a significant change in the closure and post-closure stage and the total environmental and engineering costs can be incurred. The environmental impact costs are therefore important in terms the overall costs for the construction of an impoundment. By choosing a diverse vegetation cover the costs can be reduced by R130 million when compared to leaving the impoundment in a state of disrepair (No cover). Similarly a grassed armouring cover can reduce the total costs by about R100 million when compared to not covering the impoundment.

Figure 206 (p. 316) illustrates the apportionment of environmental impact costs and basic engineering costs for the results presented in Figure 205 (p. 316). The figure is also used to illustrate the concept that the total tailings impoundment development cost is made up of two category costs namely the environmental protection costs and basic construction costs. These costs can now be quantified by using the costing system described in this thesis.

7.2 Decision-making system

Because decision making regarding the acceptability of the sustainable configuration of a tailings impoundment is a complex task it is important that approaches have to be developed and expanded in order to facilitate transparent decision making amongst the relevant stakeholders. Any given approach or method used to provide input into the decision-making process needs to keep a holistic perspective of sustainability during the key stages of development and must address biophysical, socio-cultural and economic aspects as well as specific related criteria to facilitate "holistic" judgment (Rademeyer et al., 2007).

The environmental and engineering costing system described is generic in nature and although developed for upstream ring-dyke metalliferous impoundments can be expanded to other types of waste disposal problems. Almost all decisions are unique in character, controlling variables and the preferred solution and ought to be specifically developed for other applications. The system although simplistic provides structure to important considerations and questions.

It is essential to understand the process by which environmental engineers derive at a decision, hence the requirement for a detailed methodology for making sense of the decision-making process. The configuration of a tailings impoundment is a multi-dimensional and -objective decision process using computer support to model some of the environmental aspect influence changes resulting from changes in impoundment configuration. The manipulation of data, retrieval and display of results has a remarkable impact on how decision makers reach consensus on outcomes. It was the intent of this study to exploit the available decision-making tools and models to facilitate innovative and effective decision making. It has been found that some of the tools are easy to use providing quick results while others require in-depth specialist knowledge. The system facilitates rational decision making and uses computer-based support tools and models to integrate environmental impact costs and engineering costs for various impoundment configurations.

This study provides decision makers with:

- a system to quantify and compare environmental impacts; and
- a demonstration of how models and tools can be used to provide environmental practitioners with support.

The system developed and described is useful and involves the following characteristics:

- large amounts of data are assessed to make conceptual use of it;
- it was necessary to quantify key environmental aspect impacts in order to arrive at a solution; and
- the approach can provide input into the DSS framework developed for the WRC (Rademeyer et al., 2007).

Important to note is that the process described allows decision makers such as specialists, professional planners and researchers to draw on analytical and decision-support tools helping with, although not resolving, complex decision problems. The approach does not make decisions but provides information that facilitates informed decision making.

7.3 Valuation of environmental impacts

Similar to the Multiple Accounts Analysis (MAA) method of analysis as discussed in Section 2.9.3 the approach presented in this thesis also relies on the assigning of values to impacts in order to evaluate the potential impact on the environment as a result of change in tailings impoundment configuration. MAA is typically used to compare alternatives with each other such as comparing alternative sites for a new tailings impoundment or to evaluate rehabilitation alternatives for a mine that needs to close. It is a tool and involves three basic steps:

- identify the impacts;
- quantify the impacts; and
- assess and compare the alternatives.

MAA is in essence a value-based analysis whereby numerical values to indicators are assigned using ranking and scaling techniques. Details of the method and framework are provided in Section 2.9.3. The assessment and comparison of the alternative configurations discussed in this thesis is done by valuating the impacts, i.e. assigning costs to the impacts. This is useful as it provides decision makers with a rational and transparent method to assess the costs of each alternative. The approach demonstrates how the impacts on visual perception, air quality, and water quality can be quantified and valuated.

The context of the three environmental aspects included in the environmental and engineering costing system is provided by Figure 38 (p. 65) which simplistically groups environmental aspects into socio-cultural, biophysical and economic elements. The configurations modelled were ranked by, for example, modelling the visual perception zones of influence for each alternative and presenting the information graphically on a comparative plot (Figure 164, p. 272).

The plots for all the environmental aspects modelled were overlaid and presented on a comparative plot (Figure 169, p. 276) which was used to compare the various configurations with each other. Philosophically this is no different than ranking and scaling the environmental aspects for each alternative. The weighting of each alternative takes place when the environmental aspects are valuated. The total cost of an alternative configuration is determined by the sum of the valuated environmental aspects. The configuration (slope or cover choice) is less favourable the higher the total environmental costs are.

The systems does not include all of the environmental aspects listed in Figure 38 (p. 65) as it was decided that it is more important to create a robust system which can be expanded with time by including other environmental aspects such as the impact on heritage, tourism, the living environment, and land capability and production.

Change in productivity and impact on land capability by the take of land (permanent loss of land) under the footprint of an impoundment may be important in certain instances such as where the land is used for the production of crops. The following example illustrates how such impact costs can be calculated and depending on the relative importance of the environmental cost can be incorporated into the overall system. The ERGO Daggafontein site is used to illustrate the potential loss in productivity as a result of the take of land.

Change in productivity

An impoundment can influence the productivity of other systems. The valuation can be straightforward if the change in production can be quantified and market prices are available. For example if the effect of increased dust fallout on the production of crops is known, the loss in yield could be calculated. The monetary value of the changed yield is attributable to the tailings impoundment and hence an economic cost of the project. The loss in production must have an assessable market value. Because the lower production is accompanied by lower costs of production, the change in net benefits yields the net impact of the externality. One of the objective valuation approaches (Table 5, p. 67 and Figure 39, p. 69) can be used to cost change in production and will be illustrated with an example.

The change in production approach can be used to assess the impact as a result of increased dust fallout and the loss of land. However, this economic impact is not illustrated. On the other hand, the loss in production as a result of permanent loss of land under the footprint of the tailings impoundment can be calculated. Depending on the post-closure impoundment configuration (Figure 64, p. 135) a permanent loss of land can be anticipated resulting in the production loss of crops such as maize, sorghum, soya bean and sunflower sorghum. The average yield per annum, price per tonne and potential production for these cash crops are provided in Table 76.

Table 76: Average yields and prices for cash crops (van Rooyen, 2006).

	Maize			Sorghum		
	Yield (t/ha)	Average Safex price (R/t)	Potential yield (R/ha)	Yield (t/ha)	Average producer price (R/t)	Potential yield (R/ha)
2003	3,06	1004	3072	2,80	1450	4060
2004	3,15	919	2895	2,90	900	2610
2005	3,85	682	2626	3,00	450	1350
2006	3,64	1190	4332	2,90	1010	2929
Average	3,43	949	3231	2,90	953	2737

	Soya bean			Sunflower		
	Yield (t/ha)	Average Safex price (R/t)	Potential yield (R/ha)	Yield (t/ha)	Average producer price (R/t)	Potential yield (R/ha)
2003	1,18	2250	2655	1,38	1974	2724
2004	1,61	1850	2979	1,23	2185	2688
2005	1,75	1497	2620	1,34	1828	2450
2006	1,74	1596	2777	1,28	2145	2746
Average	1,57	1798	2758	1,31	2033	2652

Between 300 ha and 400 ha, depending on the impoundment overall embankment slope, could be permanently lost under the footprint of the tailings impoundment. The ERGO Daggafontein impoundment is located on land which was previously used for grazing and the cultivation of crops. For the purpose of this illustration it is assumed that all of the land under the foot print of the impoundment is suitable for the cultivation of cash crops.

Table 77: Potential loss in production due to the permanent loss of land under the impoundment.

		Potential loss in production (R/annum)			
Overall embankment slope (°)	**Footprint (ha)**	**Maize**	**Sorghum**	**Soya bean**	**Sunflower**
1:1,5	305	990 000	830 000	840 000	810 000
1:3	320	1 030 000	880 000	880 000	850 000
1:6	360	1 160 000	980 000	990 000	950 000
1:9	400	1 290 000	1 090 000	1 100 000	1 060 000

Figure 207 (p. 321) maps the land uses around the ERGO Daggafontein tailings impoundment. The main land uses consist of industry, residential, small holdings and agriculture. The agricultural land can be further sub-divided into cultivated lands, grazing, wilderness land, and wetlands and water bodies. Depending on the cash crop and if it is assumed that the area cultivated only yields one crop per annum, the potential loss in production loss could be between R2 600 and R3 300 per hectare.

The impoundment configuration with the steepest embankment slope (1:1,5) will result in a land loss of 304 ha and the flattest scenario (1:9) will require 396 ha. The difference in production loss can be as little as R800 000 and as much as R1,3 million per annum. The difference in the steepest and flattest embankment configuration for maize is almost R300 000 per annum which is close to a 30 % annual loss in production. The loss in productivity costs due the construction of the tailings impoundment can be used to help assess the costs and benefits of the impoundment in terms of the total mining costs and benefits as well as for the various impoundment configuration alternatives.

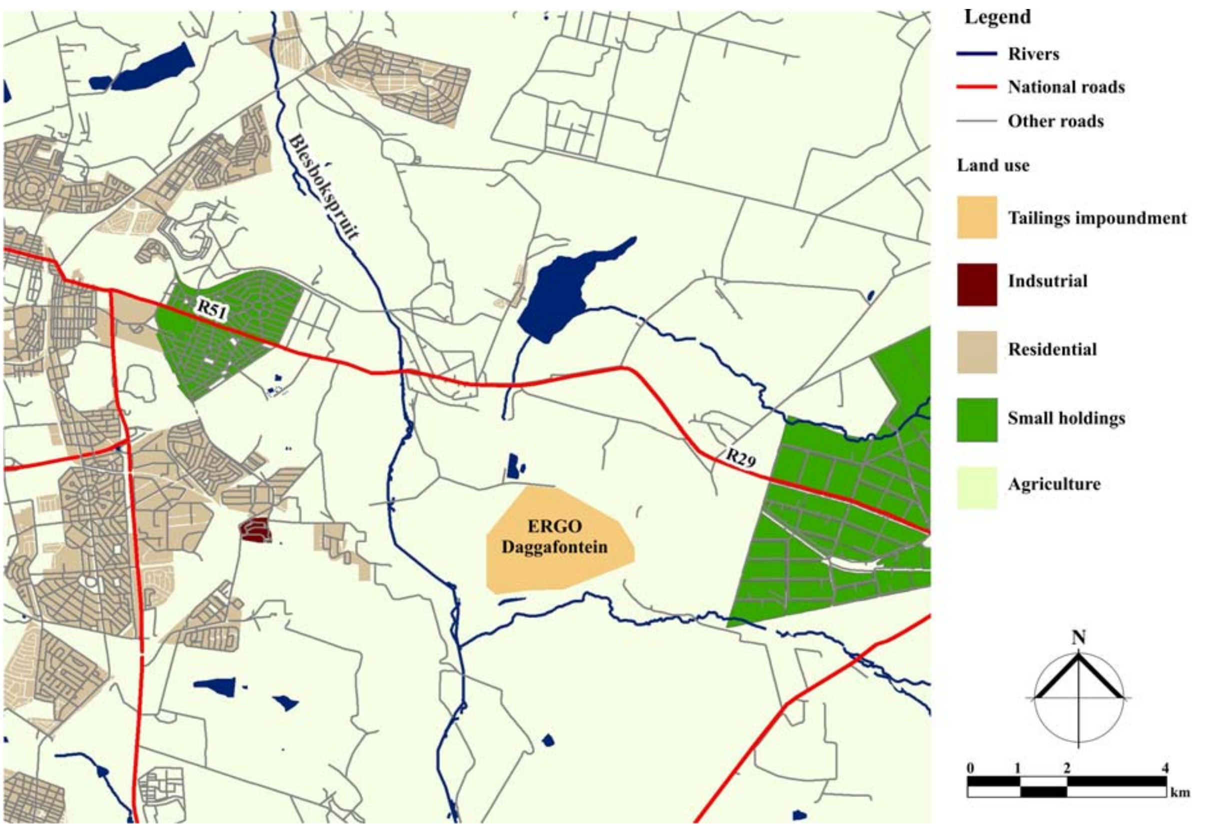


Figure 207: Regional land use map around the ERGO Daggafontein tailings impoundment.

7.4 Sphere of influence

Spatial representation of environmental impacts plays an important role when identifying potential conflicts in existing and future land use. Figure 208 (p. 322) illustrates how the environmental aspect zones of influence as well as the total environmental sphere of influence for tailings impoundments spatially represented once it has been determined.

Tailings impoundments in very few instances have any direct benefit to communities. The disposal of tailings is at the end of the chain in most mining developments and if the cost of the tailings disposal is too high it can jeopardise the viability of the operation. On the other hand, if the tailings impoundment is unsafe or it causes adverse environmental impacts after closure, there will also be a cost to society. The internalisation of the total environmental impact costs may also affect the viability of the mining operation and the construction of the tailings impoundment.

In some fortunate but rare instances, tailings impoundments have little or no effect on the environment. For example when an impoundment is constructed on naturally impervious foundations the effect on the water regime can be expected to be minimal as the source of water pollution is contained and will not impact on the groundwater regime. In such cases, the low quantity of seepage escaping the impoundment will have a negligible effect on the flow system. Where seepage cannot be contained and the discharge does not meet water quality criteria it may be sensible to place the impoundment sufficiently far from sensitive users by sensibly using buffer distances.

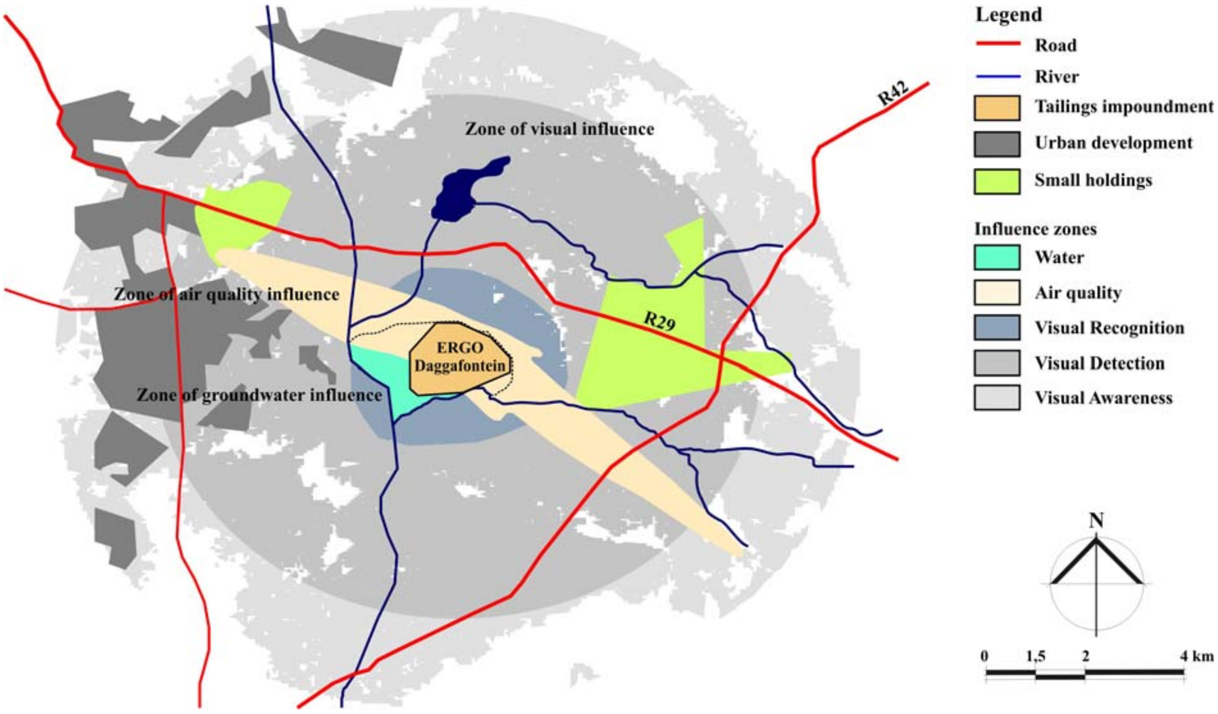


Figure 208: Total environmental sphere of influence modelled and spatially represented.

More intense involvement, such as suburban and urban development, with which higher land value is typically associated, usually requires drastic land disturbance. The rehabilitation steps to such end use are generally less expensive and involved. Most of the cost and effort is in the installation of new use. In contrast, to return a previously wilderness area to a near-wilderness state may require extensive rehabilitation efforts at high cost.

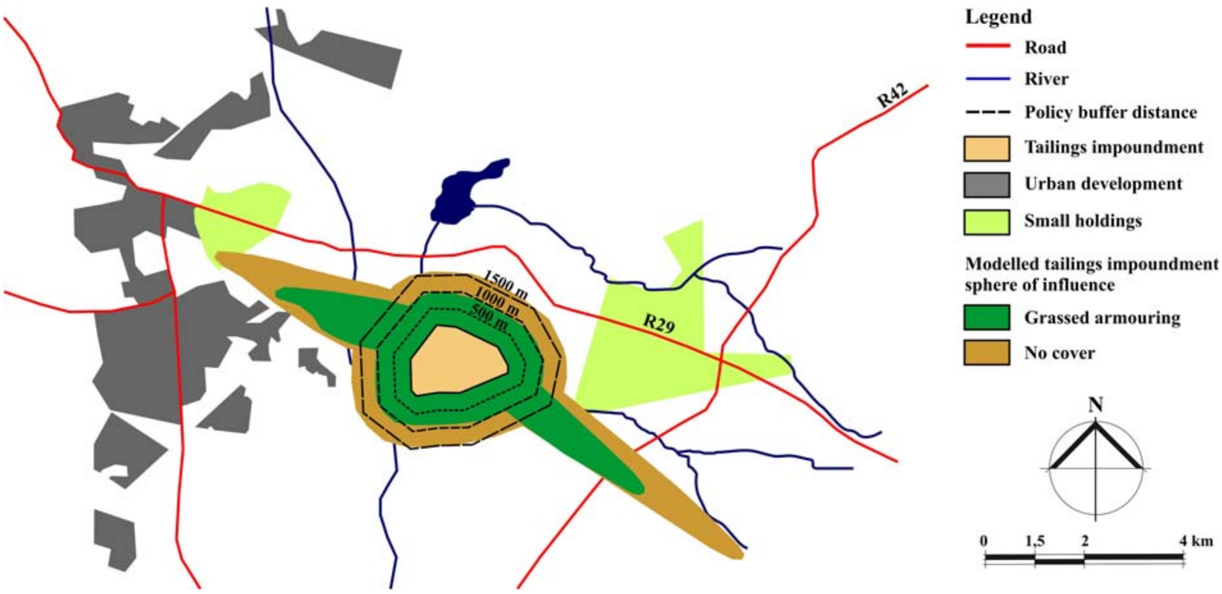


Figure 209: Comparing modelled zones of influence with typical policy buffer distances.

It may then be of economic advantage to plan an alternative future use at high-intensity level. The cost of rehabilitation as part of the mining process can be minimized. High intensity use ensures relief from long-term responsibility. In many cases such a goal is part of the preplanning process. However, the social value of a shopping centre or residential area in the middle of nowhere is questionable.

Delineation of alternative long-term uses requires compliance with socio-economic and public constraints as well as with goals of the mining company. In recognition of public welfare, regulatory authorities would be required to exercise strategic planning mechanisms with regard to laws, regulations, and planning and zoning.

Planning goals in determining acceptable future long-term alternatives must be developed by government regulatory authorities. In the most rigorous of cases, the alternatives may be extremely limited by zoning restrictions or future long-term land use plans for a region. In the least restrictive cases, virtually any alternative will usually have varying degrees of acceptability to stakeholders. From a practical viewpoint, the process defies specific detailing. The long-term post-closure use must be linked to the design, construction, operation and closure of the impoundment in space, time, and concept. Such linking is perhaps achieved by looking at alternative configurations during the concept design stage.

The construction of a tailings impoundment, because of its potential spatial and temporal boundaries, must be an integral part of the regional land use planning process. The ideal is that the planning process will result in an impoundment configuration that is compatible with existing and future uses within the tailings impoundment environmental sphere of influence. Deciding on a suitable site and impoundment configuration must be informed by strategic planning initiatives which take cognisance of short as well as long term zoning and land use into account. The essence of sustainable tailings impoundment configuration is about deciding on a final configuration which can support a preferred land use, how it will be constructed, and what it will cost to construct, operate, rehabilitate and manage the scheme in that particular locality.

7.5 Sustainable development

Despite its widespread popularity, the idea of sustainability is far from being clearly defined. Although the core of the vision seems simple such as a lasting and non-destructive way to live on Earth, the questions are and remain many. Probably the simplest widely used definition of sustainability is Brundtland's definition of meeting the needs of today's population without diminishing the ability of future populations to meet their needs. Sustainability in this sense could mean using resources without diminishing their future availability or quality. Even more simply, it requires living within our ecological means. Disposing of mining waste in such a manner that it impacts on the environment and diminishes future generations to use the land to meet their needs cannot be sustainable in the long term.

There is strong evidence that constructing tailings impoundments without considering the long-term environmental impacts associated with the configuration (i.e. impoundment shape, embankment slope and cover) can significantly increase the overall tailings impoundment costs, and in some cases even prevents them from being used after closure.

Turning an undulating hillside into a constant percent slope undermines ecological function because it changes environmental form. Similarly, constructing a tailings impoundment with constant percent embankment slopes also undermines the ecological functioning of the landscape. For those who are concerned with sustainability, the relationship between natural form and ecological function needs to be carefully studied. Although real understanding of this relationship is still developing, it is quite clear that it is far more than a backward looking aesthetic.

Although no one really knows what a sustainable tailings impoundment landscape looks like, the following suggestions are made:

- The sustainable tailings impoundment landscape does not exclude human presence or engineering design.
- The sustainable tailings impoundment landscape does not waste energy or resources on trying to disguise human influence. Rather, it eliminates functional as well as visual influences that are destructive or disruptive.
- The sustainable tailings impoundment landscape follows natural and regional form whenever this can improve the ecological functioning of a built or rehabilitated landscape.

7.6 Rehabilitation

The rehabilitation of tailings impoundments:

- is expensive;
- uses energy; and
- requires labour and time.

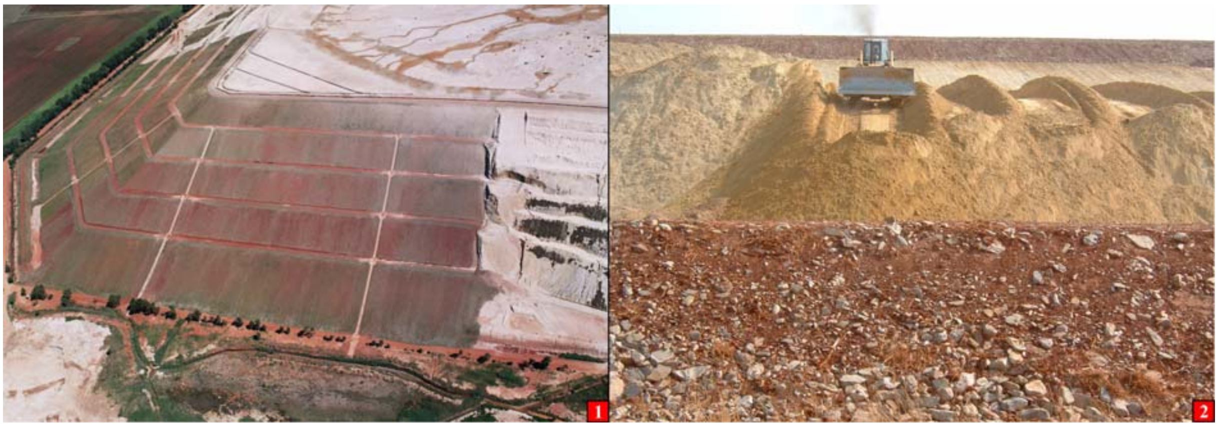
It appears to be cheaper to design, construct, and operate an impoundment with the envisaged final embankment configuration than it is to construct an impoundment with steep embankment slopes in the first place and later on flatten such mechanically.

Landform grading

Proper landform grading has been shown to decrease erosion and fits well with scientific theory about the geomorphologic evolution of natural slopes. It seems likely that properly designed embankment slopes will revegetate more quickly and cost-effectively especially if they offer a diversity of concave and convex, shaded and sunny, exposed and sheltered plant habitats. Implementing the stepped slope approach (Figure 210, p. 325) avoids some of the problems of conventional grading. Essentially stepped slopes are horizontal benches that are constructed as the slope is being graded, i.e. a modern version of the terraced slopes that has been used for centuries by traditional society practice agriculture on hillsides.

As water collects on each bench and begins to flow, it drops to the step below, dissipating its energy. Because it flows more slowly and puddles on each step, water falling on the slope has more time to infiltrate the soil, aiding plant establishment. Over time, the embankments of the step-ins do erode, but this only deposits loose soil on the benches below and serves as a rooting medium for seeds.

Step-in intervals can vary with their widths in proportion to an appropriate slope ratio. The steps are cut with a bulldozer when the excavation is made. The steps should be cut with the dozer travelling in alternate direction to prevent material from piling up at one end of the slope.



[1] Oblique view of a rehabilitated section at the ERGO Daggafontein tailings impoundment (photograph AngloGold Ashanti).

[2] View of mechanical reshaping at the ERGO Daggafontein tailings impoundment.

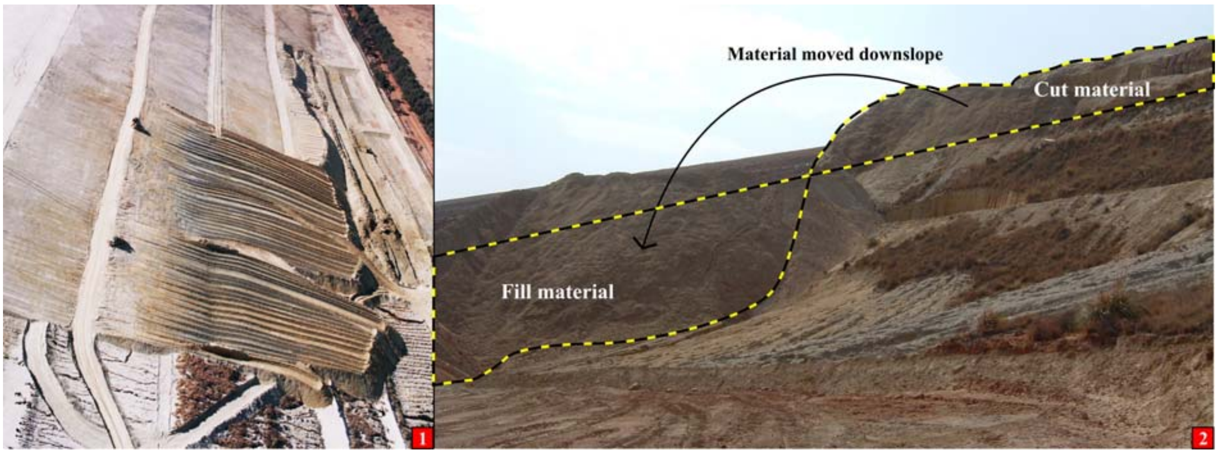
Figure 210: Creating stepped embankment slopes at the ERGO Daggafontein tailings impoundment using heavy machinery.

Grade subsoil not topsoil

If a final vegetative cover will be required and the tailings preclude in situ revegetation then it will be a prerequisite to subsoil and topsoil separately. Irrespective of the final impoundment configuration, it will be required to grade the impoundment and some instances the subsoil cover before placing the topsoil or growing medium. Topsoil is usually stockpiled and reapplied to graded or otherwise altered areas. The completed impoundment site will have a blanket of topsoil over the tailings or subsoil.

Balance cut and fill

Handling, moving and transporting soil is a costly exercise. It is for this reason that it is standard practice for large engineering projects to balance cut and fill on site and that soil need not be trucked in or carted off site. This concept can contribute to sustainability and should be considered in the design and construction stages of a project.



[1] Oblique view of the mechanical reshaping of the ERGO Daggafontein tailings impoundment (photograph courtesy of AngloGold Ashanti).

[2] Schematic showing the concept of cut and fill on the ERGO Daggafontein tailings impoundment side slope.

Figure 211: Stepped sloped grading balancing cut and fill.

Vegetating tailings impoundments

The lack of trees and shrubs severely limits the tailings impoundment's potential for creating wildlife habitats and not to mention visual variety. Woody vegetation provides perching sites for birds which in turn disperse seeds, helping to plant other areas with pioneer woody species. This planting strategy is called "habitat islands." Although the overall aim of planting woody species on tailings impoundments is to reduce wind and water erosion, planting of indigenous woody species such as *Rhus lancea*, *Rhus pendulina* and *Combretum erythrophyllum* in situ in the tailings also contributes to the reduction in rehabilitation costs. Isabel Weiersbye of the School of Animal, Plant and Environmental Science at the Witswatersrand University is the programme leader of the initiative to use indigenous species, inoculated with growth-promoting mycorrhizae, during the rehabilitation on tailings impoundments (Figure 212). The advantage of this approach is that significant cost savings are possible in that suitable soils required for sustaining vegetation do not have to be imported and that very little additional amelioration of the in situ tailings is required. The woody vegetation produces organic material from fine roots and leaves which contribute to the increase of the anthropogenic soil organic content which in turn encourages increased microbial activity.

[1,2] Photographs of woody vegetation trials on tailings impoundment in the Welkom gold mining region.

Figure 212: Woody vegetation planted in situ on tailings impoundments.

The initial trials on the project have shown that woody and semi-woody species can be established in situ with minimal amelioration and no irrigation. The mycorrhizae serve to make the plants tolerant to the droughty, low nutrient, and heavy metal content conditions of the tailings (Knoll, 2004:24).

Tailings impoundment landscapes

Tailings impoundments are structurally unique in the built environment. In extreme cases they are sealed on all sides to isolate the mine residue from the environment, preventing pollution, and acting as huge containers within the landscape which must not be punctured. Tailings impoundments, as they close, present remarkable opportunities for the development of new open space. If the slopes and cover are properly designed a park can be created which presents blank slates for what might be called high value consumer landscapes such as golf courses, wildlife reserves, and community parks built on rehabilitated land. Developing tailings impoundments relieves the pressure to develop greenfields sites for these uses.

1 and 2 The McLeod High tailings impoundment was reshaped to create an environmentally stable sculptural landscape (photographs courtesy of Martha Swartz Partners).

Figure 213: Integrating tailings impoundment design with long-term regional land development objectives.

7.7 Integrated environmental planning and design

The outcome of the research is a comprehensive model of the life cycle of tailings impoundments from conceptual planning through to closure allowing operations within the cycle to be evaluated in terms of their direct engineering costs and their environmental impacts. This enables, at the planning stage, comparison in a rational and consistent way of, for example, the direct costs and other impacts of alternative end uses; the influences of different covers and the influences of different embankment slope angles. It is also possible to compare the opposing strategies of either minimising construction and operation costs – whilst adhering to environmental controls – and accepting larger end rehabilitation costs, or, alternatively having more costly construction and operation but lesser closure and post-closure costs to achieve the planned sustainable end use, which will be compatible with the aesthetical, economical, environmental and social requirements of the area in which the facility is located.

The principles and much of the detail of the proposed methodology can equally apply to coal and other non-metalliferous tailings impoundments. At this stage, however, because of the dramatic growth in metalliferous mining the system was first developed for the platinum and gold industries using upstream deposited ring-dyke impoundments for containing mine residue.

The engineering cost model was developed and calibrated which can be used as a standardised system for cost estimation for tailings impoundments. This model was supplemented by the environmental impact evaluation modelling to form the comprehensive model which was the ultimate aim of the overall research.

It is believed that the development of the proposed system will, because of its rationality, enable effective long term planning decisions to be made which will satisfy the requirements of the ethos of sustainable development; hence, the system could form the basis through which regulating authorities will in future assess the acceptability of planning proposals for tailings impoundments.

Society has advanced to the point where all our engineering endeavours should be viewed against the criteria of sustainability. Responsible industry shares this view and the question is not whether we should strive for it, but how best can it be achieved. It is the contention of this study that one means of advancing this in the mining field is to undertake the paradigm shift of considering tailings impoundment as an integrated system from planning to sustainable closure. The research project developed models for such a system in which costs and impacts can be rationally assessed so that the system can be optimised. In addition, it is my opinion that a rational system can positively inform legislation on tailings impoundment closure.

The result of integrating environmental planning with the engineering design can best be illustrated in a concept tailings impoundment rehabilitation plan aimed at creating a sustainable and regenerative landform (Figure 214) and also by comparing its profile with that of a typical impoundment (Figure 215 and Figure 216). Four slope configurations (1:3, 1:4, 1:6 and <1:6) in combination with three surface covers (T – tailings in situ, R – Rock cladding, A – Armouring i.e. topsoil and rock mix) are applied to the tailings impoundment and indicated in the legend of Figure 214. The combination of different slope geometries and surface cover follows a rational and analytic process considering factors such as slope aspect, flora and fauna specie distribution as well as macro- and micro climatic conditions, specific to the site location.

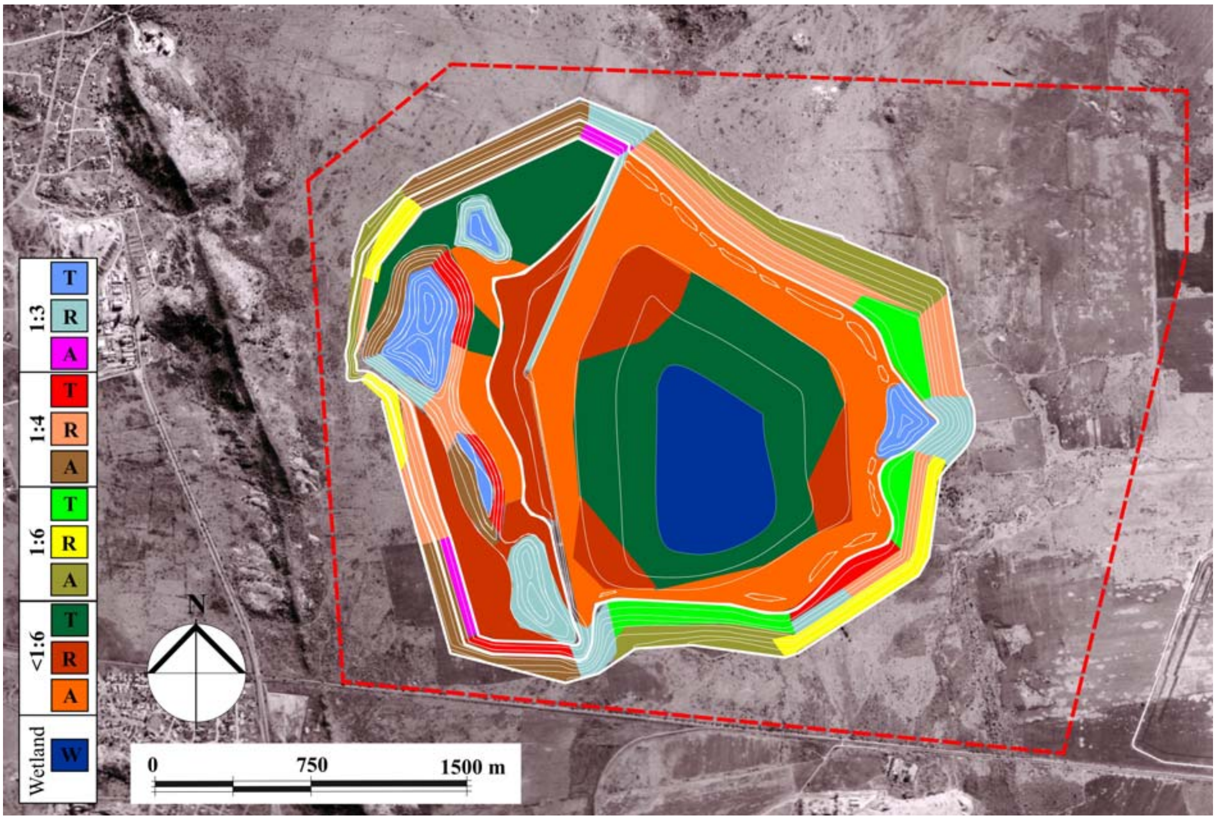


Figure 214: Hypothetical regenerative impoundment landform (Rademeyer and van den Berg, 2005).

Figure 215: Typical tailings impoundment profile (van den Berg, 2004).

Figure 216: Tailings impoundment profile that is sensitive towards the natural landscape (van den Berg, 2004).

The hypothetical outcome satisfies the design brief through applying surface stabilising practices in combination with landform design principles. Habitat creation is a function of the context in that it is guided by local ecological systems and vegetation distributions. It is believed that these two aspects will result in an aesthetically pleasing landform, unlike the unsightly mine residue deposits that are so common in the South African landscape.

Configuration of tailings impoundments necessarily includes rehabilitation with the aim of eliminating or reducing adverse environmental impacts and creating a new landform that conform to the principles of sustainable development and something that will be acceptable in the long-term. The process is driven primarily by legislation which ensures that the mine owner must comply with the intention of achieving those end conditions, which are defined in broad terms by guidelines, hence the need to rationally define the end conditions.

Two measures can encourage rational decision making and better planning:

- development of regional landscape plans requiring injection of ideals into the planning process;
- modification of single-objective impoundment schemes to improve the contextual relationship with the landscape. This can be seen as impact mitigation in environmental assessment terms.

Tailings impoundment schemes should be modified in order to produce multi-objective project designs. Design modifications can prevent negative environmental impacts and promote positive environmental impacts. Although it is a legal requirement to assess the impacts of a scheme on the biophysical, socio-cultural and economic environment, insufficient attention is paid to the impacts on the surrounding land use.

Envisaging the final tailings impoundment during the initial planning stage may result in a differently designed facility. This could result in lower final rehabilitation costs possibly at the expense of higher initial costs. High decommissioning and closure costs can easily negate short-term benefits of disposal strategies which do not facilitate easy rehabilitation. Important to note is that it is perfectly feasible to do the afore-mentioned and lastly, to rationally inform the approach it goes without saying that costs would have to be considered. The cost of doing something and the cost of not doing something in terms of sustainable impoundment landform planning and design would have to be compared and it might well be that it is in fact cheaper to do the right thing from the start…

The approach presented in this thesis does not replace sound application of knowledge and judgement but is simply a systematic rational application of these. Any approach should remain easy to facilitate reaching consensus. It is a tool intended to help with transparent decision-making between regulatory authorities, proponents and consultants. Although decision-making for the sustainable design, operation and closure of tailings impoundments is not an easy task the approach and results presented in this thesis can already be used to aid decision-making. The application of the findings although simple in concept, will require some experience to ensure its effective use.

The following conclusions are made with regard to the configuration of tailings impoundments:

- A holistic planning approach is necessary to understand the impact of tailings impoundments on the environment.
- Post-closure land use of an impoundment is a function of the final landform's ability to sustain an end use acceptable to all stakeholders.

- The final landform and use must be informed by both present and future land planning initiatives within the impoundment sphere of influence. The potential conflict between land uses in the sphere of influence will require management.
- Conflict in land use as a result of a tailings impoundment can be controlled by changing its design.
- Failure to incorporate the final configuration and anticipated end land use from the start will result in an impoundment that is difficult and expensive to rehabilitate during the closure stage.
- Embankment slope and impoundment cover are two of the key aspects that constrain post-closure use of an impoundment.
- Access onto an impoundment is a function of the embankment configuration. Steep embankments slopes support less uses than flatter slopes. The flat impoundment top does not have the same constraints than steep embankments.
- Rehabilitation during the closure stage comprises two significant engineering cost items, namely bulk earthworks required to mechanically flatten slopes and reshape an impoundment, and the construction of a suitable cover in support of the post-closure land use.
- It is cheaper to construct an impoundment with its final embankment side slope configuration during the operation stage through the hydraulic deposition of tailings than it is to mechanically flatten the slopes during the closure stage.
- Flattening side slopes increases the tailings impoundment footprint which could, depending on the final choice in cover, result in an increased environmental sphere of influence.
- Final cover, more so than embankment slope, controls the extent of the environmental sphere of influence.
- Environmental impact prediction, evaluation, planning, and implementation must be conducted at meaningful temporal and spatial boundaries. Long enough periods must be allowed for to assess the cumulative impacts during the post-closure stage of a scheme. The latter must be based on the sphere of influence even if political boundaries are crossed.
- The match between site characteristics, environmental attributes, planned end land use, and selected management technologies must result in an impoundment configuration that is acceptable to stakeholders. Mismatches of the afore-mentioned can result in significant environmental impacts and require continued external inputs to maintain the closed impoundment.

The following practices are recommended for tailings impoundment design:

- Involve a multi-disciplinary team to assist with the identification of alternative technologies, site selection, concept design and final design.
- The final embankment slope must be determined prior to construction and deposited during the operation stage.
- If a soil will be required during rehabilitation as a growing medium, then the soils should be stripped and stockpiled separately for use during rehabilitation.
- It is preferable that plant species which are drought tolerant and can grow directly in tailings should be identified and used where possible. This will negate the need to import and cover the tailings impoundment with a suitable growing medium. Further research is required in this regard.

7.8 Meeting legislative requirements

The continued expansion of metals mining to meet global demand will result in an increased need to dispose of mining waste. However, legislation regarding new mining project is such that details need to be provided by proponents as to how environmental impacts will be managed and how the areas disturbed by mining activities will be rehabilitated. The South African government has launched an integrated Phepafatso strategy. Phepafatso means that you must clean up in Tswana and it is expected that this approach will change environmental practices in South Africa.

New environmental EIA regulations came into effect during July 2006 with one of its objectives to streamline decision making with regard to the environmental assessment process. Mining projects are currently excluded from this new process and will continue to be regulated by the Department of Minerals and Energy (DME) until further notice. This however does not change the fact that there is a need to rationally inform decision making when considering tailings impoundments.

The long-term risk to the environment from tailings impoundments include:

- the potential for failure resulting in the flow of slurry; and
- the impact on environmental aspects such as visual perception, air quality, and water quality.

The risks are site specific and depend on:

- the nature of the material impounded;
- the configuration of the tailings impoundment; and
- how the impoundment will be rehabilitated.

In some instances the sphere of influence could result in restrictions on future land use which places an obligation on both the proponent and the local planning authorities. It is therefore important that planning authorities considering tailings impoundment applications ensure that:

- the environmental sphere of influence is determined;
- the final impoundment configuration must be finalised prior to construction;
- the proposed impoundment land use will be compatible with regional plans;
- future land use conflicts are anticipated and identified as part of the initial planning and site selection; and
- rehabilitation and long-term environmental costs are estimated to ensure that adequate funding is available.

7.9 Summary

South Africa has a diverse and unique geology and despite occupying only 1 % of earth's land surface, it produces most of the world's chromium, diamonds, gold, manganese, platinum group metals, and vanadium. Mining of South Africa's mineral resources has given rise to hundreds of mine residue deposits (MRDs) which cover large tracts of land. Tailings is a significant part at most precious metals mining operations and the disposal of tailings can result in unintended but unfortunate impacts on the environment.

Tailings disposal facilities are complex. The design of a facility can include a composite liner (soil, geosynthetic clay liner, and a geomembrane), a leachate collection system consisting of piping and gravel and geocomposite drain layers, a final cover capping system (soil, geosynthetic clay liner, and a geomembrane), and surface and subsurface drainage systems in the cover soils. The cover and liner can be designed to minimize water infiltration and oxygen penetration into the tailings, and discharge of contaminants from the facility into the groundwater. It is however important that whatever the tailings disposal facility configuration entail, that the design must provide for the protection of the environment.

The term sphere of influence is used in this study to describe the three-dimensional tailings impoundment impact zone on the environment. This sphere is the spatial overlay or sum of the different environmental aspect zones of influence. It is useful in the quantification and valuation of environmental impacts related to tailings impoundments. Measured key criteria must meet agreed numeric standards within the sphere of influence.

It is required by South African law to define future land use objectives prior to the commissioning of any mining activity. This, although not necessarily explicitly stated, implies that the future land use of tailings impoundments, an integral and inseparable part of mining, must be determined during the development stage of a mine and not as an afterthought during decommissioning and closure of the impoundment.
The main reason for actively pursuing a pro-active rather than reactive planning approach lies in the constraints imposed by reactive rehabilitation and having to remedy post-closure environmental impacts.

Man has since the beginning of time expressed himself in the landscape constructing man-made landforms. This study demonstrates how environmental aspects can influence engineering design. The study integrates elements to satisfy not only engineering but also environmental, social and economic criteria.

The following environmental aspects have been successfully modelled and integrated with engineering costs in this study:
- visual perception zone of influence;
- air quality zone of influence; and
- water quality calculated as the sulphate mass flux.

The starting premise of this thesis is that most of the difficulty decision makers have with the configuration of tailings impoundments comes from maybe too much emphasis on the bits and pieces and not enough on the synthesis of key elements. This study presents an innovative approach to integrating environmental impacts with engineering costs.

The system examines and describes key issues relating to the configuration of tailings impoundments and can be used to answer critical questions such as:

`Is it better to flatten tailings embankment side slopes?`

and

`Which cover is likely to be most acceptable?`

Although many factors influence the configuration of tailings impoundments it is believed that the system is robust enough to be useful for comparing the change in slope and cover.

Predictive simulation models are used to quantify environmental impacts as measured data is not available for all the scenarios described in this study. To develop comprehensive data sets for alternative impoundment configurations is costly and takes time. Predictive modelling has the advantages of being less expensive and quicker than obtaining long-term monitoring data for alternative impoundment configurations. The disadvantages are those associated with most predictive models namely uncertainty and errors in model structure, parameter estimation, and model output. A range of available predictive models of varying complexity was used in this study. It was found that the importance of the consequence of the environmental impact directs the appropriate choice in model.

An acceptable post-closure impoundment configuration can only be achieved where engineering costs, environmental concerns, land use conflicts, and stakeholder desires are in balance. The difficult bit is that what is considered acceptable today may be different in a couple of years because of changing values, knowledge base, or political factors.
This thesis describes the valuation of different impoundment configurations to evaluate the acceptability of tailings impoundment configurations. The most appropriate or acceptable alternative design depends on the specific site characteristics, the type of tailings and how it is stored, and the potential long-term environmental impact costs. A rational and informed decision can only be made if all these factors are accounted for. The goal will therefore be to improve the quality of the technical information used to select an impoundment configuration which is not only cost effective but meets regulatory standards.

The future application of the approach will require that the results are interpreted, weighted, and made precise for each site specific case. In one case, the impact on air quality may be the overwhelming consideration and in another, it may be the preservation of a groundwater resource or the creation of a post-closure landform that will blend in with the existing landscape. But the environmental issues addressed in this thesis are general enough to be useful in evaluating schemes and at least as a start rationally inform the drawing up of objectives during tailings impoundment conceptualisation.

The South African Constitution provides people the right to an environment that is not harmful to health or well-being, and that is protected for the benefit of present and future generations. These rights are to be ensured through measures that prevent pollution and ecological degradation. The basis of the polluter pays principle is firmly entrenched in legislation and requires that the costs of environmental impact should be borne by those responsible for the impact (DWAF, 2006). The National Water Act No. 36 of 1998 (NWA, 1998) specifically refers to the polluter pays principle as an economic mechanism for achieving effective and efficient water use.

Legislation requires that when an activity results in an environmental impact, the party in control of the activity has to pay:

- the direct costs of the impact;
- the cost to remedy the impact; or
- compensate society for the impact incurred.

This study presents a system to determine such costs.

Section 38(1)(d) of the Mineral and Petroleum Resources Development Act No. 28 of 2002 (MPRDA, 2002) stipulates that a tailings impoundment must be rehabilitated to a predetermined state with a land use which conforms to the generally accepted principle of sustainable development. Integrating closure plans and designs with regional land use programmes will result in a post-closure tailings impoundment land use that is not in conflict with future regional land uses. To prevent future land use conflicts and defer unnecessary costs it is imperative that tailings impoundment environmental impacts are integrated during the conceptualisation and design stages with engineering life-cycle costs. Similar to the NWA (1998), it also states in Section 38(1)(e) that the holder is responsible for any environmental damage, pollution or ecological degradation inside and outside its boundaries.

The system developed and the approach described in this study can assist to determine the financial implications of such requirements and can provide input into rational decision making when considering rehabilitation alternatives. The system also provides costs for rehabilitation during closure as well as cost for residual environmental impacts. The determination of these costs is a requirement of the MPRDA (2002).

Proponents are required to contribute towards a rehabilitation fund so that external costs are internalized based on the economic polluter pays principle. The fundamental underlying principle for the minerals industry may be that the permission to mine, process and deposit tailings should not be given unless it can be demonstrated that the post-mining tailings impoundment landscape will at least be stable, non-polluting and useful.

The study emphasises the importance of planning the after-use of a tailings impoundment prior to approvals is given for the construction thereof. Among other things a conceptual closure plan should be submitted at the feasibility stage which includes detailed information on the final tailings impoundment configuration and associated rehabilitation. It can be concluded that a better tailings impoundment after use can be achieved at a lower cost if adequate planning takes place.

CHAPTER EIGHT: CONCLUSIONS

"If we knew what it was we were doing, it would not be called research, would it?"

Albert Einstein (Quotations, 2007)

"We don't see things as they are. We see them as we are."

Anais Nin (Arden, 2003:123)

"The best time to begin is now. If you wish to leave something behind tomorrow, you must begin today."

Anton Rupert (Dommisse, 2005:413)

8.1 Decision-making system

"...a decision is a judgement and, as such, is rarely a choice between right and wrong but at best a choice between 'almost right' and 'almost wrong'."

Drucker (1967)

Decision making with regard to the configuration of tailings impoundments is multi-dimensional, multi-objective, and complex. The study describes a system whereby environmental impacts and engineering costs are rationally evaluated over the life of upstream deposited ring-dyke tailings impoundments. It demonstrates how a combination of models, techniques and approaches can be used to integrate various environmental and technical aspects to rationally inform decision-making with regard to the planning and design of tailings impoundments.

The following conclusions are drawn from the study with regard to tailings impoundment decision making:

- Decisions are unique in character, controlling variables and the preferred solution and must be specifically refined for each scheme.
- Site-specific information and decision-support tools such as databases, impact prediction models, and geographic information systems must be used to assist with making decisions.
- The system allows professional planners, specialists and researchers to draw on analytical and decision-support tools helping with, although not necessarily resolving, complex problems.

The system has the following characteristics:

- The system is simplistic, understandable, transparent and auditable.
- The system is supported by models and examines the influence of environmental impacts on engineering design.
- The system integrates key environmental aspects successfully with engineering configuration decisions.
- Environmental aspect zones of influence for visual perception and air quality, and sulphates calculated as mass flux are included in the system.
- Some of the models are easy to understand and use providing quick results (such as the use of Darcy flow equations) while others require in-depth specialist knowledge on the subject (such as the predictive air quality modelling).
- Although several factors influence the configuration of an impoundment, it can be said that the system and environmental aspect zones of influence provide sufficient structure to inform decisions having a bearing on impoundment design.
- The system is sufficiently robust to allow the addition of information and knowledge if and when it becomes available.

The system has the following advantages:

- The system integrates environmental impact costs and engineering costs.
- The system exploits joint capabilities of specialists and the generalist information.
- It provides spatial context to environmental aspects.
- It combines techniques, tools, methods, and computer models to facilitate effective and transparent decision making.

The following contributed to developing the system:

- Specialist understanding of the decision situation, opinions, and input were a major input to the overall design of the system.
- An understanding in sufficient detail and at the appropriate level of existing decision-making processes.

The system, models, and approach presented in this thesis can be used and acted on by decision makers tasked with the difficult and complex activity of tailings impoundment configuration. The successful outcome of using the proposed approach will be where consensus is reached amongst all stakeholders as to the acceptability of a scheme's configuration and its impact on the environment.

8.2 Engineering costs

The result from this part of the overall research programme is that a comprehensive engineering cost model for upstream spigotted ring-dike tailings impoundments is available which is sufficiently reliable not only to estimate the overall life-cycle cost but also check costs of for example modifying the overall embankment side slope, cover, and environmental protection measures.

The engineering cost model is conceptually straightforward and since it comprises linked spreadsheets using available computer software it is simple and flexible to operate.

The benefits to decision makers tasked with the management at different levels are primarily that:

- The model allows for different unit rates for different impoundments to be captured allowing correlation between sites and allows for differences in impoundment configuration, topography and location.
- Reliable predictive estimates can be made of future closure costs and that these estimates can be readily modified from time to time to deal with changed quantities, changes in specifications and escalating costs.
- The system also operates as a management tool in that any high cost item can be identified and examined to determine whether savings can be made by changing methods or specifications.

Although the system described is currently operating it must be noted that as with any system it is anticipated that use will indicate areas where improvements can be made. The simplicity and flexibility of the system ensures this.

8.3 Visual perception

A visual impact methodology that is objective and contains defensible measurements has been developed to assess the impact of ring-dyke tailings impoundments on the receiving environment. Visual perception thresholds are determined for various impoundment configurations. A panel of visual experts evaluated visualisations of the various configurations applying the nominal group technique (NGT) study method. Visual perception distances were determined for different covers and embankment slopes. Although there is variance in the perception distances when comparing embankment slopes for the same covers it appears that the overall embankment slope on an impoundment does not have a significant influence on the perception thereof. This is counter intuitive to what was originally thought.

Literature suggests that visual perception decreases over distance; however specific distances for tailings impoundments do not exist. It was required to develop a procedure to quantify visual influence and to test the effect of changing tailings impoundment configurations (mitigation measures). A procedure to determine visual perception threshold distances for tailings impoundments has been developed. The ERGO Daggafontein tailings impoundment was used for most of the modelling in this study as it is one of the largest upstream ring-dyke impoundments of its kind. It is also located within a flat terrain which assisted with taking unobscured panorama photographs. The study demonstrates a method to determine visual perception distance values and applies it to different impoundment configurations demonstrating the efficacy of mitigation.

The visual perception study uses computer manipulated panorama photographs to simulate hypothetical landform modifications (such as the different configurations depicting various scenarios) with high realism. Psychophysical concepts of visual threshold (awareness, detection and recognition) are adopted from literature, details of which are provided in Section 2.10. Visual attributes such as form, silhouette, colour and texture are designated as experimental variables (Figure 100, p. 191).

Visual perception distance threshold values are used to quantify visual perception zones of influences (ZVIs) which can now be used for landscape planning and management purposes. Although it is indicated that there are threshold distances between awareness, detection, and recognition it is unlikely that these distances will be absolute events.

The thresholds were obtained through controlled computer slide-viewing tests using simulated images with modified visual attributes such as overall side slope angle and cover. Analysis yielded average and specific thresholds of high apparent reliability. This is demonstrated by delineating the initial results in envelopes (Figure 130, p. 236) and using mean values to plot trendlines. The mean trendlines facilitate the interpretation, comparison, and communication of the results (Figure 132, p. 237).

Even though visual perception distances must ideally be determined on a case-by-case basis, the results form this specific part of the overall research can be used in first order assessments, especially during the conceptualisation stage of a scheme, to inform the level of visual impact assessment (VIA) required and setting the limits of additional ZVI studies. Cognisance should be taken that the visual perception distances are maybe on the conservative side as a result of the size of the tailings impoundment used to determine the distances.

Visual perception distance functions are communicated in a simple graphical form for various impoundment configurations. The results may in a sense be "obvious" or just what would be expected, that is that the level of perception would decrease with an increase in viewing distance. The observations are supported by numerical results determined by an experiment conducted rationally and transparently.

Simulated mitigation measures make a large difference to visual perception threshold distances and the overall ZVI. This quantitative information can be used to determine the visual impact of an impoundment. The enclosing ZVI could essentially sterilise the land for uses such as tourism and conservation as well as impact on the value of property. It is further postulated that the assessment of the change in land use within the ZVI discloses a monetary value of the visual impact.

VIA for tailings impoundments must be conducted differently than for example the assessment of linear developments such as transmission lines. The use of the test tailings impoundment in the study gave conservative results, that is larger threshold distances than what may have been expected. This is partly because ring-dyke impoundments are large-scale man-made landforms within the landscape and is distinguished from most other man-made elements due to sheer size, scale and in certain instances unnatural covers.

Visual perception threshold distances within the zone of visual influence (ZVI) can be obtained following the method described in this study. An important observation is the demonstration that different impoundment configurations (relating the overall embankment side slope and covers) have a significant influence on the viewing distances and hence influence the land surface area impacted upon. Impoundments can be configured such that the perception thresholds within the ZVI can be manipulated. Although the research does not test the preference of people viewing a scheme, it does test the ability of viewers to become aware of, detect man-made landforms in the landscape and recognise tailings impoundments as a result of its configuration.

Specific conclusions on conducting visual impact analysis on tailings impoundments:

- VIA for tailings impoundments must be conducted differently from for example the assessment of linear developments such as transmission lines.
- The use of a regularly shaped man-made landform in the study gave conservative results, that is greater threshold distances as what was expected. This is in part because impoundments are large-scale man-made landforms within the landscape and also because it is distinguished from most other man-made elements due to sheer size and scale.

The following observations are made regarding the Nominal Group Technique (NGT) study method:

- The expert NGT group was representative enough to ensure statistically robust sampling.
- The sample population was drawn from landscape architecture and environmental planning professional streams suggesting high homogeneity.
- The experimental results shows considerable consistency, i.e. the plotted result shows increasing impact with the increase of stimulus level and the decrease in distance from the tailings impoundment.
- Active participation of the experts is crucial. It can be said that the participant's feedback on the whole process have been positive and the process worked well.
- The opinions of the experts offered valued input and insights into the problem studied and assisted in flagging of important considerations and issues.

The following conclusions are drawn from the study with regard to the visual perception distances:

- Visual perception distance functions can be determined and communicated in a simple graphical form for various impoundment configurations.
- The visual perception distance study results (Figure 145, p. 247) show considerable consistency. The plotted result shows increasing impact with the increase of stimulus level and the decrease in distance from the tailings impoundment as had been expected.
- A significant observation is the demonstration that different impoundment configurations, i.e. covers and overall embankment side slopes, have a significant influence on the viewing distances and hence influence the land surface area impacted upon.
- The enclosing negative zone of visual influence (ZVI) could essentially sterilise the land for uses such as tourism and conservation as well as impact on the value of property.
- It is further postulated that the assessment of the change in land use within the ZVI could disclose a quantitative monetary value of the visual impact.
- It is evident from the experiment and consensus results that tailings impoundments can be configured such that the perception viewing distances within the ZVI can be manipulated.

8.4 Air quality

Air quality is of vital concern in many locations. Prior to the construction of a tailings impoundment an impact assessment must be undertaken indicating the effect of the tailings impoundment on air quality. It is important that the characteristics of the tailings impoundment be known prior to the prediction of the potential effect air quality. Even though an objective of constructing a tailings impoundment may be to limit impacts to human health, monitoring such effects are extremely difficult because of substantial uncertainties about the exposure of different populations groups to pollutants, their response to different levels of exposure, and the cumulative nature of damage.

Credible modelling of the air quality zones of influence requires significant effort and resources. Modelling emissions off tailings impoundments is complex and requires applying professional judgement. It must be emphasized that mathematical modelling of complex atmospheric processes involves uncertainty which can be made worse when data is lacking or unreliable. The modelled results in this study must therefore be used with care when applying it outside the context of this thesis and when using it in formal decision making. However, the approach presented and the results from the scenarios modelled in the air quality study are summarised and presented in such a way that it can be used to inform decision making especially during the development stage.

There is also uncertainty about the research on which the costing of respiratory hospital admissions is based. The approach to in this study uses respiratory hospital admissions to cost the likely impact that a tailings impoundment will have and is not all inclusive. Quantitative evidence is not available for every health effect suspected of being associated with air pollution. Also, non-health related effects such as materials damage, soiling, vegetation losses and visibility degradation is not included in the costing of the air quality impact. The omissions suggest that the results presented in this thesis are likely to underestimate the total effects of air pollution resulting from a tailings impoundment.

8.5 Water quality

Water quality impacts from tailings impoundments are important when considering the environmental impact associated with mining, both in terms of consequences and cost. Drainage from tailings impoundments is generally of poorer quality than ambient water quality. Deterioration may occur through salt mobilisation, excessive alkalinity, or more generally acidity.

An analytical model was developed that integrates the post-operation water pathways and impacts with the other environmental aspects modelled such as visual perception and air quality

The model has the following characteristics:

- It is simple and easy to use.
- The mass balance model calculates the post-operation steady-state impact on the receiving environment with an acceptable degree of accuracy. The results were compared to the results of a detailed numerical model in Section 4.5.1.
- The impact of the mass flux and not only concentrations must be considered on downstream concentrations.
- Due to net evaporation, mass that dilutes in a stream could concentrate in downstream dams and rivers.

8.6 Environmental impact valuation

The economic valuation of tailings impoundment environmental impacts and integrating such with the engineering costs are extremely useful in raising the profile of the environmental aspects relating to upstream deposited ring-dyke tailings impoundments. Using the methodology described in this thesis may not guarantee an acceptable outcome but is likely to facilitate choice between developing an impoundment or conserving the land. Also, the alternative land uses of the scenarios are compared through the valuation of environmental change. This assists to identify the most critical aspects determining the sustainability of the proposed tailings impoundment end land use. When conflicts are unavoidable, quantitative decision-support systems and models allow optimisation among competing management objectives. Such decision-support systems and models need not be complex. Rather, it was found that systems and tools of varying complexity are essential for successful decision making.

Closure objectives which form part of the required environmental management plan must inter alia identify key objectives, define future land use objectives and provide proposed closure costs. It is the latter which transforms laudable aims into reality and with the increasing stringency of regulations and standards, the necessity for reliable closure cost estimates has become paramount.

The engineering life-cycle costs are fairly insensitive to overall embankment slope angle (Figure 172, p. 280) and it is therefore advised that the preferred final embankment slope must be determined prior to construction. As upstream spigotted ring-dyke tailings impoundments uses hydraulically placed tailings to construct the outer embankment and occurs simultaneously to the disposing of the remaining fines. There is therefore little or no economic incentive for over steep slopes if only considering the cost of placing the tailings. It is imperative that an embankment slope angle has to satisfy safety constraints and achieve economic design.

The lowest environmental and engineering cost option may not necessarily be the best, preferred or most acceptable option when constructing a tailings impoundment.

The following quote introduces the thesis and set the scene for everything which followed. It is maybe appropriate to reflect on what Vick (1983:129) said a quarter of a century ago...

> "In the past, selecting a preferred alternative *tailings* disposal method or tailings impoundment site was a relatively simple procedure. *Engineering* cost estimates could be generated for each option, and the lowest cost option would ordinarily be the hands-down winner. More recently, however, environmental considerations have gained increasing importance, and perhaps nowhere else in mining operations are these environmental issues of more significance than in tailings disposal *and tailings impoundment configuration*. Environmental factors are often of equal or greater importance than economic issues in tailings disposal planning *and design*..."

> "At present *[1983]* tailings disposal alternatives having different combination of economic and environmental attributes are often compared and selected on an informal ad hoc basis. Since few formal guidelines exist conducting the evaluation procedure, disposal decisions made by mining companies are sometimes viewed by regulatory agencies as lacking objectivity, and similar evaluation of alternatives by regulatory agencies may appear arbitrary to the mining company. At the core of the conflict is often the way in which alternatives are evaluated and selected."
>
> (Italics indicate own words)

The overall aim of this research was to develop a rational system and present a structured approach to evaluate change in tailings impoundment slope and cover. It has not only been demonstrated that it is possible to combine environmental impacts with engineering costs but it is also possible to valuate environmental impacts which allow the environmental impact costs to be integrated with engineering costs in a system. This system is useful for rational decision making.

8.7 Recommendations

A system and approach to integrate environmental planning with engineering design is presented in this thesis and has been developed to the point where it can be used to guide decision making. It must however be refined further by including some of the other environmental aspects and calibrating some of the predictive models used.

To achieve this it will be necessary to pursue the following:

- Ongoing research is necessary to calibrate and refine predictive models.
- Compare the visual perception results presented in this study to impoundments in different environmental settings and expand the results and findings accordingly. This can be done by applying the method developed in this research to other mining regions within the South African landscape such as impoundments located in the Northern Province, Mpumalanga and the North-West Province.
- Monitor air quality and seepage at existing tailings impoundments to verify predictions and calibrate the models used in this study.
- Review procedures and develop methodologies for best practice tailings impoundment rehabilitation especially in South Africa where upstream deposited ring-dyke impoundments are still being constructed.
- Test and demonstrate the system developed in this study on the design of new tailings impoundments. Since new and promising technologies and approaches that could play a role in minimizing environmental resource degradation caused by tailings impoundments will be developed subsequent to this study it is important to start with demonstrating the system. The system can be used as the basis for further research or could be used as a reference by industry.

‘Writing a *thesis* is an adventure: to begin with it is a toy and an amusement, and then it becomes a mistress, and then it becomes a tyrant, and then the last phase is that just as you are about to be reconciled to your servitude, you kill the monster and fling him out to the public.’ (Italics indicate own words)

Winston Churchill

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List of acronyms and abbreviations

°C	Degree Celsius
μ	Micro ($x10^{-6}$)
$\mu g/m^3$	micrograms per cubic metre
AMD	Acid mine drainage
AQA	Air Quality Act No. 39 of 2004
ASLA	American Society of Landscape Architects
ASTM	American Society for Testing and Materials
ATSDR	Agency for Toxic Substances and Disease Registry
Au	gold
BAM	Betta attenuation monitor
CARA	Conservation of Agricultural Resources Act No. 43 of 1983
CBD	Central business district
CDSM	Chief Directorate: Surveys and Mapping
CIL	Carbon-in-leach
CM	Chamber of Mines of South Africa
COD	Chemical oxygen demand
CPI	Consumer price index
CSIR	Council for Scientific and Industrial Research
DEAT	Department of Environment and Tourism, Republic of South Africa
DME	Department of Minerals and Energy, Republic of South Africa
DME (QLD)	Department of Minerals and Energy, Queensland, Australia
DSS	Decision-support system
DST	Decision-support tool

DWAF	Department of Water Affairs and Forestry, Republic of South Africa
EC	Electrical conductivity
ECA	Environmental Conservation Act No. 73 of 1989
Ed.	Editor
Eds.	Editors
EIA	Environmental impact assessment
EMF	Environmental management framework
EMP	Environmental management plan
EMPR	Environmental management programme report
EMProgramme	Environmental management programme
EPA	Environmental Protection Agency
ERGO	East Rand Gold and Uranium Company Limited
ERWAT	East Rand Water
ESRI	Environmental Systems Research Institute
et al.	‘et alia’; and others
FP	Fine particulates
GDACE	Gauteng Department of Agriculture, Conservation and Environment
GDP	Gross domestic product
GIS	Geographical information system
GN	Government notice
GPS	Geographical positioning system
HDS	High-density separation
i.e.	‘id est’; in other words; that is
IAP	Interested and affected party
IDP	Integrated development plan
IEM	Integrated environmental management

IEPD	Integrated environmental planning and design
IIED	International Institute for Environment and Development
IP	Inhalable particulates
Ir	Iridium
IUCN	International Union for the Conservation of Nature and Natural Resources
k	Permeability
kg	Kilogram
kt	Kiloton
LDO	Land development objectives
LI	Landscape Institute
m	Metre
M	Mega (10^6)
m.a.s.l.	Metres above sea level
m/s	Metre per second
m^3	Cubic metre
MA	Minerals Act No. 50 of 1991
MAA	Multiple accounts analysis
MAC	Mining Association of Canada
mm	Millimetre
MMSD	Mining, Minerals and Sustainable Development
MPRDA	Minerals and Petroleum Resources Development Act No. 28 of 2002
MRD	Mine residue deposit
Mt	Mega tonne
Mtpm	Mega tonne per month
NA	Not available
NCHM	National Cultural History Museum

NEDLAC	National Economic Development and Labour Council
NEMA	National Environmental Management Act No. 107 of 1998
NGT	Nominal group technique
NHMRC	National Health and Medical Research Council
NPV	Net present value
NR	Not relevant
NRF	National Research Foundation
NSW EPA	New South Wales Environmental Protection Agency
NWA	National Water Act No. 36 of 1998
Os	Osmium
OVA	Objective valuation approaches
ozt	Troy ounce (32,151 ozt = 1000 g)
p.	Page
Pd	Palladium
PGE	Platinum group element
PGM	Platinum group metal
PM_{10}	Fine particles with aerodynamic diameters less than 10 µm
$PM_{2,5}$	Fine particles with aerodynamic diameters less than 2,5 µm
pp.	Pages
Pt	Platinum
q	Darcy flux
RA	Risk assessment
Rh	Rhodium
RO	Reverse osmosis
RP	Respirable particulates
RPM	Rustenburg Platinum Mines (Pty) Ltd

RQO	Resource quality objective
RSA	Republic of South Africa
Ru	Ruthenium
RUSLE	Revised Universal Soil Loss Equation
s	Second
SABS	South African Bureau of Standards
SAHRA	South African Heritage Resources Agency
SEA	Strategic environmental assessment
SEF	Strategic Environmental Focus (Pty) Ltd
SP	Suspended particulates
SRK	Steffen Robertson and Kirsten (Pty) Ltd
SVA	Subjective valuation approach
TDF	Tailings disposal facility
TDS	Total dissolved solids
TEOM	Tapered element oscillating microbalance
THRIP	Technology and Human Resources for Industry Programme
tpa	Dry tonnes per annum
tpm	Dry tonnes per month
TSF	Tailings storage facility
TSP	Total suspended particulates
TSS	Total suspended solids
TWQR	Target water quality ranges
UP	University of Pretoria
US EPA	United States Environmental Protection Agency
USGS	United States Geological Survey
USLE	Universal Soil Loss Equation

VAC	Visual absorption capacity
VIA	Visual impact assessment
Vol.	Volume
WDCS	Waste discharge charge system
WHO	World Health Organisation
WRC	Water Research Commission
WSSD	World Summit on Sustainable Development
WWCW	Waste water care works
ZVI	Zone of visual influence

List of technical terms

acid mine drainage	Also referred to as acid mine drainage (AMD) or acid rock drainage (ARD). Acid drainage is the seepage of sulphuric acid solutions from mines and tailings, produced by the interaction of oxygen in ground and surface water with sulphide minerals exposed by mining (DME, 2006:4).
aquifer	Bear (1979) and NWA (1998) describes an aquifer as a geologic formation, or group of formations such as porous, water-saturated layers of sand, gravel, or bed rock which contains water and permits significant amounts of water to move through it under ordinary field conditions. Parsons (2004) describes it as strata or a group of interconnected strata comprising of saturated earth material capable of conducting groundwater and of yielding useable quantities of groundwater to borehole(s) and/ or springs(a supply rate of 0,1 L/s is considered a useable quantity). The emphasis of UNEP's definition is on a geologic formation's ability to yield an economically significant amount of water (UNEP, 2005:80).
bulk density	The mass of dry soil per unit bulk volume. The bulk volume is determined before drying to constant mass at 1050 *°C*. Values range roughly from 1000 - 1800 kg/m^3, although higher values may be found in compacted soils (van der Walt and van Rooyen, 1990: 20).
chemical oxygen demand	Chemical oxygen demand (COD) is an indicator of the potential environmental impact of effluent to water. The COD is a laboratory measure of the quantity of oxygen required to oxidise the constituents of a liquid effluent. The lower the COD, the lower the potential for reduction in the concentration of dissolved oxygen in the receiving water (UNEP, 2005:80).
closure	A process which begins during the pre-feasibility phase of a mining project, and continues through operations to lease relinquishment. It sets clear objectives and guidelines, makes financial provision and establishes effective stakeholder engagement leading to successful relinquishment of lease (DME, 2006:4).
concentrate	Concentrate is the product of ore treatment and contains metal at a higher concentration than the source ore. In metallurgical processes for the production of nickel and copper, concentrate is smelted to produce a metallic compound suitable for further refining (UNEP, 2005:80).

concentration	The purpose of concentration is to separate those particles with high values (concentrate) from those with lower values (tailings). Methods for concentration vary according to ore type, but three general classes are in use: gravity separation, magnetic separation, and froth flotation (Vick, 1983:6).
configuration	Configuration is the term use to refer to a particular combined arrangement of embankment side slope and cover for an impoundment which can result in several configurations.
confined aquifer	A confined aquifer is a formation in which the groundwater is isolated from the atmosphere at the point of discharge by impermeable geologic formations; confined groundwater is generally subject to pressure greater than atmospheric.
conservation	The management of the biosphere so that it may yield the greatest sustainable benefit to present generations while maintaining its potential to meet the needs and aspirations of future generations. The wise use of natural resources to prevent loss of ecosystem function and integrity.
contamination	The introduction of any poisonous or polluting substance into the environment (Parsons, 2004 and Oxford, 2002).
cumulative effects	The summation of effects that result from changes caused by a development on conjunction with other past, present or reasonably foreseeable actions (LI, 2002:119).
dam	The term includes any settling dam, slurry dam, evaporation dam, catchment or barrier dam and any other form of impoundment used for the storage of unpolluted water or water containing waste (DWAF, 1999).
decision	A decision is defined as an action that must be taken when there is no more time for gathering facts (Moody, 1983:4).
decision-making	The sequence of steps, actions or procedures that result in decisions, at any stage of a scheme (DEAT, 2002:21).
decision-support system	A decision-support system (DSS) is a system that supports decision making by assisting in the organisation of factors and relations between the latter within a rational framework (Sage, 1991:1).
decommissioning	The activity or process that begins after cessation of mineral production (including metallurgical plant production) and ends with closure. It involves, inter alia, the removal of unwanted infrastructure, the making safe of dangerous excavations and surface rehabilitation with a view to minimising the adverse environmental impacts of mining activities remaining after cessation of mineral production. It includes the aftercare or maintenance that may be needed until closure (CM, 1996:1).

deposit	A dump, heap, pile or filling which usually projects above the natural ground surface. Deposits can be formed by mechanical or hydraulic deposition of material. Deposit includes terms such as slimes dams, tailings impoundments, and mineral, tailings, course waste and waste-rock dumps (CM, 1996:1).
dirty water system	The term includes any dam, other form of impoundment, canal, works, pipeline, residue deposit and any other structure or facility constructed for the retention or conveyance of water containing waste (DWAF, 1999).
dispersion (groundwater)	Dispersion is the measure of spreading and mixing of chemical constituents in groundwater caused by diffusion and mixing due to microscopic variations in velocities within and between pores.
disposal *versus* deposition	From a larger point of view, it is only tailings deposition i.e. placement that ceases at the end of the operation stage and not the disposal thereof. Tailings management will and must continue until such time as the deposited tailings is assured to be permanently stable and environmentally innocuous (Vick, 1983:324).
dolerite	A fine-grained gabbro. In RSA usage, the preferred term for what is called diabase in the U.S.A. Etymol. Greek doleros, deceitful, in reference to the fine-grained character of the rock which makes it difficult to identify megascopically (van der Walt et al., 1990: 43).
ecosystem	Organisms together with their abiotic environment, forming an interacting system, inhabiting an identifiable space.
effective soil depth	The depth of soil material that plant roots can penetrate readily to obtain water and plant nutrients. The depth to a layer that differs sufficiently from the over-lying material in physical or chemical proper-ties to prevent or seriously retard the growth of roots (van der Walt et al., 1990: 47).
effluent	Liquid fraction of the tailings slurry or pulp with soluble chemicals.

environment	Environment has a number of definitions depending on the context:
	• environment means the aggregate of surrounding objects, conditions and influences that influence the life and habits of man or any other organism or collection of organisms (ECA, 1989);
	• environment means the surroundings within which humans exist and that are made up of:-
	  • the land, water and atmosphere of the earth;
	  • micro organisms, plant and animal life;
	  • any part or combination of the afore-mentioned and the interrelationships among and between them; and
	  • the physical, chemical, aesthetic and cultural properties and conditions of the foregoing that influence human health and well-being (NEMA, 1998);
	• environment means the associated cultural, social, soil, biotic,

atmospheric, surface an ground water aspects associated with landfill that are, or could potentially be, impacted on by the landfill (DWAF, 1998:G-4);

- or the environment is defined as those parts of the socio-cultural, biophysical and economic environment affected by the scheme (DEAT, 2002:20).

environmental impact	An environmental impact is any change in a state of any component of the environment, whether adverse or beneficial, such as water, air, land, natural resources, flora, fauna, and that wholly or partially results from activities, projects or developments (DEAT, 2002:20 and SABS, 1998:5).
erosion	Erosion includes a group of processes by which soil are entrained and transported across a given surface through the action of water, wind, ice or other agents, including the subsidence of soil (CARA, 1983; Galetovic, 1998:1-1).
facility	The term "facility", in relation to an activity, includes any installation and appurtenant works for the storage, stockpiling, disposal, handling or processing of any substance (DWAF, 1999:2).
fatal flaw	Any problem, issue or conflict (real or perceived) that could result in a scheme being rejected or stopped (DEAT, 2002:21).
fault	A fault is a fracture or a zone of fractures along which there has been displacement.
fauna	The animal life of a region.
flora	The plant life of a region.
flux	Flow of energy, fluid, or particles per unit of area per unit of time (Park, 2007).
forb	A herbaceous plant other that grasses.
freeboard	The vertical height difference between the lowest point on the perimeter wall and the supernatant water level on the dam at any time (SABS, 1998:5).
geographical information system	Computerised database of geographical information that can be easily updated and manipulated (LI, 2002:119).
gradation	Gradation refers to the grain size distribution.
grassland	A natural vegetation formation type in which grasses and forb species are dominant.
groundwater	Also known as subsurface water is water occurring below the ground in the saturated zone. (Bear, 1979). Water found in the subsurface in the saturated zone below the water table or piezometric surface, i.e. the water table marks the upper surface of groundwater systems (Parsons, 2004).

groundwater resource	Subterranean water that occurs naturally or that can be obtained from below the ground surface, of such quality and in such quantities as would be required to sustain a recognised water use (SABS, 1998:5).
groundwater table	Groundwater table is the surface between the zone of saturation and the zone of aeration – i.e. the surface of an unconfined aquifer.
gully erosion	The erosion process whereby water accumulates in narrow channels and, over short periods, removes the soil from this narrow area to considerable depths, ranging from 300 mm to 600 mm to more than 20 m (van der Walt et al., 1990:50).
habitat	Type of environment in which fauna and flora lives.
hazard	Hazard refers to the capacity of a substance, a structure, an activity or an event to produce an adverse effect on life or property, including health, safety or environment (DME (QLD), 1995).
hydraulic conductivity	Hydraulic conductivity (*k*) is a measure of the amount of water transmitted through a porous medium in unit time under a unit hydraulic gradient through a unit area measured perpendicular to the area (Vick, 1983:257). Also known as permeability.
hydraulic gradient	The term hydraulic gradient can imply a hydraulic potential gradient, hydraulic pressure gradient or hydraulic head gradient. In each case the gradient is the change in magnitude (of potential, pressure or head) per unit of distance in the direction of maximum rate of increase thereof. The hydraulic gradient generally determines the rate and direction of water flow in soil (van der Walt et al., 1990: 148).
hydraulic head	The elevation with respect to a specified reference level at which water stands in a piezometer connected to the point in question in the soil. Its definition can be extended to soil above the water table if the piezometer is replaced by a tension meter. The hydraulic head in systems under atmospheric pressure may be identified with a potential expressed in terms of the height of a water column. More specifically it is the sum of the gravitational and hydrostatic pressure (or metric) potentials, expressed as a head (H = hg + hp) (van der Walt et al., 1990: 148).
hypothesis	A supposition or proposed explanation made on the basis of limited evidence as a starting point for further investigation (Oxford, 2002:570).
indigenous	Any species of plant, shrub or tree that occurs naturally in South Africa.

land capability	This is the extent to which land can meet the needs of one or more uses under defined conditions of management, including climate, on the total suitability for use without damage for crops that require regular tillage, for grazing, for woodland, and for wildlife. Land capability involves consideration of (i) the risks of land damage from erosion and other causes and (ii) the difficulties in land use owing to physical land characteristics, including climate (van der Walt et al., 1990: 79).
land use	The primary use of the land, including both rural and urban activities (LI, 2002:120). Land use is not a feature of the environment as such but represents the current status of the land surface as a whole and therefore also reflects the condition of the environment (van Riet et al., 1997:13)
landform	An element of and within the landscape with specific shape characteristics. This may also refer to an artificial element which can be compared to a natural landform and is subject to the same geomorphologic processes (Rademeyer and van den Berg, 2005; Park, 2007). It is the combinations of slope and elevation that produce the shape and form of the land (LI, 2002:120).
landscape	Depending on the context, landscape can have any of the following meanings: • Scenery, either natural or modified by human activities which is often used to refer to scenery that can be seen from a single viewpoint (Park, 2007). • All the natural features, such as fields, hills, forests, and water that . distinguish one part of the earth's surface from another pad; usually. that portion of land or territory which the eye can comprehend in a 6 single .view (van der Walt et al., 1990: 81). • Landscape is made up of a landform component (topography), landcover (vegetation, built form, soil colour, water and other man-made infrastructure), and atmospheric conditions. • A tract of land with its distinguishing characteristics and features, especially considered as a product of shaping processes and agents (DME, 2006:4). • Human perception of the land conditioned by knowledge and identity with a place (LI, 2002:120).
leaching	Leaching involves removal of minerals from the ground particles by direct contact with solvent, usually a strong acid or alkaline solution depending on the type of ore (Vick, 1883:8).
mine residue	Mine residue includes any debris, discard, tailings, slimes, screenings, slurry, rock, foundry sand, beneficiation plant waste, ash and any other waste product derived from or incidental to the operation of a mine or activity and which is stockpiled, stored or accumulated for potential re-use or recycling or which is disposed of (DWAF, 1999:2).

mine residue deposit	Mine residue deposit includes any dump, tailings impoundment, slimes dam, ash dump, rock dump, in-pit deposit and any other heap, pile or accumulation of residue remaining at termination, cancellation or expiry of a prospecting right, mining right, mining permit, exploration right or production right (MPRDA, 2002).
mine residue deposit	The term Mine Residue Deposit (MPRDA, 2002:16) is the generic term used for describing mining waste to the panel of visual experts participating in the research, whereas the terms Tailings Disposal Facility (TDF), tailings dam and tailings impoundment are interchangeably used throughout this thesis.
mine residue stockpile	Mine residue stockpile means any debris, discard, tailings, slimes, screening, slurry, rock, foundry sand, beneficiation plant waste, ash or any other product derived from or incidental to a mining operation and which is stockpiled, stored or accumulated for potential re-use, or which is disposed of, by the holder of a mining right, mining permit or production right (MPRDA, 2002).
mineral	A mineral includes inter alia sand, soil, clay, gravel, rock, ore, coal and tailings. A mineral occurs in, on or under the earth, water or tailings, as a liquid, solid or gas (DME, 2000).
mineral waste	Mineral wastes comprise of; mined rock, which has no economic ore, tailings, which are the fine sand like residue after the mineral has been extracted from the rock and slag, which is the solid residue from the smelting process. The generation of mineral wastes is directly related to ore type, economic grade and the type of mine (DME, 2006:4).
mineral waste deposits	Mined rock particles, varying in size, that contain no economically viable ore (DME, 2006:4).
mineral waste residues	Refers to tailings impoundments, slimes dams, rock dumps and sand dumps (DME, 2006:4).
mining	Mining is the making of any excavation for the purpose of winning a mineral, and it includes any other associated activities and processes (DME, 2000).
mitigation	Measures including any process, activity or design to avoid, reduce, remedy or compensate for adverse landscape and visual effects of a development project (LI, 2002:121).
non-renewable resources	Resources that exist in a fixed quantity in the earth's crust and thus theoretically can be completely depleted are called non-renewable resources. It must be noted that these resources can be depleted much faster than they are formed.
ore	Metalliferous rock from which metallic compounds are extracted as valuables.

overburden	Material recently deposited by a transportation mode that occurs immediately adjacent to the surface horizon of a contemporaneous soil. A term used to designate disturbed or undisturbed material of any nature, consolidated or unconsolidated, that overlies a deposit of useful materials, ores, lignites, or coals, especially those deposits mined from the surface by open cuts (van der Walt et al., 1990: 100).
partial closure	The closure of a part, section or portion of a mine. The environmental management issues that need to be addressed for partial closure are the same, as those required for closure of the whole mine.
particulates	Fine solid particles which remain individually dispersed in air (UNEP, 2005:81).
permeability	A measure of the rate at which water can percolate through soil or rock, usually expressed in cubic metres per second (m^3/s). Also known as hydraulic conductivity (Park, 2007).
phreatic aquifer	An aquifer in which a water table (= phreatic surface) serves as its upper boundary. A phreatic aquifer is directly recharged from the ground surface above it, except where impervious layers exist between the phreatic surface and the ground surface (Bear, 1979).
phreatic surface	The phreatic surface is the level of saturation in the impoundment and the embankment – i.e. the surface along which pressure in the fluid equals atmospheric pressure. In natural systems without flow it is often equal to the water table.
pioneer species	Hardened, annual plants, which can grow in very unfavourable conditions. Benefits of having these species include less runoff and more available moisture, cooler soil surfaces and less evaporation, protection against wind and build up of organic matter thereby increased enrichment of the soil.
piping	Piping refers to subsurface erosion along a seepage pathway within or beneath an embankment which results in the formation of a low-pressure conduit allowing concentrated flow.
pollution	Pollution is the contamination of resources such as water, air, soil and land with harmful or poisonous substances.
porosity	Porosity is the percentage of the bulk volume of a rock or soil that is occupied by interstices, whether isolated or connected.
post-closure after use	The use of which a mining site, or part of a site, is determined when mineral extraction is completed.
potentially renewable resource	A potentially renewable resource can be renewed fairly rapidly (hours to several decades) through natural processes. Examples of such resources include forest trees, grassland grasses, wild animals, fresh lake and stream water, fresh air, and fertile soil.

qualitative	Relating to or involving comparisons based on qualities.
quantitative	Expressible as a quantity or relating to or concerned with the measurement by quantity (Oxford, 2002:955).
rare species	Species, which have naturally small populations, and species, which have been reduced to small (often unstable) populations by man's activities.
reclamation	The return of a disturbed site to an agreed-upon land use.
red data	A list of species, fauna and flora that require environmental protection. Based on the IUCN definitions.
rehabilitation	The return of disturbed land to a stable, productive and self-sustaining condition, after taking into account beneficial uses of the site and surrounding land.
remediation	The clean-up or mitigation of pollution or of contamination of soils or water by pre-determined methods.
renewable resources	Solar, wind and wave energy is considered to be a renewable resource because on a human time scale it is essentially inexhaustible. It is expected to last at least 6,5 billion years while the sun completes its life cycle.
residue	Residue includes any debris, discard, tailings, slimes, screenings, slurry, rock, foundry sand, beneficiation plant waste, ash and any other waste product derived from or incidental to the operation of a mine or activity and which is stockpiled, stored or accumulated for potential re-use or recycling or which is disposed of (DWAF, 1999:2).
residue deposit	The term residue deposit, includes any dump, tailings impoundment, slimes dam, ash dump, rock dump, in-pit deposit and any other heap, pile or accumulation of residue (DWAF, 1999).
residue deposit	Means any residue stockpile remaining at termination, cancellation or expiry of a prospecting right, mining right, mining permit, exploration right or production right (MPRDA, 2002).
residue stockpile	means any debris, discard, tailings, slimes, screening, slurry, rock, foundry sand, beneficiation plant waste, ash or any other product derived from or incidental to a mining operation and which is stockpiled, stored or accumulated for potential re-use, or which is disposed of , by the holder of a mining right, mining permit or production right (MPRDA, 2002).
resource	Resources whose location, grade and quality are known, or estimated from specific geological evidence, and includes economic, marginally economic and sub-economic components. It also encompasses demonstrated and inferred subdivisions (DME, 2000a).

restoration	Recreating the original topography and re-establishing the previous land use in a self-sustaining condition.
rill erosion	An erosion process in which numerous small channels a few centimetres deep are formed; occurs mainly on recently cultivated soils (van der Walt et al., 1990: 50).
ring dike impoundment layout	The ring dike impoundment layout method is best suited for flat terrains and requires a relatively high quantity of embankment fill in relation to the storage volume produced. Also, ring-type impoundments are usually laid out with a regular geometry (Vick, 1983: 119).
risk	Risk refers to a combination of the probability, or frequency, of occurrence of a defined hazard and the magnitude of the consequences of the occurrence. Hazard refers to an attribute or situation that in particular circumstances could lead to harm (DEFRA, 2000). Risk, in relation to tailings impoundments, includes the potential for failure leading to the flow of slurry or the discharge of tailings or seepage into the environment through mechanisms such as wind and water resulting in environmental impacts.
runoff	That portion of the precipitation on an area which is discharged from the area through stream channels, That which is lost without entering the soil is called surface runoff and that which enters the soil before reaching the stream is called ground water runoff or seepage flow from ground water. (In soil science "runoff" usually refers to the water lost by surface flow; in geology and hydrology "runoff" usually includes both surface and subsurface flow) (van der Walt et al., 1990: 116).
saltation	A mode of sediment transport in which the particles are moved progressively forward in a series of short intermittent leaps, jumps, hops or bounces from a surface; e.g. sand particles skipping downwind by impact and rebound along a desert surface, or bounding downstream under the influence of eddy currents that are not turbulent enough to retain the particles in suspension and thereby return them to the stream bed at some distance downstream (van der Walt et al., 1990: 116).
saturated zone	The subsurface zone below the water table where interstices are filled with water under pressure greater than that of the atmosphere (Parsons, 2004).
scenario	A picture of a possible feature (LI, 2002:121).

sediment	(1) Any material carried in suspension by water, which would settle to the bottom if the water lost velocity. (2) Fine water-borne matter deposited or accumulated in beds. Sediment is ordinarily transported as suspended sediment, by saltation or as bed load (van der Walt et al., 1990: 11p).
sediment yield	The sediment yield from a surface is the sum of the soil losses minus deposition in macro-topographic depressions, at the toe of the hill slope, along field boundaries, or in terraces and channels sculpted into the hill slope (Galetovic, 1998:1-1).
sheet erosion	The removal of a fairly uniform layer of soil from the land surface by runoff water (van der Walt et al., 1990: 50).
significance	Impact magnitude is the measurable change, i.e. intensity, duration and likelihood. Impact significance is the value placed on the change by different affected parties, i.e. level of significance and acceptability. It is an anthropocentric concept, which makes use of value judgements and science-based criteria, i.e. socio-cultural, biophysical and economic. Such judgements reflect the political reality of impact assessment in which significance is translated into public acceptability of impacts (DEAT, 2002:21).
simulation	Simulation is to create a representative and accurate two-dimensional image of a future or proposed scheme through the use of computer modified photographs and computer graphics.
slope	The vertical difference in height between the highest and the lowest points of a portion of land. The ratio method defines slope as a ratio of the horizontal distance to the vertical elevation difference. The percentage method defines slope as a percentage, dividing the difference in the vertical elevation by the horizontal distance and converting this decimal to a percentage.
slope aspect or slope orientation	The slope and direction of the land surface. Combines with the sun's vertical angle and planar direction to determine the relative amount of solar radiation incident on the ground surface at any given time (Motloch, 2001).
soil	A mixture of organic and inorganic substances, the composition and structure of the latter is derived from the parent rock material. Soil also contains bacteria, fungi, viruses and micro-arthropods, nematodes and worms.
soil loss	Soil loss is that material actually removed from the particular hill slope or hill slope segment. The soil loss may be less than erosion due to on-site deposition in micro-topographic depressions on the hill slope (Galetovic, 1998:1-1).

species diversity	A measure of the number and relative abundance of species (see biodiversity).
species richness	The number of species in an area or habitat.
sphere of influence	Sphere of influence is the term used in this report to describe the three-dimensional mine residue storage or disposal facility zone of influence within which an effect on the environment is anticipated. This zone is the spatial overlay or sum of the different environmental aspect zones of influence and is also representative of a particular configuration at a specific moment in time.
spigotting discharge method	Spigotting accomplishes the deposition of an above-water tailings beach around the perimeter of a tailings impoundment and requires the tailings discharge pipe be relocated periodically to from a series of adjacent and overlapping deltas (Vick, 1983:10).
spoil	Bulk waste material produced along with the marketable mineral: production waste, substandard and unmarketable material, overburden, etc. that has to be disposed of.
stakeholders	A subgroup of the public whose interest may be positively or negatively affected by a proposal or activity and/or who are concerned with a scheme or activity and its consequences. The term therefore includes the proponent, authorities and all interested and affected parties (IAPs) (DEAT, 2002:23).
stockpile	The term "stockpile", includes any heap, pile, slurry pond and accumulation of any substance where such substance is stored as a product or stored for use at any mine or activity (DWAF, 1999).
subsoil	Subsoil means those layers of soil and weathered rock immediately beneath the topsoil that overlay the hard rock formation.
subsurface water	All water found below the surface of the earth, including soil water, capillary water and groundwater (Parsons, 2004:2-3).
sustainable development	Sustainable development means the integration of social, economic and environmental factors into planning, implementation and decision making so as to ensure that mineral and petroleum resources development serves present and future generations (MPRDA, 2002 and NEMA, 1998).
tailings	Tailings is any fine-grained waste materials from metallurgical processing including slimes and residue. It mainly comprises finely ground rock and may contain process chemical residues (DME, 2000; UNEP, 2005:80; Vermeulen, 2002).
tailings storage facility	TSF - The overall area used to confine tailings, and may include one or more tailings impoundment compartment. The facility's functions are to provide a site for waste residue disposal, achieve solids settling and improve water quality.

threatened species	Species, which have naturally small populations, and species, which have been reduced to small (often unstable) populations by man's activities.
threshold	A specified level in grading effects, for example, of magnitude, sensitivity or significance (LI, 2002:121).
topsoil	The upper layer of soil which supports plant growth. Generally this layer contains nutrients, organic matter and seed (UNEP, 2005:82).
total dissolved solids	Total dissolved solids (TDS) is a term that expresses the quantity of dissolved material in a sample of water.
transmissivity	Transmissivity (T) is the rate at which groundwater can flow through an aquifer and is defined as the product of hydraulic conductivity and saturated aquifer thickness (Park, 2007; Vick, 1983:257).
upstream raising method	This raising method requires that a starter dike is constructed, and the tailings is discharged peripherally from the crest to form a beach. The beach then becomes the foundation for a second perimeter dike. This process continues as the embankment increases in height (Vick, 1983:71).
VAC	Visual Absorption Capacity is the capacity the surrounding environment has to camouflage or reduce the visual impact of the impoundment.
vadose zone	Vadose zone is the zone containing water under pressure less than that of the atmosphere, including soil water, intermediate vadose water, and capillary water. This zone is that between the land surface and the surface of the zone of saturation, that is, the water table.
variable	The term variable refers to whatever characteristic being investigates or analysed (Wisniewski, 1997:15).
visual absorption capacity	Visual Absorption Capacity is the capacity the surrounding environment has to camouflage or reduce the visual impact of the impoundment.
visual envelope	Extent of potential visibility to or from a specific area or feature (LI, 2002:121).
visual impact	Any positive or negative change in appearance of the landscape as a result of development (Park, 2007).
visualisation	Computer simulation, photomontage or other technique to illustrate the appearance of a development (LI, 2002:121).
water table	Water table is the surface between the vadose zone and the groundwater, that surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere (Parsons, 2004).

wetlands	Areas of land that are periodically or permanently waterlogged for a sufficient period of time to sustain aquatic processes and biological activity adapted to the wet environment. Wetlands include vleis, bogs, mires, swamps, marshes, dolomitic eyes and pans.
worst-case situation	Principle applied where the environmental effects may vary, for example, seasonally to ensure the most severe potential impact is assessed (LI, 2002:121).
zone of visual influence	Area within which a proposed development may have an influence or effect on visual amenity (LI, 2002:121).

APPENDICES

The Influence of Environmental Impacts on Tailings Impoundment Design

APPENDIX A: VISUAL

Appendix A1: Details of the NGT participants

Appendix A2: Presentation of Visualisations to experts

Appendix A3: Presentation of Visualisations to experts

Appendix A4: Zone of visual perception results

Appendix A1: Details of the NGT study participants

The following people, listed alphabetically, were on the panel of experts for the visual perception study using the nominal group technique study method.

Bakker, K.A.
Breedlove, G.
Fisher, R.
Gärtner, R.
Hindes, C.
Marais, V.
O'Rourke, E.
Rademeyer, B.
Rust, E.
Saidi, F.
Trichard, L.G.
van den Berg, M.J.
van Rensen, C.
van Wyk, F.H.
Vosloo, P.
Young, G.A.

CREDENTIALS

Bakker Karel A

Personal information

Nationality:	South African
Parent Firm:	University of Pretoria
Home language:	English / Afrikaans

Educational qualifications

- PhD (Arch) - University of Pretoria (January 2001)
- M.Arch (cum laude) - University of Pretoria (1993)
- B.Arch - University of Pretoria (1981)

Registration

- Member of the SA Council of Architects
- Member South African Institute of Architects National Heritage Committee
- Member of the International Committee on Monuments and Sites (ICOMOS). (The International Committee on Monuments and Sites is an international conservation body)

Key areas of expertise

- Prof Bakker is a professor at the Department of Architecture at the University of Pretoria and also practices as an architect with Cultmatrix CC (Heritage Management Consultants). His main fields of research are: Archaic Greek architecture, African architecture and settlement, urban regeneration and heritage management.

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CREDENTIALS

Breedlove Gwen

Personal information

Nationality:	South African
Parent Firm:	African EPA / University of Pretoria
Position:	Associate Professor
Home language:	English / Afrikaans

Educational qualifications

- PhD (Cultural landscape evaluations) – University of Pretoria (2003)
- ML.Arch - Texas A&M University (1986)
- BL.Arch - University of Pretoria

Registration

- Pr. LArch (SA)

Key areas of expertise

- Co-ordination, compilation, editing and review of Environmental Impact Assessments and Scoping Reports for linear and other type of projects regulated under the Environmental Conservation Act.
- Writing of Environmental Management Programme Reports (EMPRs), and Environmental Assessments and Environmental Management Programmes (EMPs) required by the Mineral and Petroleum Resources Development Act for platinum, coal, clay and aggregate mines.
- Master plan development.
- The compilation and editing of Scoping Reports.
- Visual impact assessments.
- Design and drawing of landscape plans, details, concepts and presentation perspectives for various projects.
- Art and Aesthetics in the Landscape.
- Cultural Landscape identification and classification.
- Social Ecology.
- Landscape classifications.
- Environmental Potential Atlas for South Africa with the Dept. of Env. Affairs and Tourism.
- Environmental Management Framework for South Africa with Dept. of Env. Affairs and Tourism.
- Tourism Potential Atlas for South Africa with Dept. of Env. Affairs and Tourism.

CREDENTIALS

Fisher Roger

Personal information

Nationality:	South African
Parent Firm:	University of Pretoria
Position:	Professor in Architecture
Home language:	English / Afrikaans

Educational qualifications

- PhD (Arch) - University of Pretoria (1993)
- M.Arch (cum laude) - University of Pretoria (1989)
- B.Arch - University of Pretoria (1982)

Registration

- Member of the SA Council of Architects

Key areas of expertise

- Prof Fisher is a professor at the Department of Architecture at the University of Pretoria and has been lecturing at the University for more than 20 years. He acted as Head of the Department of Architecture for the period April 2003 to August 2004. Prof Fisher has also published extensively in the fields of architecture, architectural conservation and heritage, and sustainability and the built environment.

CREDENTIALS

Gärtner Renate

Personal information

Nationality:	South African
Parent Firm:	Strategic Environmental Focus (Pty) Ltd
Position:	Project Advisor: Environmental Management Unit
Home language:	German/English/Afrikaans

Educational qualifications

- Fasset Leadership and Management Course (2004)
- Course in Environmental Law, Policy, Assessment and Reporting (2000)
- Registered as Tour Guide for Gauteng (1997)
- BL.Arch - University of Pretoria (1991)

Registration

- Certified Environmental Assessment Practitioner of South Africa
- Registered as a Professional Landscape Architect with the South African Council for the Landscape Architectural Profession

Key areas of expertise

- Environmental Impact Assessment

Project managed and undertook numerous Scoping Reports, Exemption applications and Environmental Management Plans, as required by the Environment Conservation Act No. 73 of 1989. Project experience includes the establishment of various housing typologies, infrastructure development (including roads and pipelines), resorts and filling stations as well as community development and social upliftment projects. Involved in various Blue IQ Projects funded by the Gauteng Provincial Government, which include the City Deep Industrial Development Zone, The Innovation Hub and the Automotive Supplier Park.

- Landscape Architecture

Professional experience includes the development of master plans and landscape development plans for rezoning applications. Involved in landscape designs, concepts, construction details, site inspections and maintenance supervision. Production of sketch designs, design proposals, cost estimations and motivational reports. Worked in a team on the preparation of concepts, maps, sketches and a master plan for Gaborone. Gained international experience by working at various Landscape Architect companies in Germany.

CREDENTIALS

Hindes Clinton

Personal information

Nationality:	South African
Parent Firm:	University of Pretoria
Position:	Lecturer
Home language:	English / Afrikaans

Educational qualifications

- ML.Arch (cum laude) – University of Pretoria
- BL.Arch (cum laude) – University of Pretoria

Key areas of expertise

- Landscape architectural education and curriculum development
- Design theory of landscape architecture
- History of 20th C landscape architectural design
- Site planning and design
- PhD study commencing on the role and nature of design theory in landscape architecture practice and education

CREDENTIALS

Marais Vanessa

Personal information

Nationality:	South African
Parent Firm:	Galago Ventures
Position:	Environmental Specialist
Home language:	English/Afrikaans

Educational qualifications

- BL.Arch – University of Pretoria

Registration

- Registered as a Professional Landscape Architect with the South African Council for the Landscape Architectural Profession

Key areas of expertise

Vanessa Marais is a professional Landscape Architect and has specialized in the development of management processes and guidelines for the review of environmental impact assessments. She has been extensively involved in policy decisions relating to environmental impact management within the ambit of the national context. Her field of expertise is environmental impact management, evaluation and review with analysis of processes used for environmental impact management.

While working at a big engineering firm, her experience in the field of Environmental Impact Assessments (EIAs) has enabled her to develop mechanisms for determining impacts associated with developments as well as mitigating measures for environmental management lans (EMP). Her background as Landscape Architect is an advantage in the planning and management of environmental management frameworks (EMFs). She gained valuable experience in project management while contributing to various projects in the environmental field. This experience together with her extensive knowledge of Environmental Legislation acquired at the Department of Environmental Affairs and Tourism, makes her the ideal candidate for environmental manager. She was the project leader for the Mbombela State of the Environment Report that was undertaken in 2003 and 2004. She also used the vast experience in EIAs and EMPs and externally audited environmental conditions at three construction projects, including the Kruger Mpumalanga International Airport.

A significant project she was recently involved in is the Centurion Over-Arching Environmental Framework for which the team received a Merit Award from the Institute for Landscape Architects in South Africa (ILASA) for outstanding work in the environmental field of Landscape Architecture. She was also involved in the specialist studies for the Lesedi Environmental Framework 2005.

CREDENTIALS

O'Rourke Eamon

Personal information

Nationality:	South African
Parent Firm:	Strategic Environmental Focus (Pty) Ltd
Position:	Unit Manager: Landscape Architecture
Home language:	English / Afrikaans

Educational qualifications

- BL.Arch – University of Pretoria (1992)

Registration

- Registered as a Professional Landscape Architect with the South African Council for the Landscape Architectural Profession (SACLAP)
- Member on the SACLAP Council
- Professional member of the Institute of Landscape Architects of South Africa
- Council member on the Council for the Built Environment (CBE)
- Member on the Certification Board for the certification of Environmental Assessment Practitioners

Key areas of expertise

- Environmental Impact Assessment
- Landscape design including design frameworks, master plans, concept development and detail design
- Open space planning and management
- Environmental Management Plans
- Visual impact assessment for a variety of projects (power and transmission lines, national roads, buildings

CREDENTIALS

Rademeyer Brian

Personal information

Nationality:	South African
Parent Firm:	University of Pretoria
Position:	PhD research student
Home language:	English / Afrikaans

Educational qualifications

- M.Sc. (Geography and Environmental Management) - Rand Afrikaans University (2001)
- BL.Arch - University of Pretoria (1997)

Registration

- Certified environmental practitioner of South Africa registered with the Certification Board of Environmental Assessment Practitioners of South Africa (EAPSA).

Key areas of expertise

- Writing of Environmental Management Programme Reports (EMPRs) and Environmental Assessments and Environmental Management Programmes (EMPs) required by the Mineral and Petroleum Resources Development Act 28 of 2002 (MPRDA) for platinum, coal, clay and aggregate mines.
- Compiling of Basic Assessments, Environmental Impact Assessments and Environmental Management Plans as required by the National Environmental Management Act 107 of 1998 (NEMA).
- Master Plan development.
- Landscape design.

CREDENTIALS

Rust Eben

Personal information

Nationality:	South African
Parent Firm:	University of Pretoria
Position:	Associate Professor of Geotechnical Engineering
Home language:	English / Afrikaans

Educational qualifications

- PhD, Geotechnical Engineering - University of Surrey, UK (1997)
- M.Eng, (Cum Laude), Geotechnical Engineering - University of Pretoria (1991)
- B.Eng. (Hons), Civil Engineering - University of Pretoria (1985)
- B.Sc, Civil Engineering - University of Pretoria (1979)

Registration

- Engineer 89012 (1989)

Key areas of expertise

- Specialist knowledge of theoretical soil mechanics and advanced geotechnical design
- Geotechnical in situ testing and instrumentation,
- Numerical analysis and design
- Behaviour of tropical soils and soft clays
- Earth fill dam design
- Tailings dam analysis and design
- Risk analysis
- Environmental geo-technology
- Advanced soils laboratory testing

CREDENTIALS

Saidi Finzi

Personal information

Nationality:	Zambian
Parent Firm:	University of Pretoria
Position:	Lecturer
Home language:	English / Nyanja

Educational qualifications

- ML.Arch - University of Newcastle upon Tyne (1994)
- B.Arch - Copperbelt University (1991)

Key areas of expertise

- Lecturing in various Landscape and architectural course-modules
- Design of various buildings types
- Design Competition adjudication
- Design and drawing of landscape plans, details, concepts and presentation perspectives for various projects

CREDENTIALS

Trichard Louis G

Personal information

Nationality:	South African
Parent Firm:	LTLA Development Management
Position:	Founding member
Home language:	English / Afrikaans

Educational qualifications

- BL.Arch – University of Pretoria (1977)

Registration

- Pr. LArch (SA) 88033

Key areas of expertise

- Resource Development Strategies and Management
- Landscape Management and Maintenance
- Resort Site Utilization and Conservation
- Sports, Recreation and Public Open Space Planning
- Urban Landscaping, Design and Pedestrianization
- Cemeteries, Memorial Gardens and Memorial Parks

CREDENTIALS

van den Berg Mader J

Personal information

Nationality:	South African
Parent Firm:	Strategic Environmental Focus / University of Pretoria
Position:	Qualified landscape architect
Home language:	English / Afrikaans

Educational qualifications

- ML.Arch (Prof) - University of Pretoria (2004)
- B.Sc Hons (Landscape Architecture) - University of Pretoria (2003)
- B.Sc (Landscape Architecture) - University of Pretoria (2002)

Key areas of expertise

- Environmental landscape planning and design
- Computer aided design
- Visual impact assessment
- Graphic design
- Rehabilitation planning
- Garden design and implementation
- Irrigation design and implementation

CREDENTIALS

van Rensen Chris

Personal information

Nationality:	South African
Parent Firm:	African EPA
Position:	Director
Home language:	English / Afrikaans

Educational qualifications

- B.Eng (Civil) – University of Pretoria

Key areas of expertise

- Environmental projects
- Mining related projects
- Other Engineering related projects
- Structural Engineering
- GIS systems
- Infrastructure development engineering
- Water related projects
- Roads

CREDENTIALS

van Wyk Frans H

Personal information

Nationality:	South African
Parent Firm:	University of Pretoria
Position:	Lecturer – Department of Architecture
Home language:	English/Afrikaans

Educational qualifications

- BL.Arch – University of Pretoria

Registration

- Pr . LArch (SA)

Key areas of expertise

- Landscape Architecture
- Open Space Conservation Planning
- Urban Design
- Landscape Heritage

CREDENTIALS

Vosloo Piet

Personal information

Nationality:	South African
Parent Firm:	KWP / University of Pretoria
Position:	Director in charge of KWP Landscape Architecture Division Senior Lecturer – Department of Architecture
Home language:	English/Afrikaans

Educational qualifications

- ML. Arch (cum laude) - University of Pretoria (1990)
- B.Arch - University of Pretoria (1978)
- B.Sc (Building Science) - University of Pretoria (1974)

Registration

- Registered with the SA Council for the Architectural Profession as a Pr Arch since 1978
- Registered with the SA Council for the Landscape Architectural Profession as a Pr LArch since 1993

Key areas of expertise

- Commercial, industrial, and educational facilities
- Museums and related heritage facilities
- Landscape design in various fields
- Environmental impact assessments and scoping reports
- Environmental and urban ecological planning
- Site Master planning

CREDENTIALS

Young Graham A

Personal information

Nationality:	South African
Parent Firm:	Newtown Landscape Architects / University of Pretoria
Position:	Member Newtown Landscape Architects
	Lecturer – Department of Architecture
Home language:	English/Afrikaans

Educational qualifications

- BL.Arch - University of Toronto, Canada (1978)

Registration

- Pr. LArch (SA)

Key areas of expertise

- Landscape and urban design
- Ecological planning and design
- Environmental planning including environmental impact assessments and environmental management programmes
- Visual impact assessments
- Open space planning including frameworks, resort planning and detail urban park design
- Site and landscape design for domestic, commercial and industrial sites
- Landscape master planning for quarry end-use and landfill (solid waste) end-use plans
- Landscape rehabilitation and management

Appendix A2: Presentation of visual perception study

DELPHI RESEARCH METHOD

Delphi exercise – general information *(1 of 3)*

A Delphi exercise is a discussion by knowledgeable participants with the aim of reaching an acceptable level of agreement and consensus on the results

DELPHI RESEARCH METHOD

Delphi exercise – general information *(2 of 3)*

The Delphi exercise concept is based on the premises that:

(1) opinions of experts are justified as inputs to decision-making where absolute answers are unknown;

(2) a consensus of experts will provide a more accurate response to a question than a single expert.

DELPHI RESEARCH METHOD

Delphi exercise – general information *(3 of 3)*

The general procedures for this exercise are as follows:

(1) experts are polled on a series of visualisations;

(2) responses are tabulated, analysed, and the results fed back to the experts; and

(3) experts reconsider and evaluate their answers in light of the information generated by the aggregate responses. This process is repeated until consensus is reached.

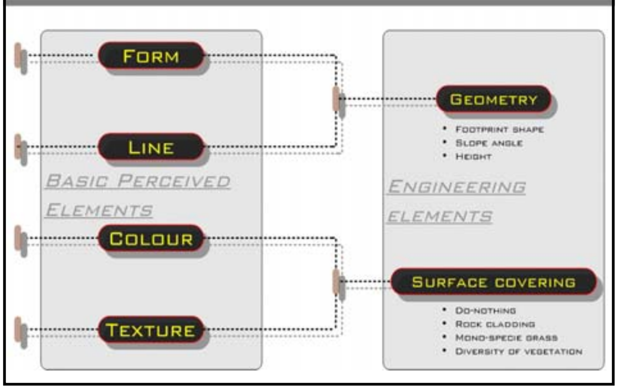
DELPHI RESEARCH METHOD

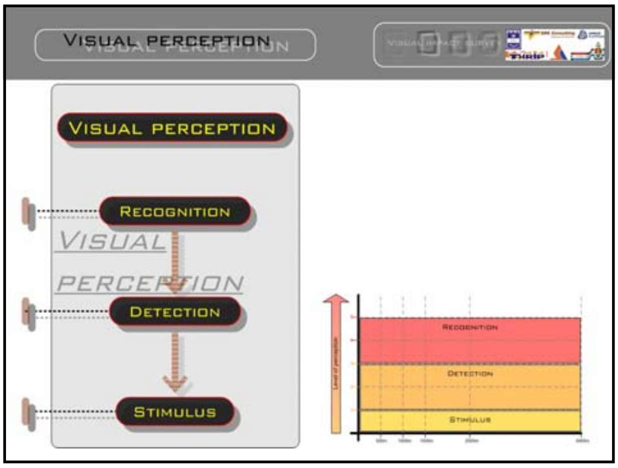
Delphi exercise – Nominal Group Technique

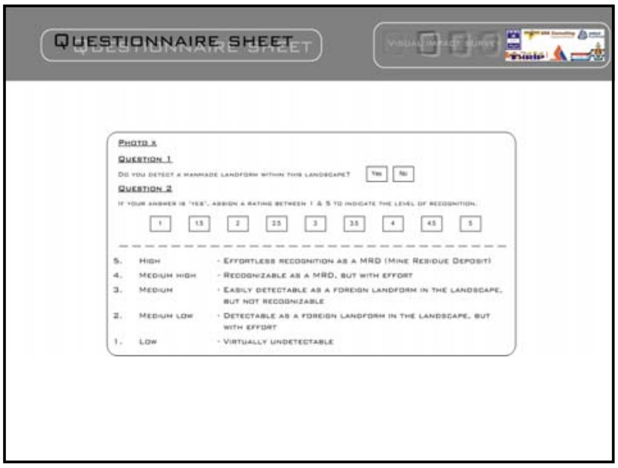
The Nominal Group Technique (NGT):

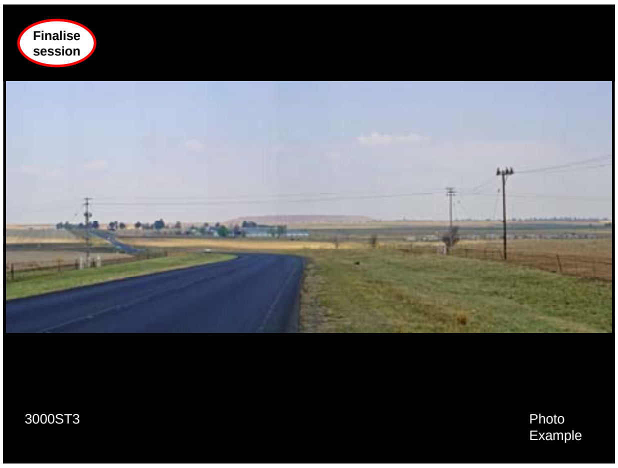
(1) employs face-to-face meetings and discussions by knowledgeable participants to obtain and combine expert opinion in the hope of reaching an agreeable conclusion; and

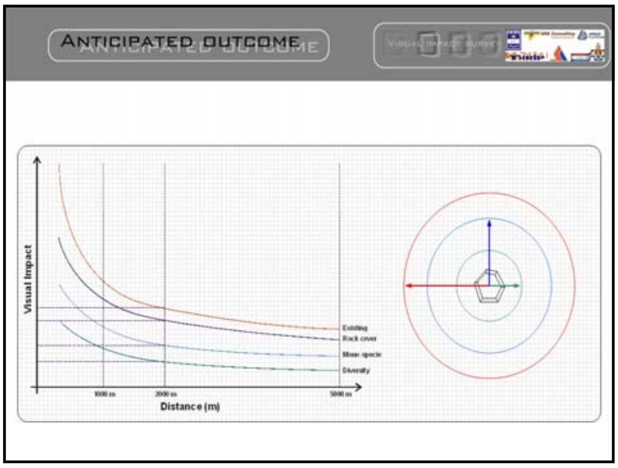
(2) allows for information to be collected in less time whereas the Delphi technique is applied where experts are not readily available or within reasonable travelling distance.




VISUAL PERCEPTION
VISUAL PERCEPTION
RECOGNITION
VISUAL PERCEPTION
DETECTION
STIMULUS
RECOGNITION
DETECTION
STIMULUS


QUESTIONNAIRE SHEET
PHOTO X
QUESTION 1
DO YOU DETECT A MANMADE LANDFORM WITHIN THIS LANDSCAPE?
Yes
No
QUESTION 2
IF YOUR ANSWER IS "YES", ASSIGN A RATING BETWEEN 1 & 5 TO INDICATE THE LEVEL OF RECOGNITION.
1 1.5 2 2.5 3 3.5 4 4.5 5
5. HIGH - EFFORTLESS RECOGNITION AS A MRD (MINE RESIDUE DEPOSIT)
4. MEDIUM HIGH - RECOGNIZABLE AS A MRD, BUT WITH EFFORT
3. MEDIUM - EASILY DETECTABLE AS A FOREIGN LANDFORM IN THE LANDSCAPE, BUT NOT RECOGNIZABLE
2. MEDIUM LOW - DETECTABLE AS A FOREIGN LANDFORM IN THE LANDSCAPE, BUT WITH EFFORT
1. LOW - VIRTUALLY UNDETECTABLE


Finalise session
3000ST3
Photo Example


ANTICIPATED OUTCOME
Visual Impact
Distance (m)
Existing
Rock cover
Diversity

Visual impact survey

25 August 2004

Click enter button to proceed with survey

7200WG6 Photo 1

3000ST3 Photo 2

8200WG3 Photo 3

800WT3 Photo 4

3000SG6 Photo 5

3600WT6 Photo 6

2000SS6 Photo 7

2500NT Photo 8

8200WD6 Photo 9

8200WR6 Photo 10

3000ST6 Photo 11

1000ST3 Photo 12

8200WG6 Photo 13

8300WT3 Photo 14

3600WG3 Photo 15

7200WT6 Photo 16

1000WG3 Photo 17

8200WT6 Photo 18

1000WD3 Photo 19

8200WR3 Photo 20

1000WR6 Photo 21

3600WS6 Photo 22

3600WT3 Photo 23

3000SR6 Photo 24

2000WT3 Photo 25

8200WT3 Photo 26

1000NT Photo 27

3000SD6 Photo 28

1000WS3 Photo29

8200WS6 Photo 30

2000SS3 Photo 31

1000WT3 Photo 32

2000SG3 Photo 33

7200WS6 Photo 34

3600WG6 Photo 35

2000SR3 Photo 36

3600WD3 Photo 37

7200WR6 Photo 38

2000SR6 Photo 39

3600WR3 Photo 40


2000ST3 Photo 41


7200WD6 Photo 42


8200WD3 Photo 43


1000WS6 Photo 44


3600WD6 Photo 45


3000SG3 Photo 46

2000SD3 Photo 47

7200WD3 Photo 48

2000ST6 Photo 49

3000SD3 Photo 50

3000SR3 Photo 51

3600WR6 Photo 52

3000SS6 Photo 53

1000WT6 Photo 54

3000SS3 Photo 55

3600WS3 Photo 56

6000WT3 Photo 57

7200WG3 Photo 58

2000SG6 Photo 59

1000WG6 Photo 60

7200WR3 Photo 61

1000WR3 Photo 62

7200WS3 Photo 63

8200WS3 Photo 64

1000WD6 Photo 65

2000SD6 Photo 66

7200WT3 Photo 67

The end. Thank you for your participation.

Appendix A3: Presentation of visual perception results

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Visual Perception Experiment

Managing the visual impact of tailings impoundments

5 October 2005

Visual Perception

DELPHI RESEARCH METHOD

- Background
- Visual impact assessment
- Experiment impoundment site
- Applying the predicted results

DELPHI RESEARCH METHOD

- **Background**
- Visual impact assessment
- Experiment impoundment site
- Applying the predicted results

DELPHI RESEARCH METHOD

Background

- *Problem statement*
- *General model*

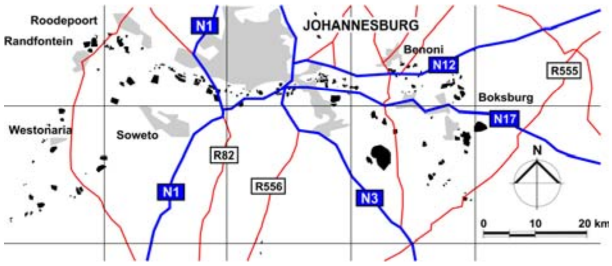
DELPHI RESEARCH METHOD

Problem statement

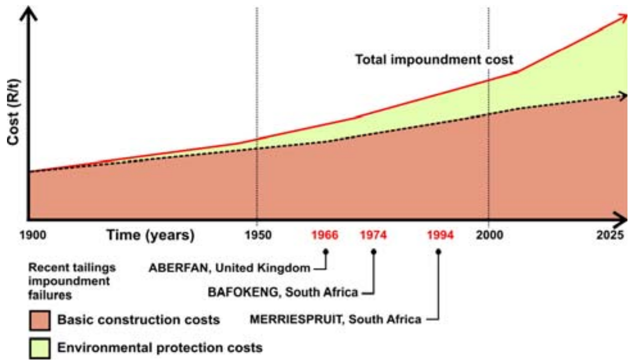
Need for rational decision-making with regard to tailings impoundment engineering costs and environmental impacts and costs

DELPHI RESEARCH METHOD

160 impoundments 15 000 ha 20 000 football fields



DELPHI RESEARCH METHOD

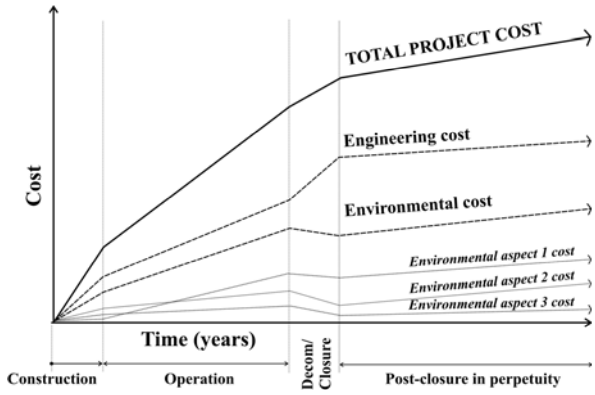


DELPHI RESEARCH METHOD

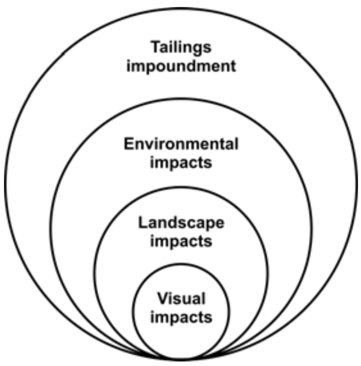
General model

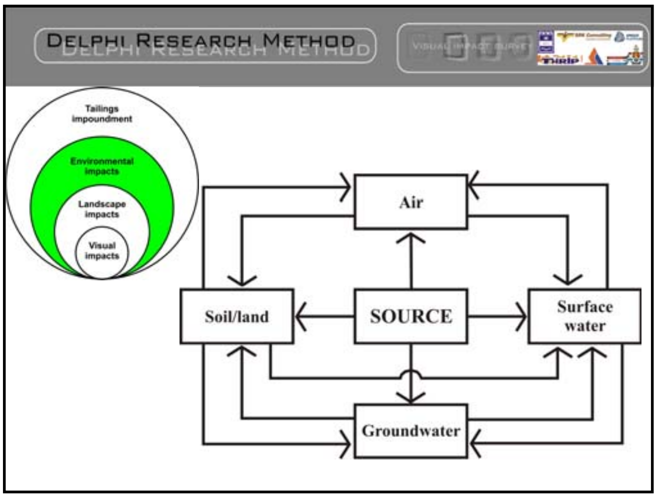
The general model being developed comprises both the basic engineering costs and environmental impacts and costs

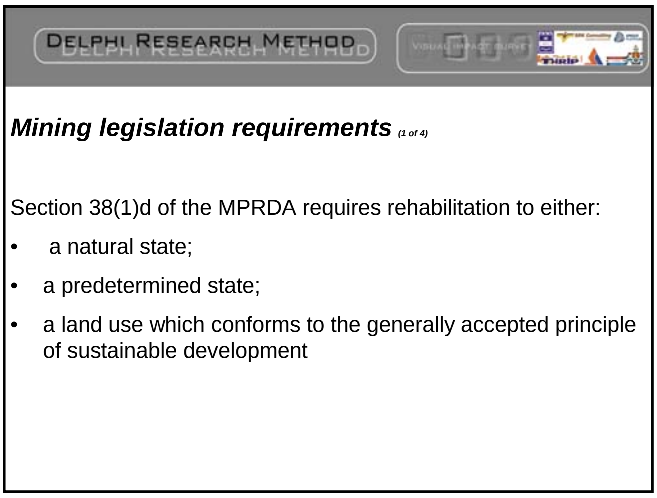
DELPHI RESEARCH METHOD

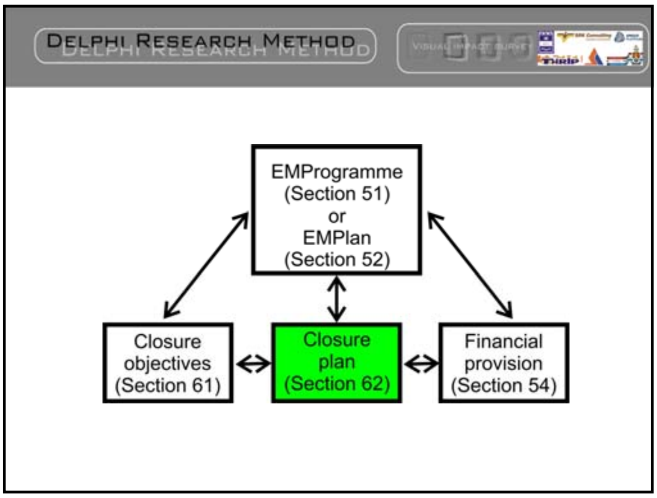


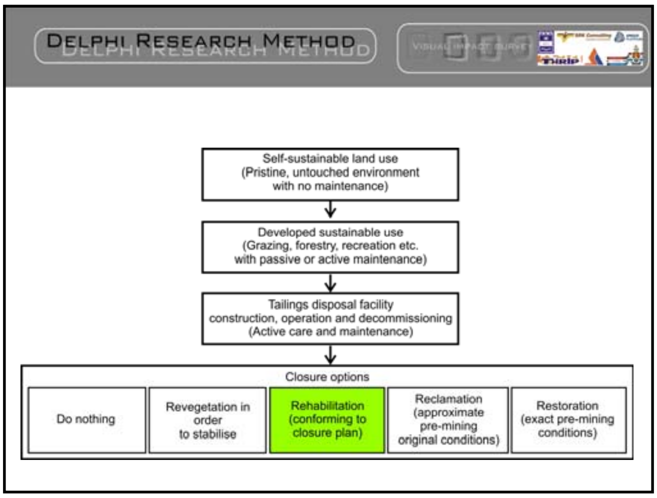
DELPHI RESEARCH METHOD

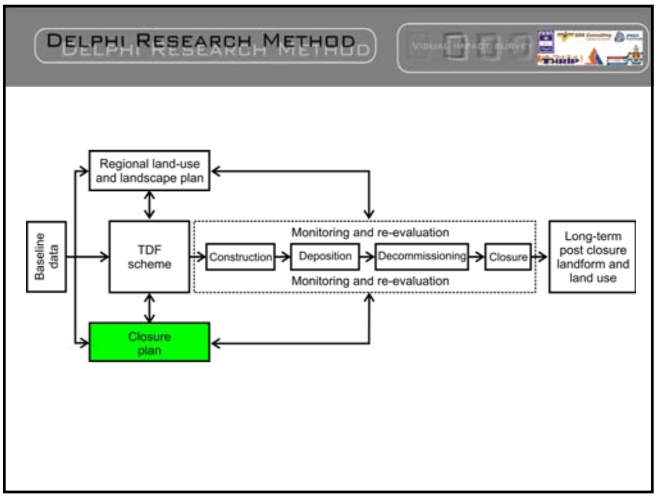


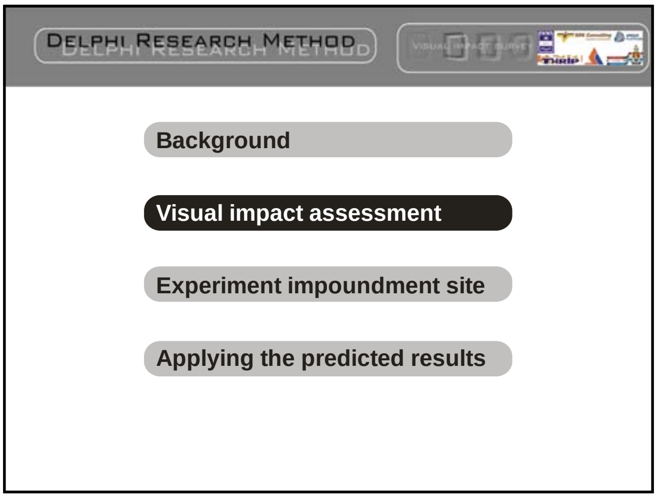

DELPHI RESEARCH METHOD
Tailings impoundment
Environmental impacts
Landscape impacts
Visual impacts
Air
Soil/land
SOURCE
Surface water
Groundwater

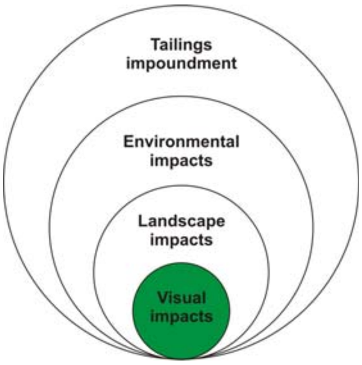

DELPHI RESEARCH METHOD
Mining legislation requirements (1 of 4)
Section 38(1)d of the MPRDA requires rehabilitation to either:
• a natural state;
• a predetermined state;
• a land use which conforms to the generally accepted principle of sustainable development


DELPHI RESEARCH METHOD
EMProgramme (Section 51) or EMPlan (Section 52)
Closure objectives (Section 61)
Closure plan (Section 62)
Financial provision (Section 54)


DELPHI RESEARCH METHOD
Self-sustainable land use (Pristine, untouched environment with no maintenance)
Developed sustainable use (Grazing, forestry, recreation etc. with passive or active maintenance)
Tailings disposal facility construction, operation and decommissioning (Active care and maintenance)
Closure options
Do nothing
Revegetation in order to stabilise
Rehabilitation (conforming to closure plan)
Reclamation (approximate pre-mining original conditions)
Restoration (exact pre-mining conditions)


DELPHI RESEARCH METHOD
Regional land-use and landscape plan
Baseline data
TDF scheme
Monitoring and re-evaluation
Construction
Deposition
Decommissioning
Closure
Monitoring and re-evaluation
Long-term post closure landform and land use
Closure plan


DELPHI RESEARCH METHOD
Background
Visual impact assessment
Experiment impoundment site
Applying the predicted results



Visual impact assessment

- *Visual impact assessment*
- *Physical characteristics*
- *Zone of visual influence*
- *Visual distance zones*
- *Visual perception*

Visual impact assessment (1 of 3)

Visual impact assessment studies require two judgements:

- estimation of the size of the impact; and
- a determination of the necessity and extent of impact mitigation

Visual impact assessment (2 of 3)

Visual impact of a scheme influenced by the following factors:

- physical and visual characteristics of a scheme;
- visibility of scheme;
- distance of observer(s) from scheme;
- the environmental setting; and
- disposition and visual preference of viewers

Visual impact assessment (3 of 3)

Visual impact of a scheme may be estimated through:

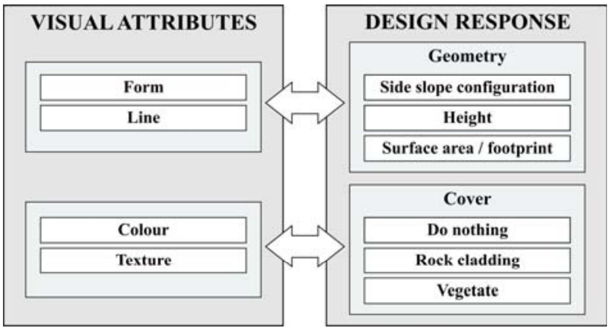
- describing the visual characteristics of scheme;
- delineate zone of visual influence;
- identify and assess viewer characteristics; and
- assess impact of the scheme on the environment

Physical characteristics of scheme (1 of 2)

Different geometries and covers can be used to camouflage or disguise a scheme.

The premise is that the visual effect may be reduced by changing the perceived appearance of the scheme.

DELPHI RESEARCH METHOD

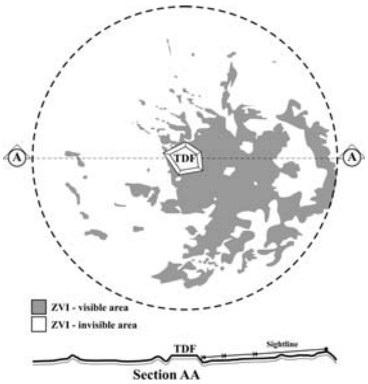


DELPHI RESEARCH METHOD

Zone of visual influence (1 of 2)

The zone of visual influence are the locations from which actual or proposed scheme or structure is visible and is generally shown on a ZVI map

DELPHI RESEARCH METHOD

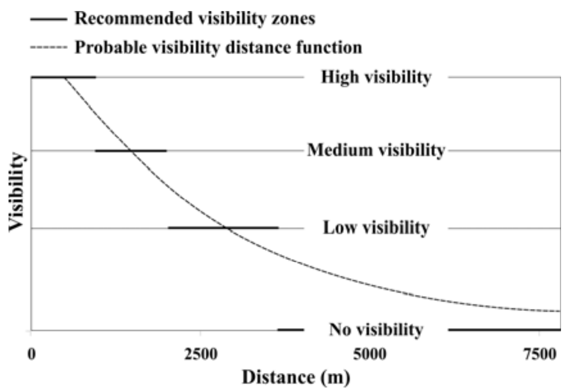


DELPHI RESEARCH METHOD

Visual distance zones (1 of 2)

It is convenient to subdivide the zone of visual influence into subzones and these are defined as visual distance zones

DELPHI RESEARCH METHOD



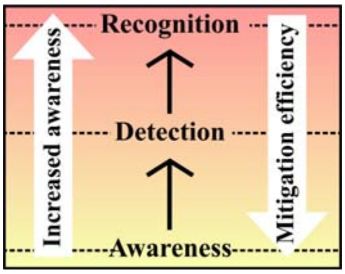
DELPHI RESEARCH METHOD

Visual perception (1 of 2)

Visual perception is not just a seeing activity but an act of interpretation - albeit largely subconscious

Although the process is the interpretation of a continuum in practice a series of thresholds occur which may be described as progressing from awareness through detection to recognition

Delphi Research Method



Delphi Research Method

- Background
- Visual impact assessment
- **Experiment impoundment site**
- Applying the predicted results

Delphi Research Method

Experiment impoundment site

- *Impoundment characteristics*
- *Photographing procedure*
- *Manipulation of photographs*
- *Assessment of visualisations*
- *Results*

Delphi Research Method

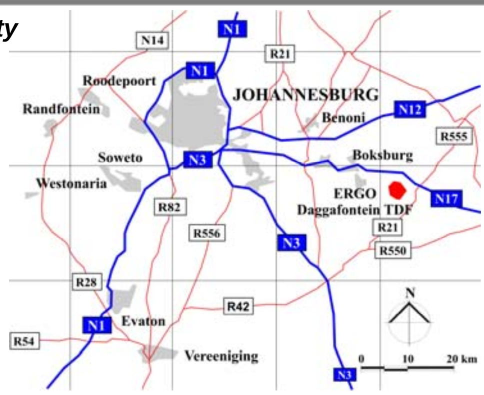
Experiment impoundment site (1 of 6)

The test impoundment site:

- abandoned scheme or in process of being closed
- within environment with low visual absorption capacity
- as many different covers possible

Delphi Research Method

Locality



Delphi Research Method

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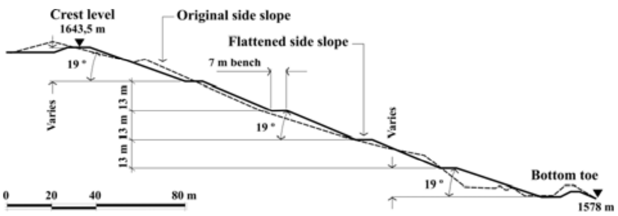
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Delphi Research Method

Profile of side slope



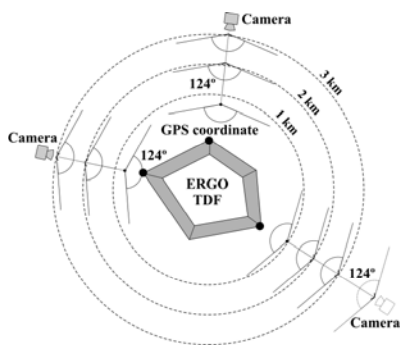
Delphi Research Method

Photographing procedure (1 of 3)

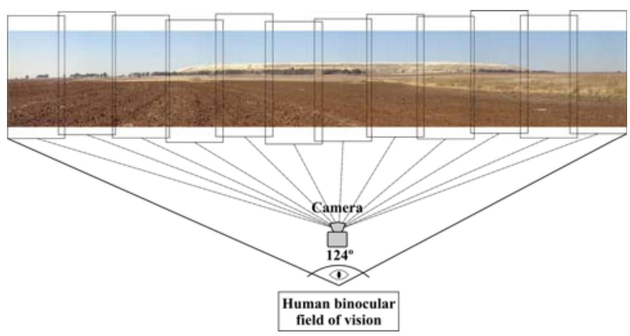
The test impoundment site:

- was photographed from distances ranging from 800 m and 8300 m
- GPS points were taken around the base of the impoundment
- photographs were taken to the nearest GPS point
- tried to limit interference from other structures and man-made elements

Delphi Research Method



Delphi Research Method



DELPHI RESEARCH METHOD

VISUAL IMPACT SURVEY

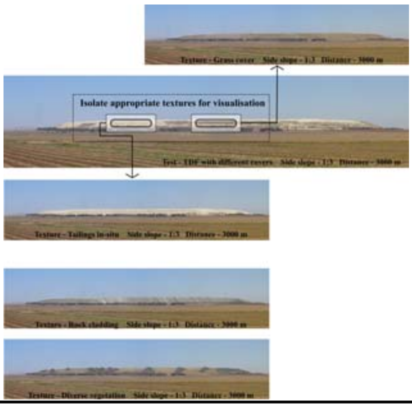
Manipulation of photographs (1 of 3)

The manipulation of site photographs included the following steps:

- photographs were taken to include all sorts of textures
- texture were isolated at different distances
- the range of textures were superimposed on to the whole panoramic photograph
- the manipulated simulations could then be viewed on a computer screen – sized to what viewer would see

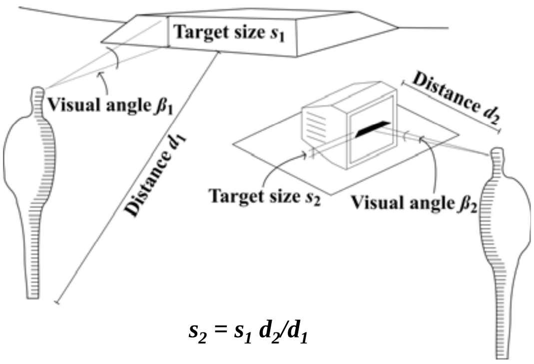
DELPHI RESEARCH METHOD

VISUAL IMPACT SURVEY



DELPHI RESEARCH METHOD

VISUAL IMPACT SURVEY



$$s_2 = s_1\, d_2/d_1$$

DELPHI RESEARCH METHOD

VISUAL IMPACT SURVEY

Assessment of visualisations (1 of 7)

The Nominal Group Technique (NGT) study method, an application from the Delphi technique, was used to assess the visualisations and develop the perception versus distance curves

DELPHI RESEARCH METHOD

VISUAL IMPACT SURVEY

Delphi technique – general information (2 of 7)

A Delphi exercise is a discussion by knowledgeable participants with the aim of reaching an acceptable level of agreement and consensus on the results

DELPHI RESEARCH METHOD

VISUAL IMPACT SURVEY

Delphi technique – general information (3 of 7)

The concept is based on the premises that:

- opinions of experts are justified as inputs to decision-making where absolute answers are unknown;
- a consensus of experts will provide a more accurate response to a question than a single expert; and
- process is repeatable and is used by researchers to produce defendable data.

DELPHI RESEARCH METHOD

Delphi technique – general information *(4 of 7)*

The general procedures are as follows:

- experts are polled on a series of visualisations;
- responses are tabulated, analysed, and the results fed back to the experts; and
- experts reconsider and evaluate their answers in light of the information generated by the aggregate responses. This process is repeated until consensus is reached.

DELPHI RESEARCH METHOD

Nominal Group Technique *(5 of 7)*

Application of the Delphi technique

The Nominal Group Technique (NGT):

- employs face-to-face meetings and discussions by knowledgeable participants to obtain and combine expert opinion in the hope of reaching an agreeable conclusion; and
- allows for information to be collected in less time whereas the Delphi technique is applied where experts are not readily available or within reasonable travelling distance.

DELPHI RESEARCH METHOD

Visualisation X

Question 1

Do you detect a manmade landform within this landscape? Yes | No

Question 2

If the answer is 'Yes', assign a rating between 1 and 5 to indicate the level of perception.

1 | 1,5 | 2 | 2,5 | 3 | 3,5 | 4 | 4,5 | 5

Level of Perception	
5. High	- Effortless recognition as a MRD
4. Medium High	- Recognizable as MRD, but with effort
3. Medium	- Easily detectable as a foreign landform in the landscape, but not recognizable as a MRD
2. Medium Low	- Detectable as a foreign landform in the landscape, but with effort
1. Low	- Virtually undetectable as a foreign landform in the landscape

Note: MRD - Mine Residue Deposit, a generic term for Tailings Disposal Facility (TDF)

DELPHI RESEARCH METHOD

Visualisations presented to panel *(7 of 7)*

- Each scenario, i.e. impoundment configuration, has different viewing distances
- Viewing distances ranged from 1000 m to 8200 m
- 12 panellists rated the manipulated panoramic photographs

3000ST3 Photo 1

3000SG6 Photo 5

3000ST6 Photo 11

8300WT3 Photo 14

3600WG3 Photo 15

3000SD6 Photo 28

2000ST6 Photo 49

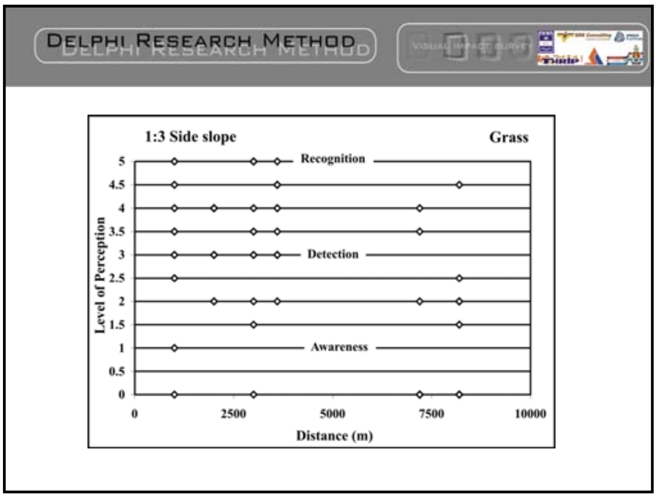
DELPHI RESEARCH METHOD

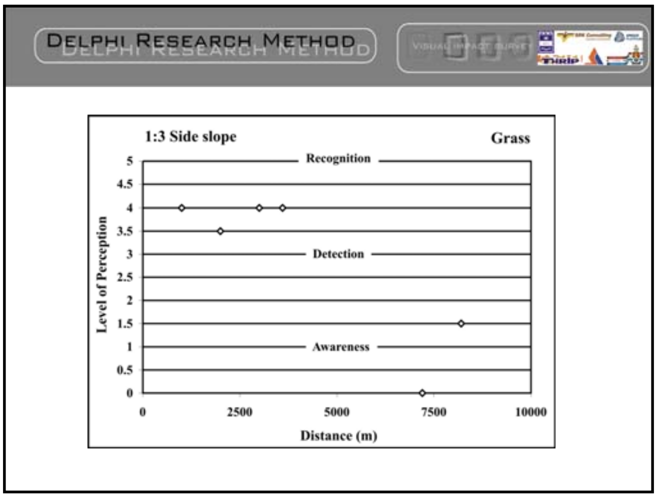
Results

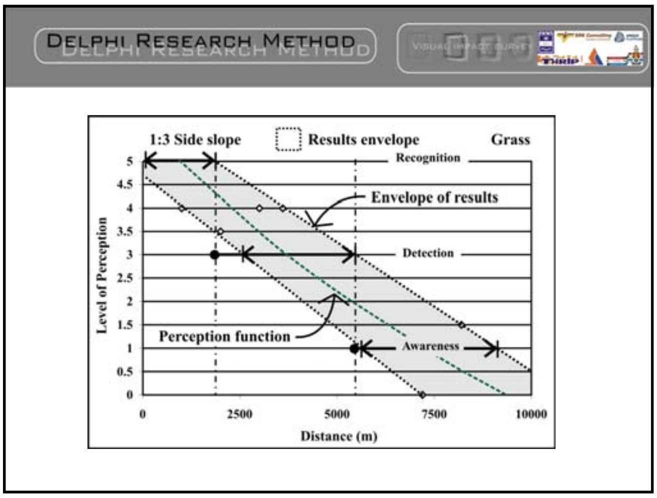
The following slides indicate:

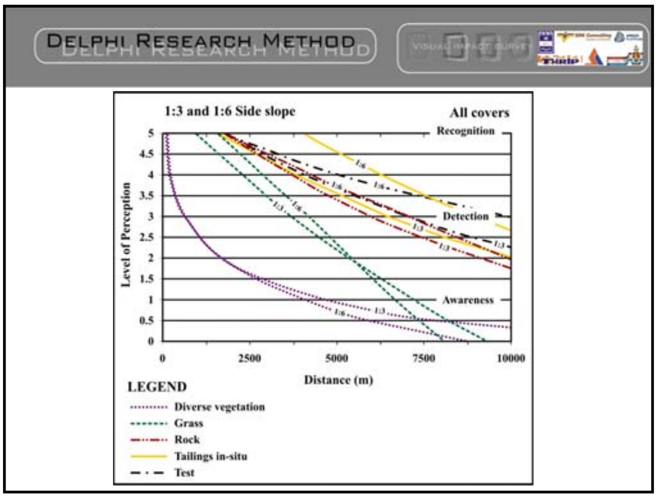
- the initial results from the experts' ratings for the manipulated simulations before discussion and reaching consensus.
- the consensus results for the same visualisations after discussion.
- the envelope indicating the limits of the consensus results indicates the range of the maximum distances or each perception level.

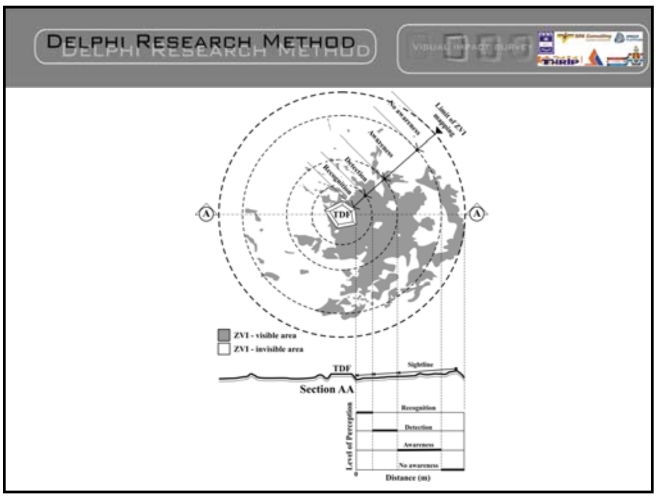
Impoundment covered with grass and an overall side slope of 1:3

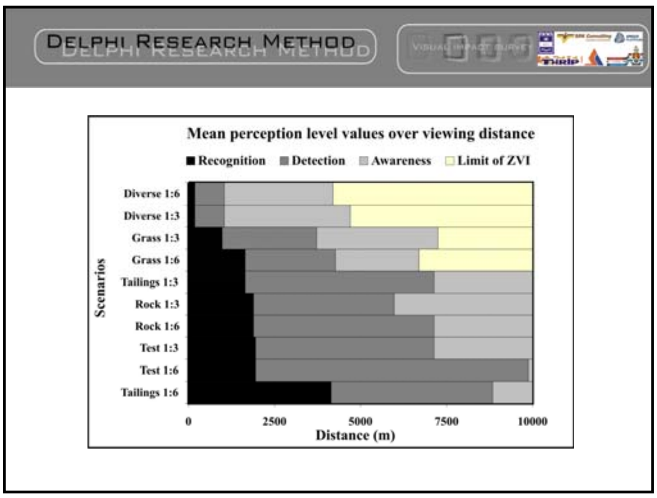

Delphi Research Method
1:3 Side slope
Grass
Recognition
Detection
Awareness
Level of Perception
Distance (m)


Delphi Research Method
1:3 Side slope
Grass
Recognition
Detection
Awareness
Level of Perception
Distance (m)

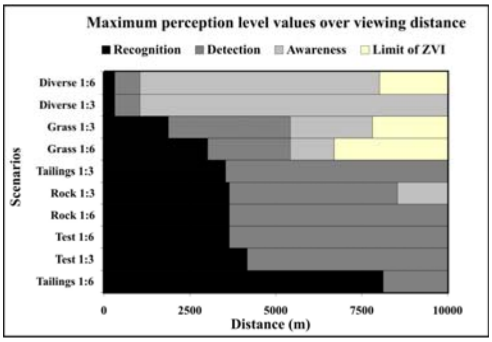

Delphi Research Method
1:3 Side slope
Results envelope
Grass
Recognition
Envelope of results
Detection
Perception function
Awareness
Level of Perception
Distance (m)


Delphi Research Method
1:3 and 1:6 Side slope
All covers
Recognition
Detection
Awareness
Level of Perception
Distance (m)
LEGEND
Diverse vegetation
Grass
Rock
Tailings in-situ
Test


Delphi Research Method
TDF
ZVI - visible area
ZVI - invisible area
Section AA
Sightline
Recognition
Detection
Awareness
No awareness
Level of Perception
Distance (m)

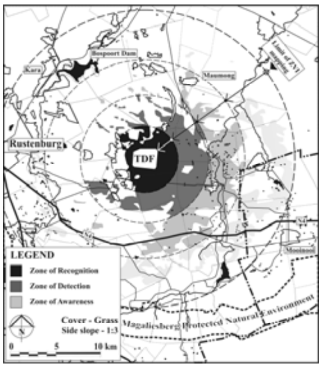

Delphi Research Method
Mean perception level values over viewing distance
Recognition
Detection
Awareness
Limit of ZVI
Diverse 1:6
Diverse 1:3
Grass 1:3
Grass 1:6
Tailings 1:3
Rock 1:3
Rock 1:6
Test 1:3
Test 1:6
Tailings 1:6
Scenarios
Distance (m)

Delphi Research Method

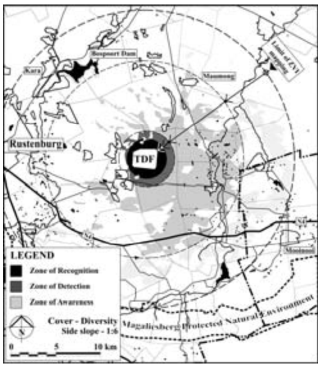


Delphi Research Method

Delphi Research Method



Delphi Research Method



Delphi Research Method

Background

Visual impact assessment

Experiment impoundment site

Applying the predicted results

Delphi Research Method

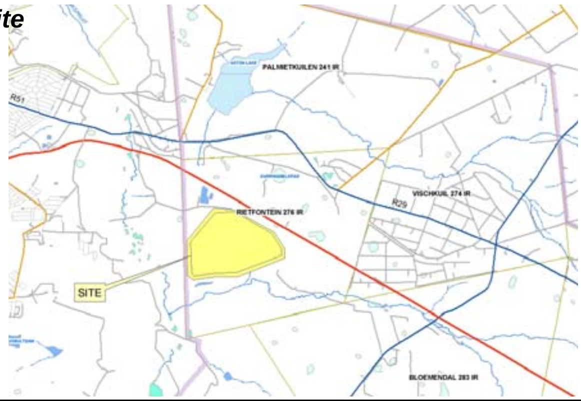
Applying the predicted results in the field

The following process was followed:

- locate suitable impoundment
- determine typical side slope and cover characteristics
- compile ZVI map using GIS
- use predicted maximum perception level versus viewing distance results to determine zones of influence
- 24 visual receptor view points were identified
- take panoramic photographs from pre-determined view points

DELPHI RESEARCH METHOD

Site



DELPHI RESEARCH METHOD

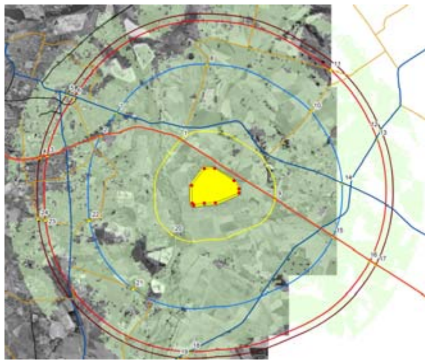
Land use

DELPHI RESEARCH METHOD

ZVI

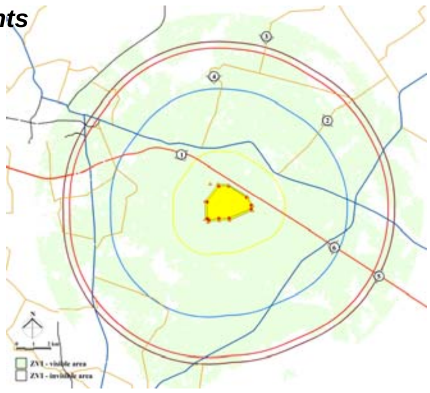
DELPHI RESEARCH METHOD

Points



DELPHI RESEARCH METHOD

View points



Visual Perception Experiment

Managing the visual impact of tailings impoundments

RESULTS FROM PREDICTED VIEWING POINTS

5 October 2005

Panel discussion

DELPHI RESEARCH METHOD

Panel discussion

Points to be discussed:

- overall experimental procedure followed
- predicted results perception versus distance curves
- general observations
- applying the results in practice
- panoramic photographs taken in the field
- research gaps

5150WT3 Photo 6

The end

Appendix A4: Zone of visual perception results

List of figures

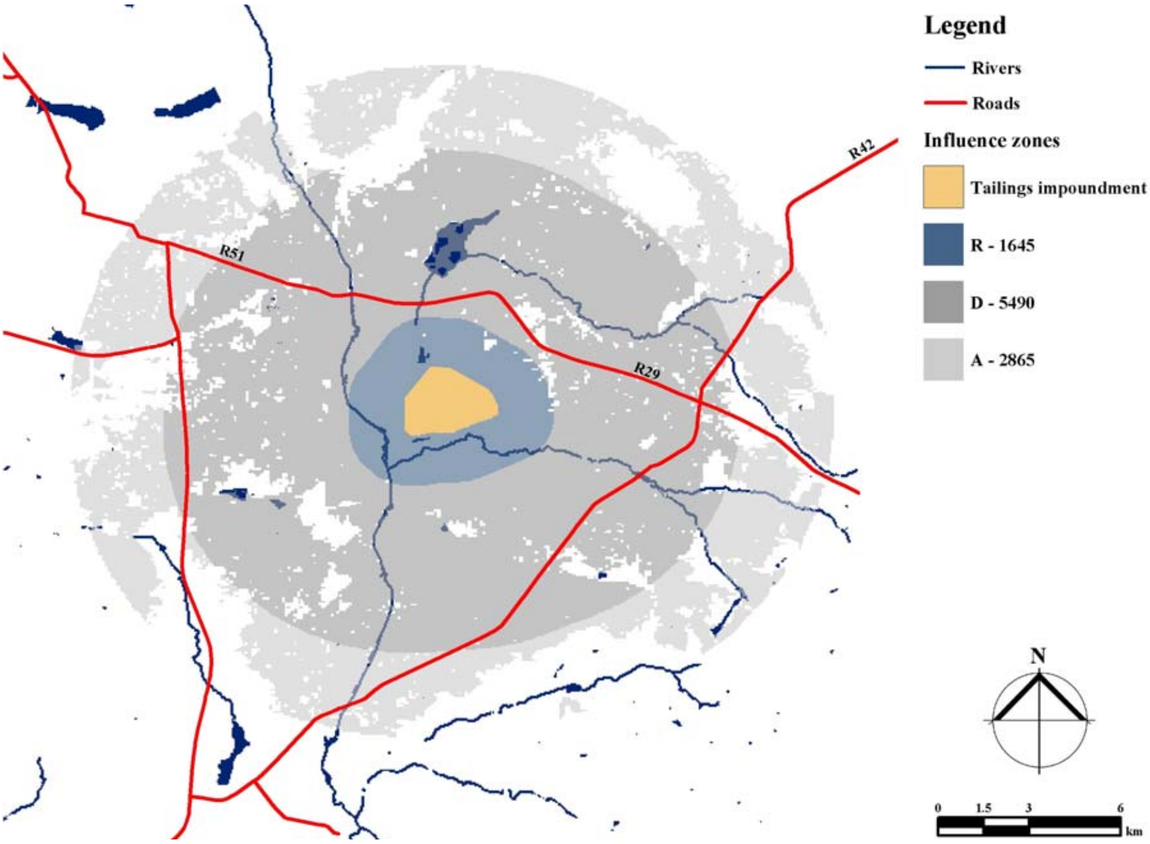


Figure A. 1: Scenario 1 visual perception zones of influence (VS1)

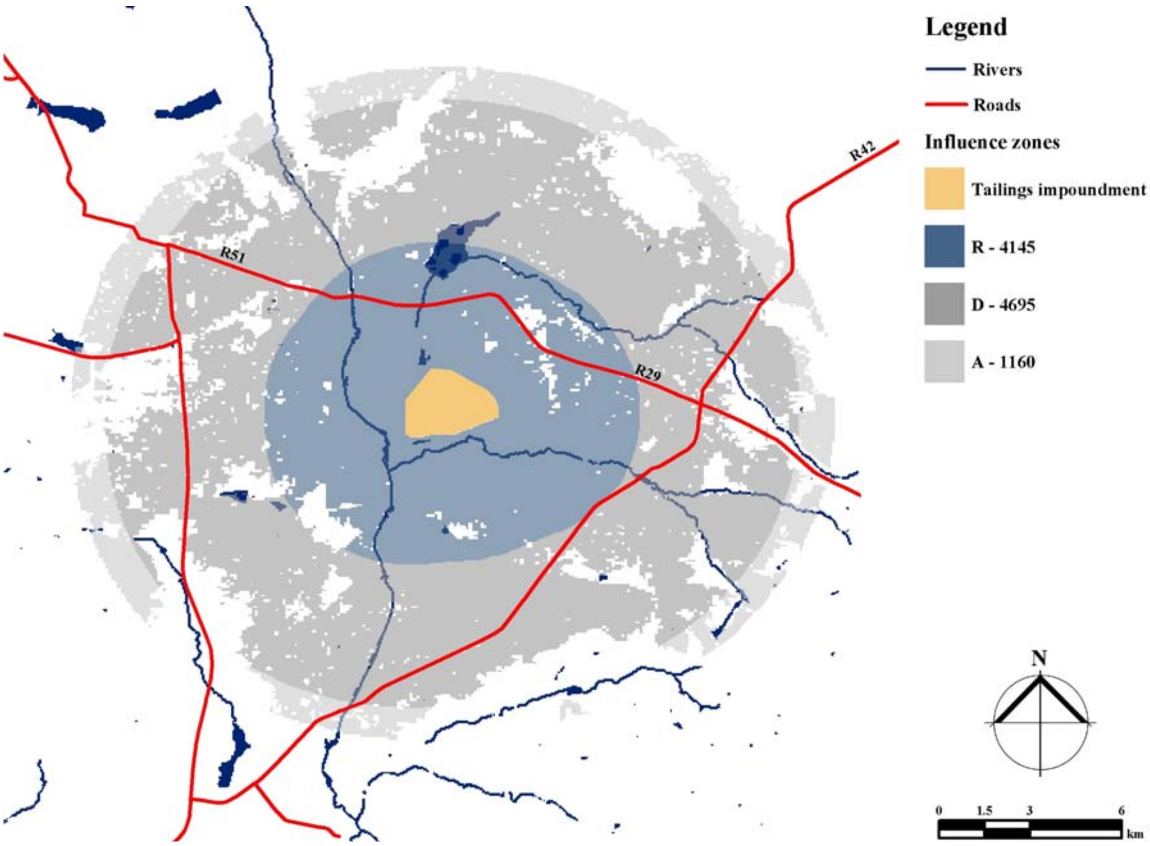


Figure A. 2: Scenario 2 visual perception zones of influence (VS2)

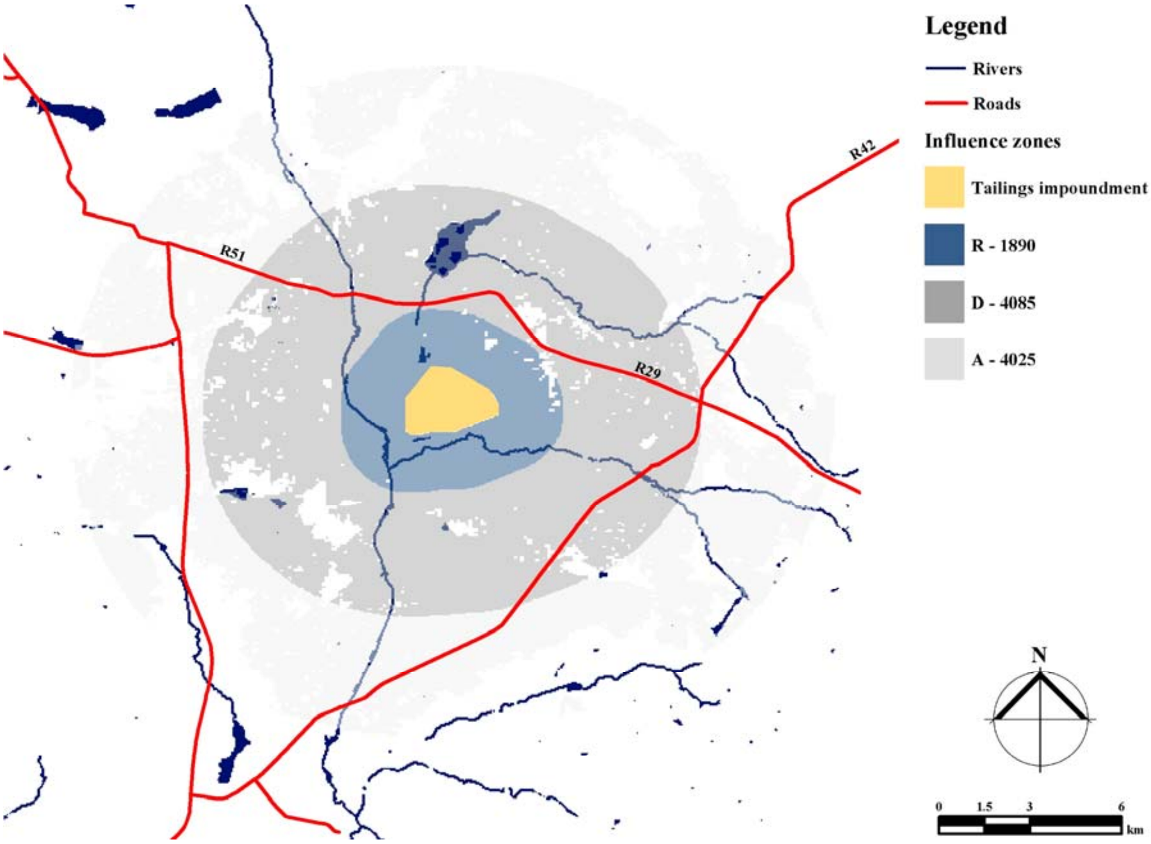


Figure A. 3: Scenario 3 visual perception zones of influence (VS3)

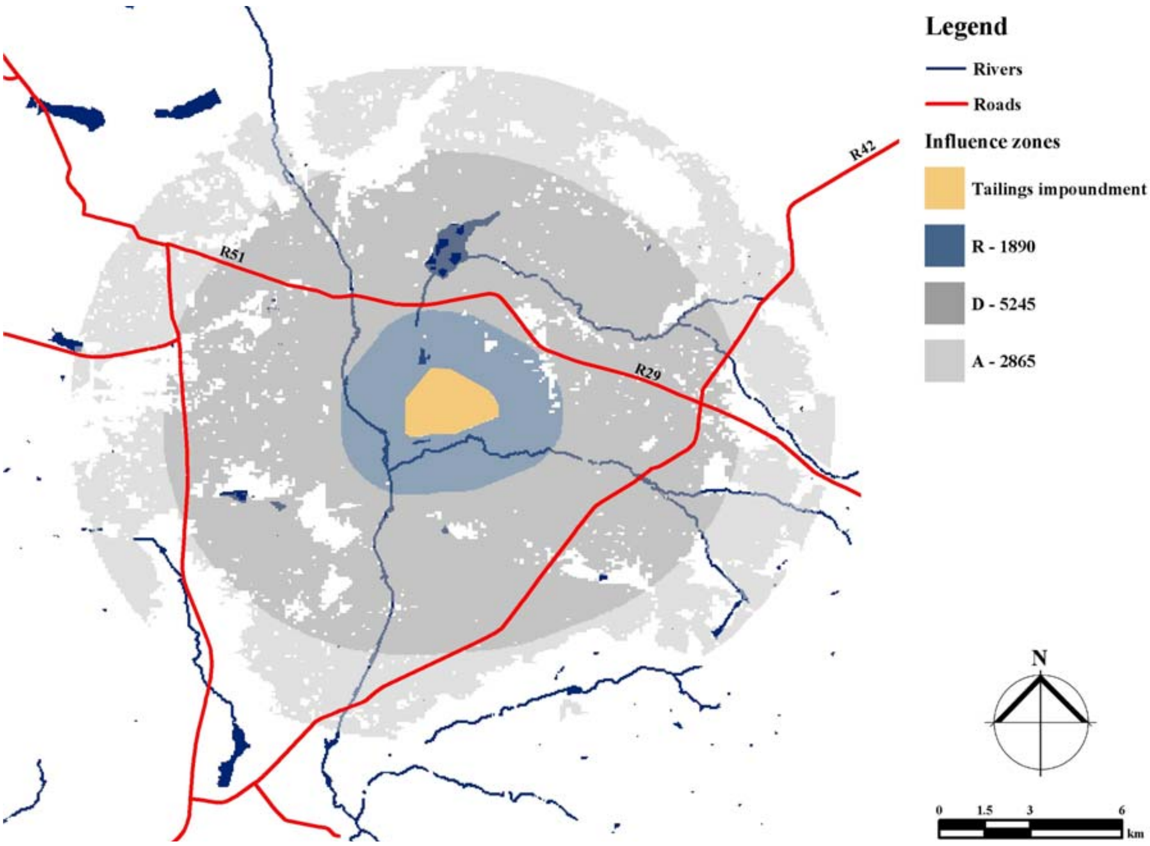


Figure A. 4: Scenario 4 visual perception zones of influence (VS4)

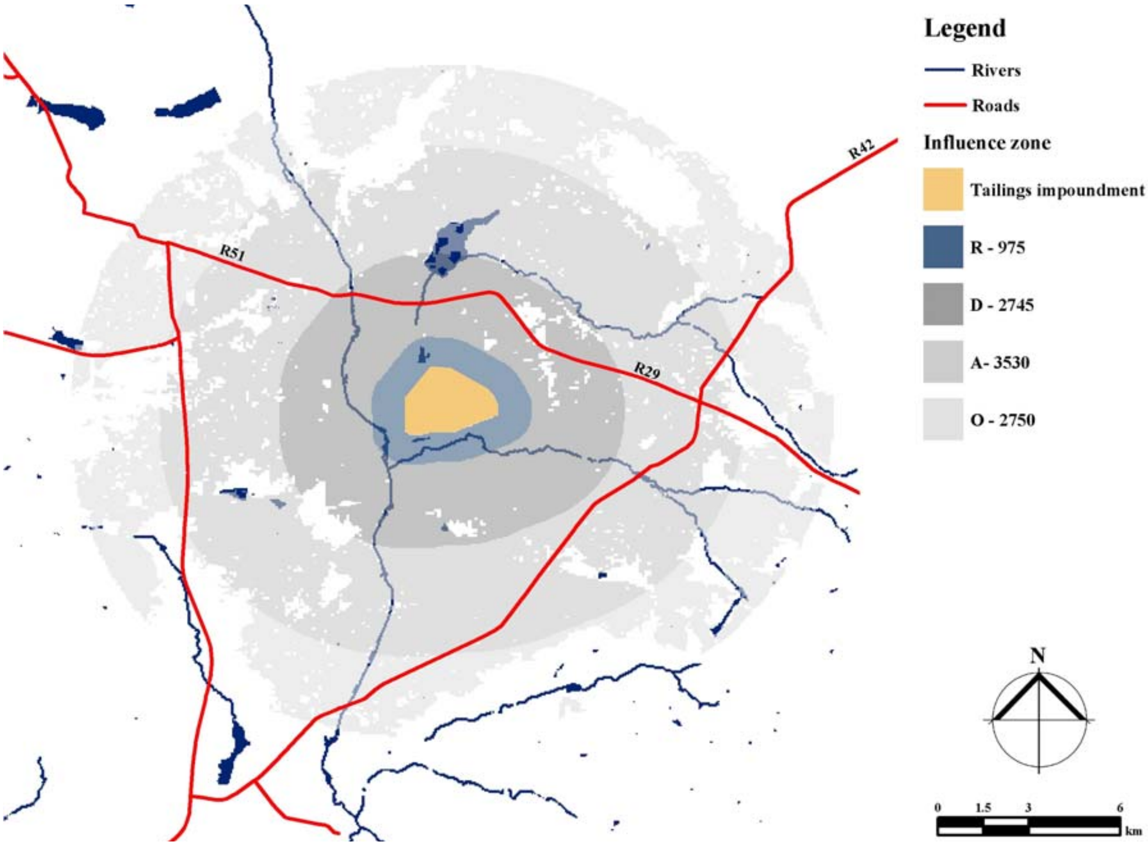


Figure A. 5: Scenario 5 visual perception zones of influence (VS5)

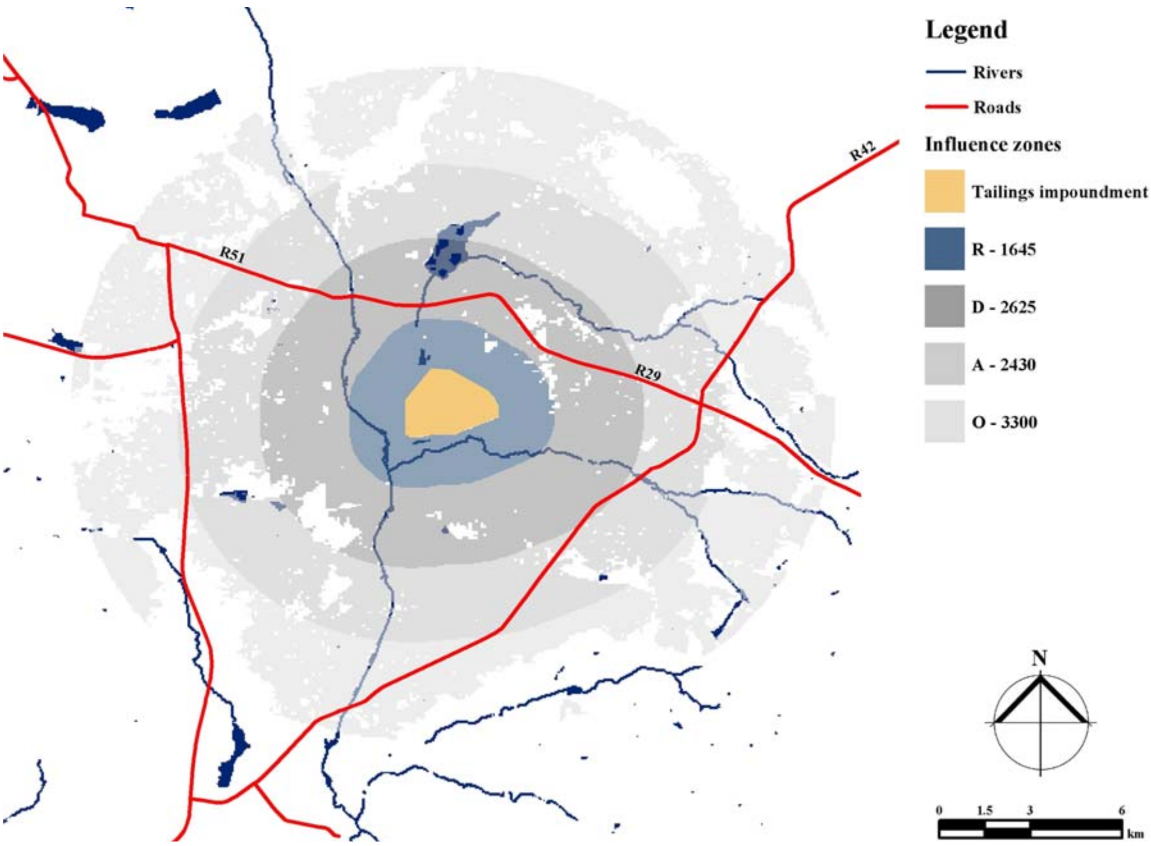


Figure A. 6: Scenario 6 visual perception zones of influence (VS6)

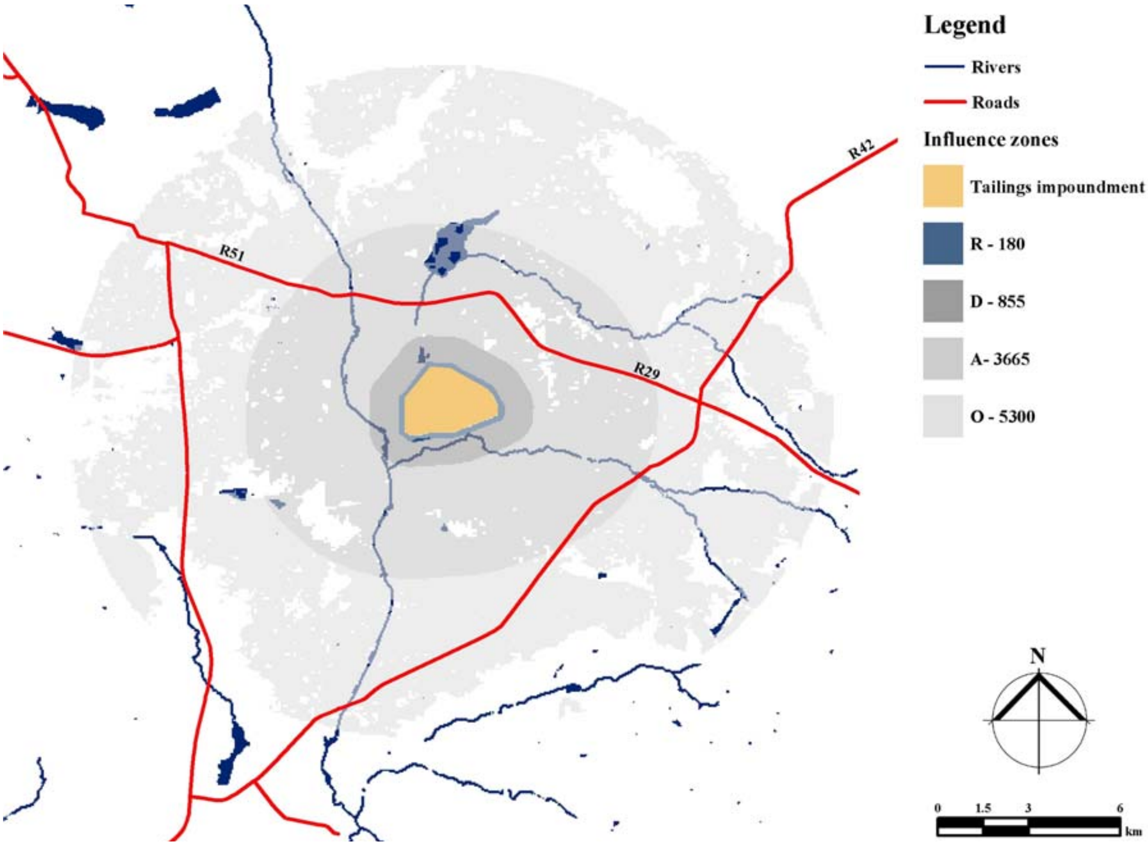


Figure A. 7: Scenario 7 visual perception zones of influence (VS7)

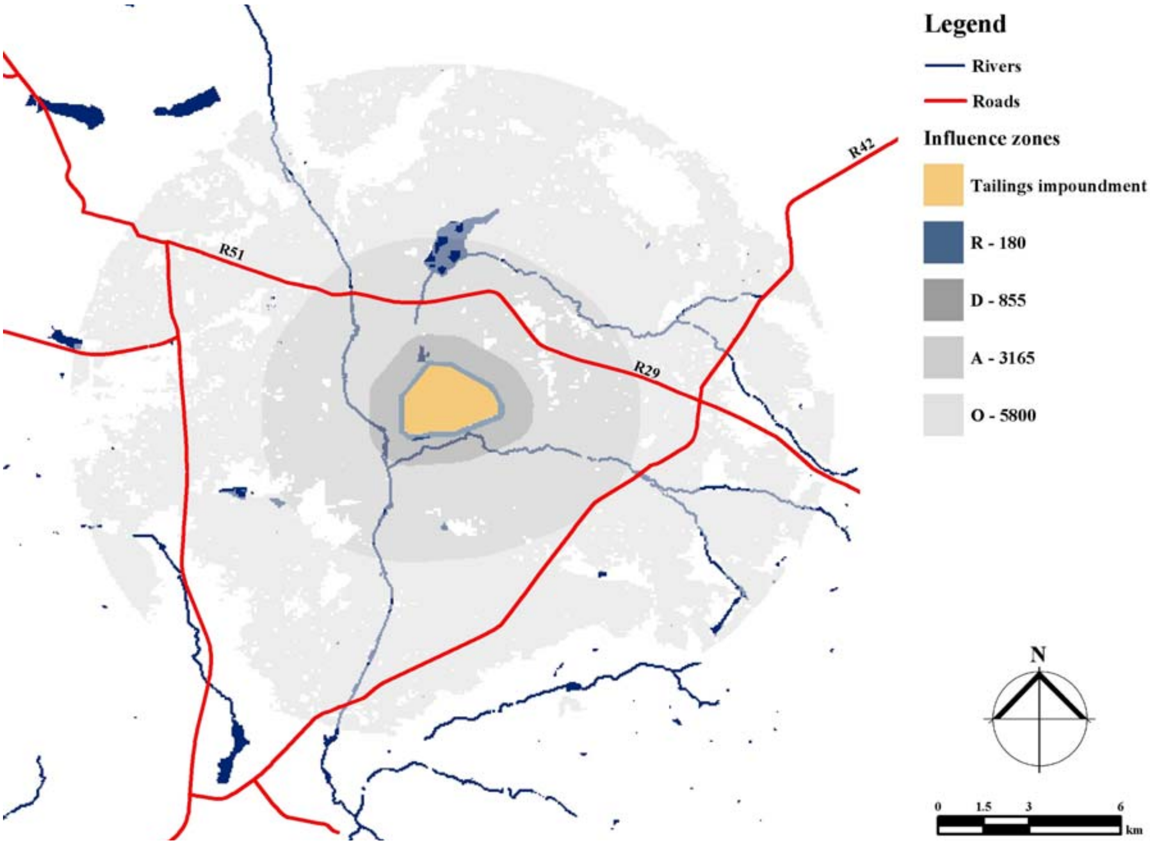


Figure A. 8: Scenario 8 visual perception zones of influence (VS8)

The Influence of Environmental Impacts on Tailings Impoundment Design

APPENDIX B: AIR

List of figures

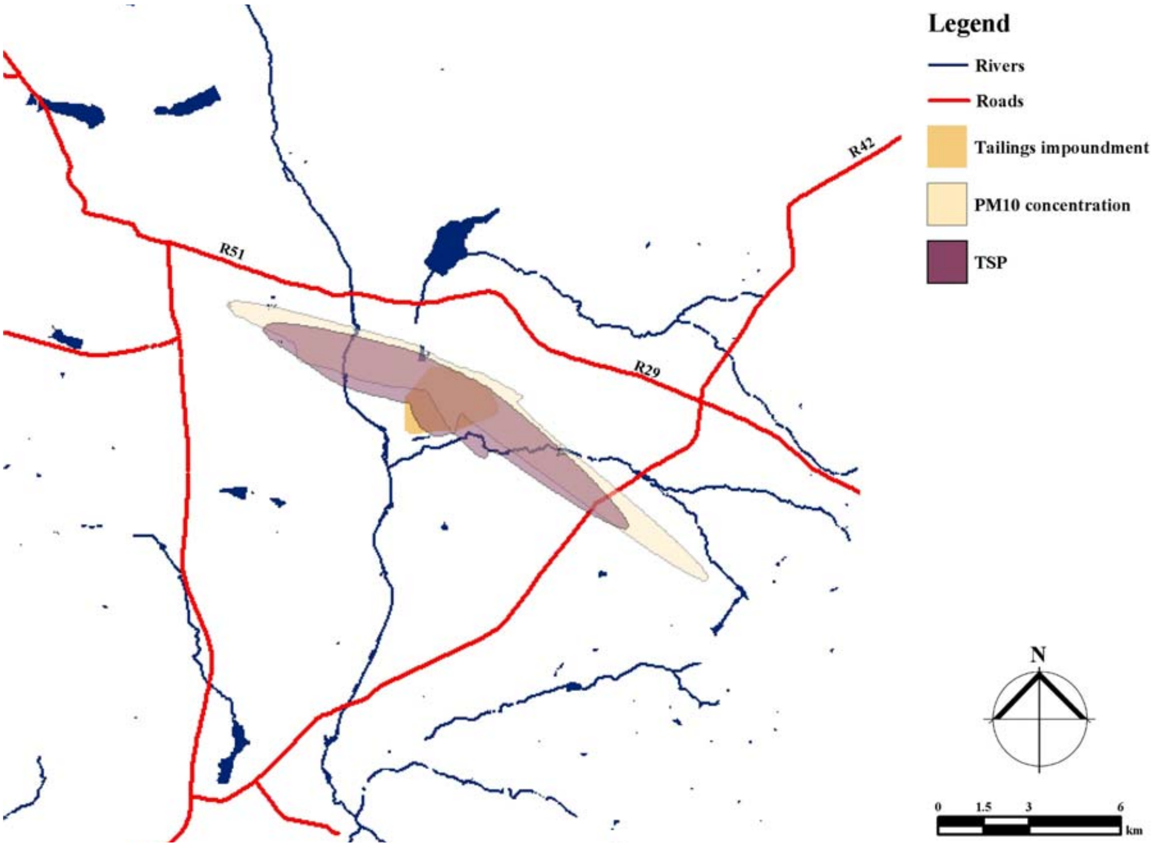


Figure B. 1: 1:1,5 embankment side slope with no cover (AS1)

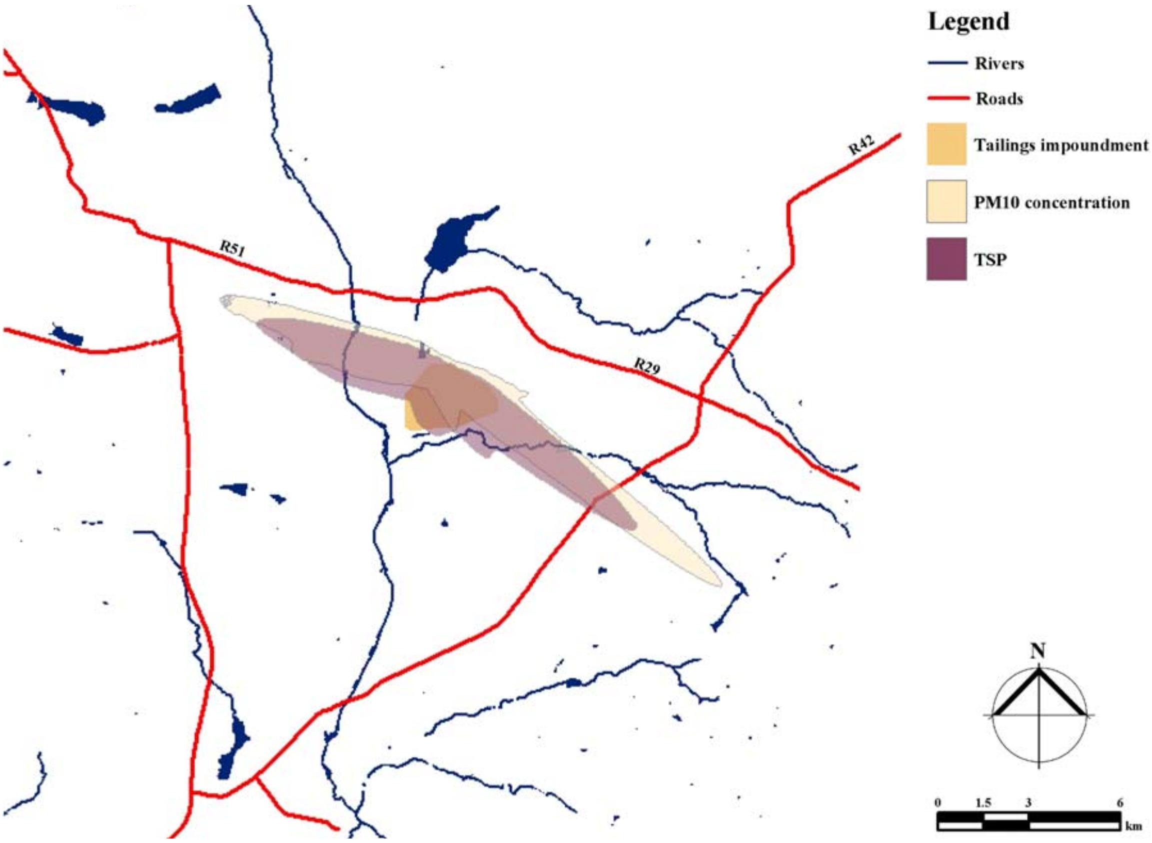


Figure B. 2: 1:3 embankment side slope with no cover (AS2)

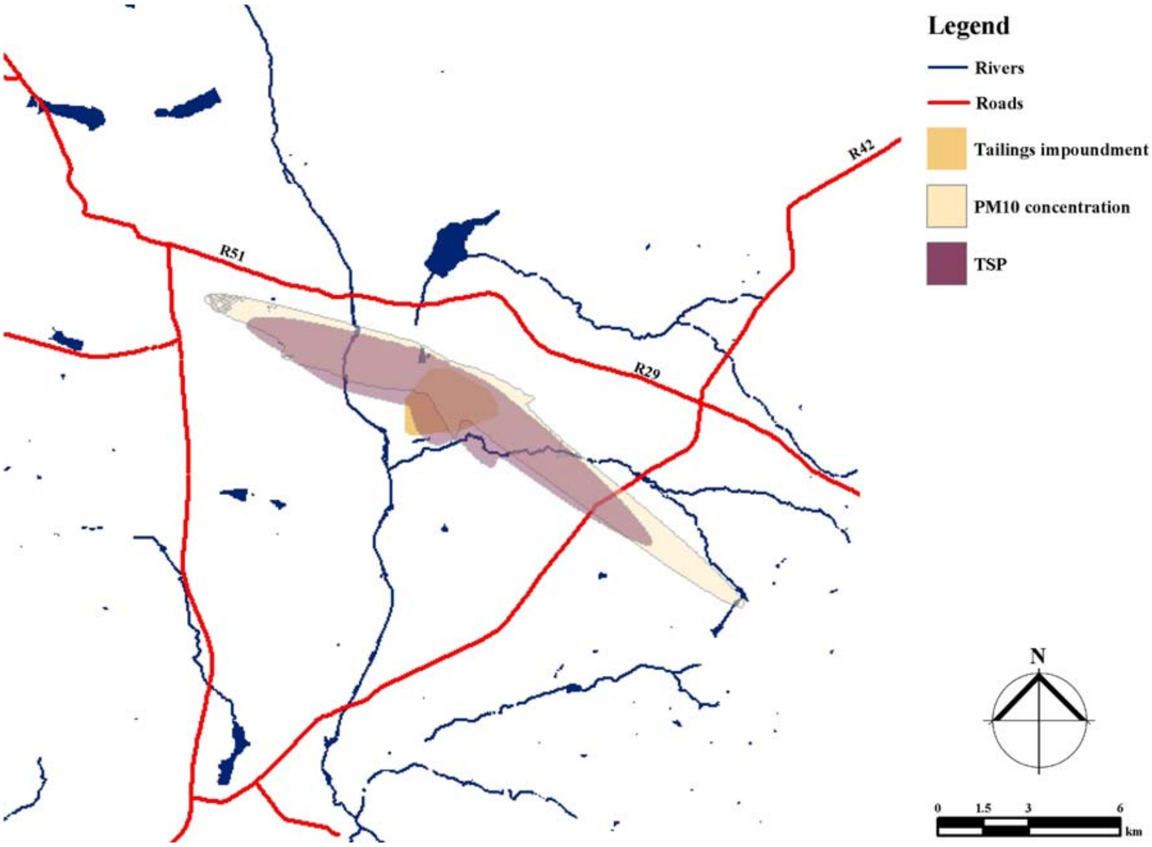


Figure B. 3: 1:6 embankment side slope with no cover (AS3)

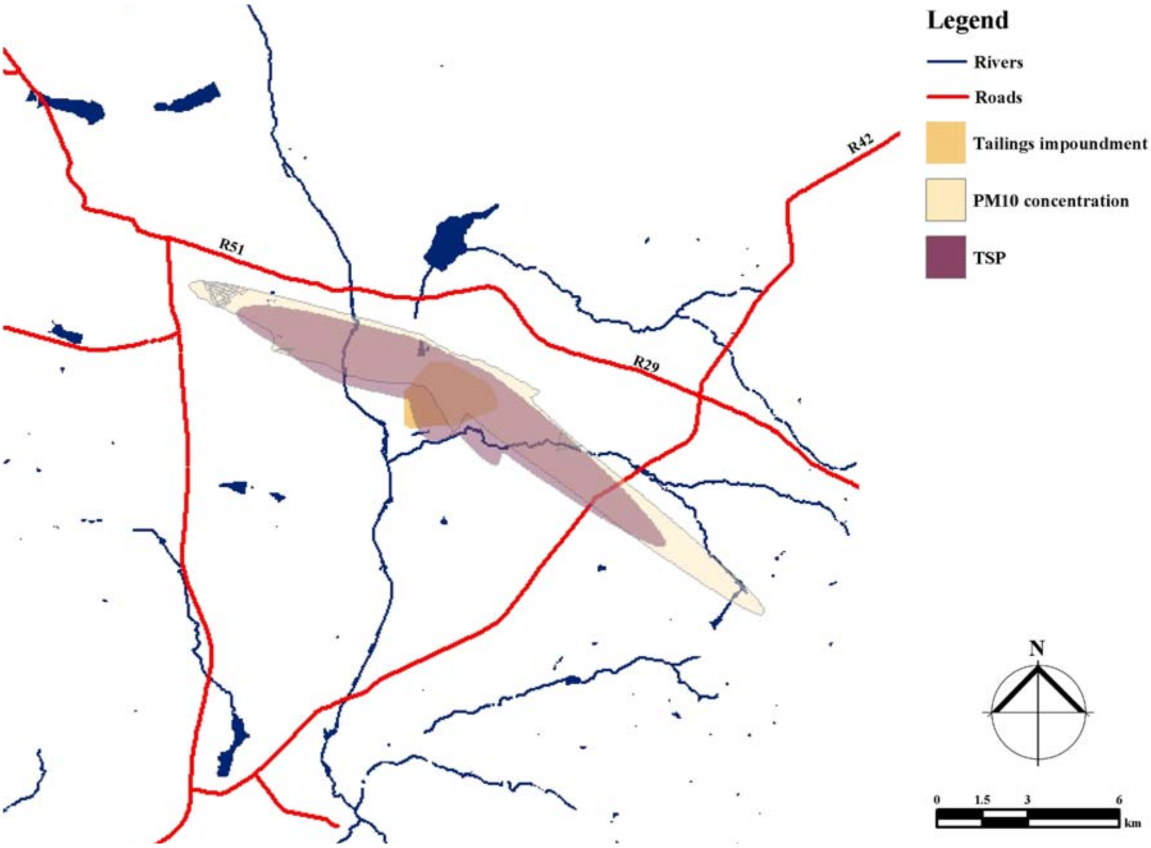


Figure B. 4: 1:9 embankment side slope with no cover (AS4)

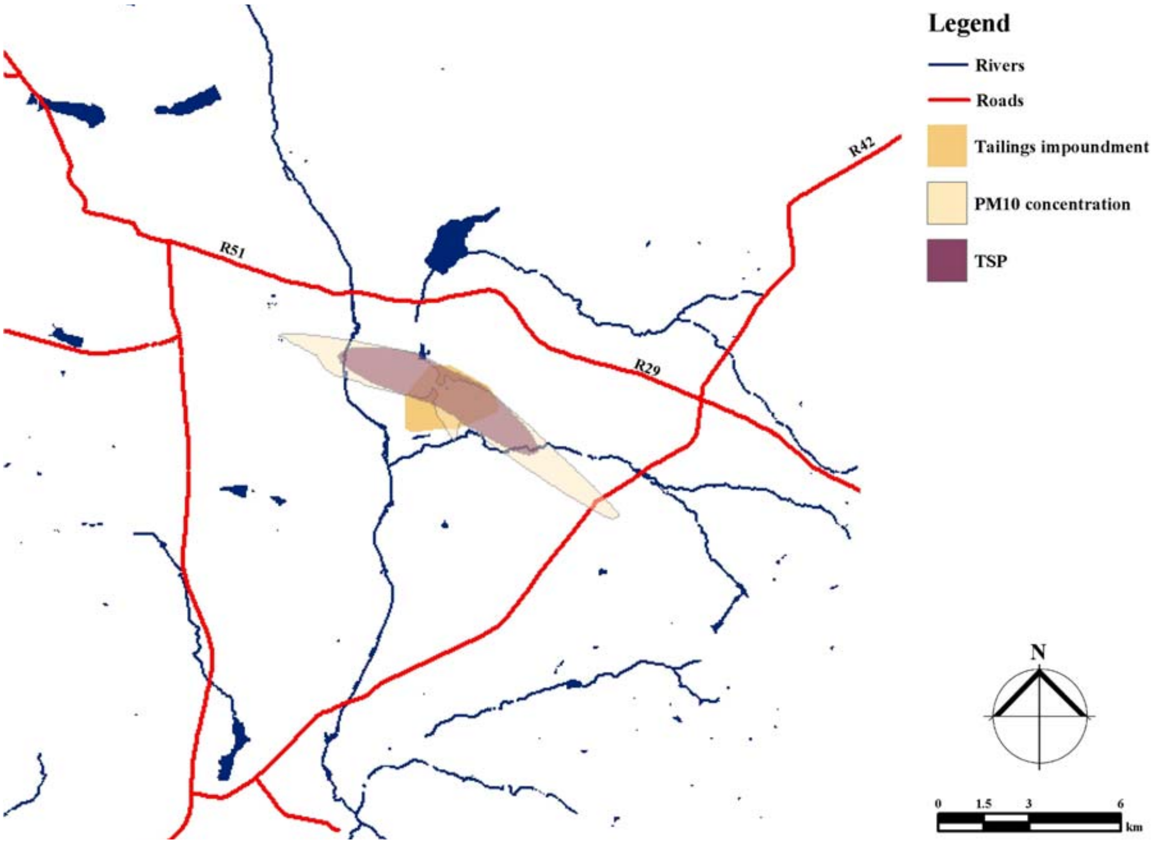


Figure B. 5: 1:1,5 embankment side slope with 50% control efficiency (AS9)

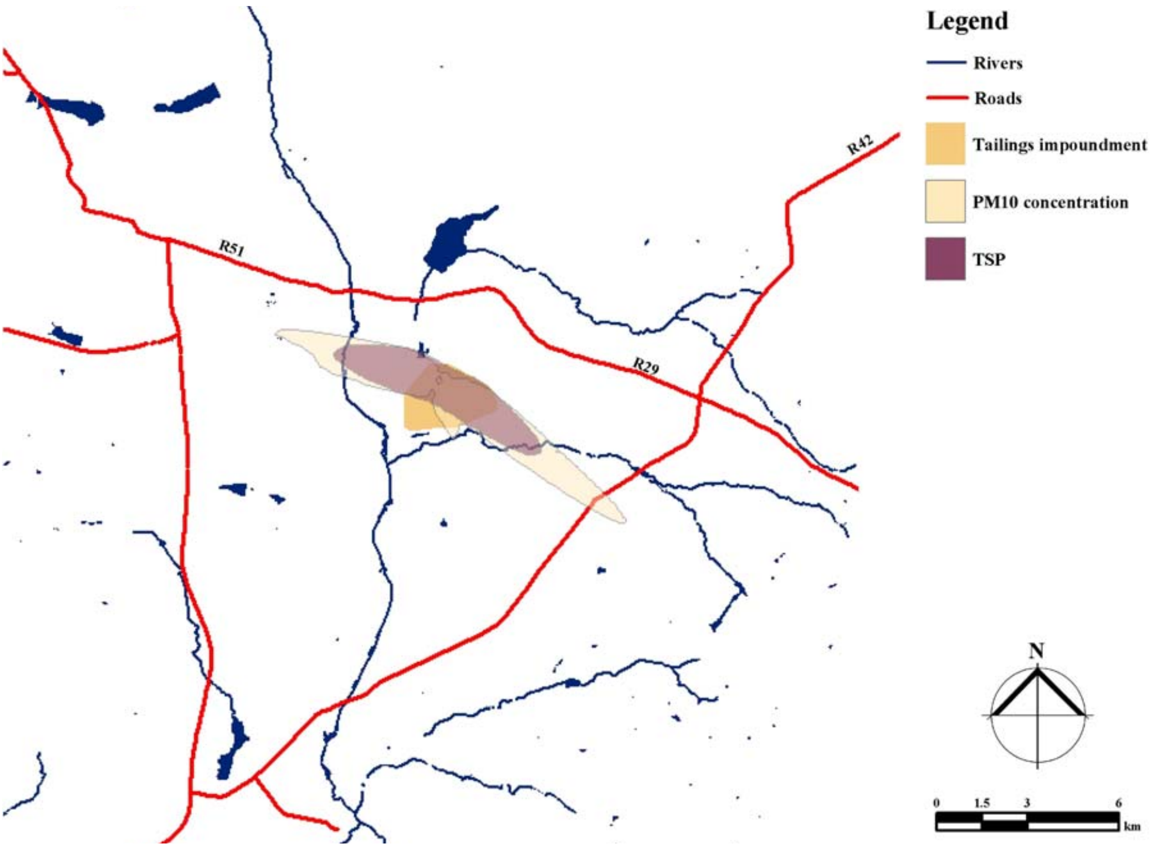


Figure B. 6: 1:3 embankment side slope with 50% control efficiency (AS10)

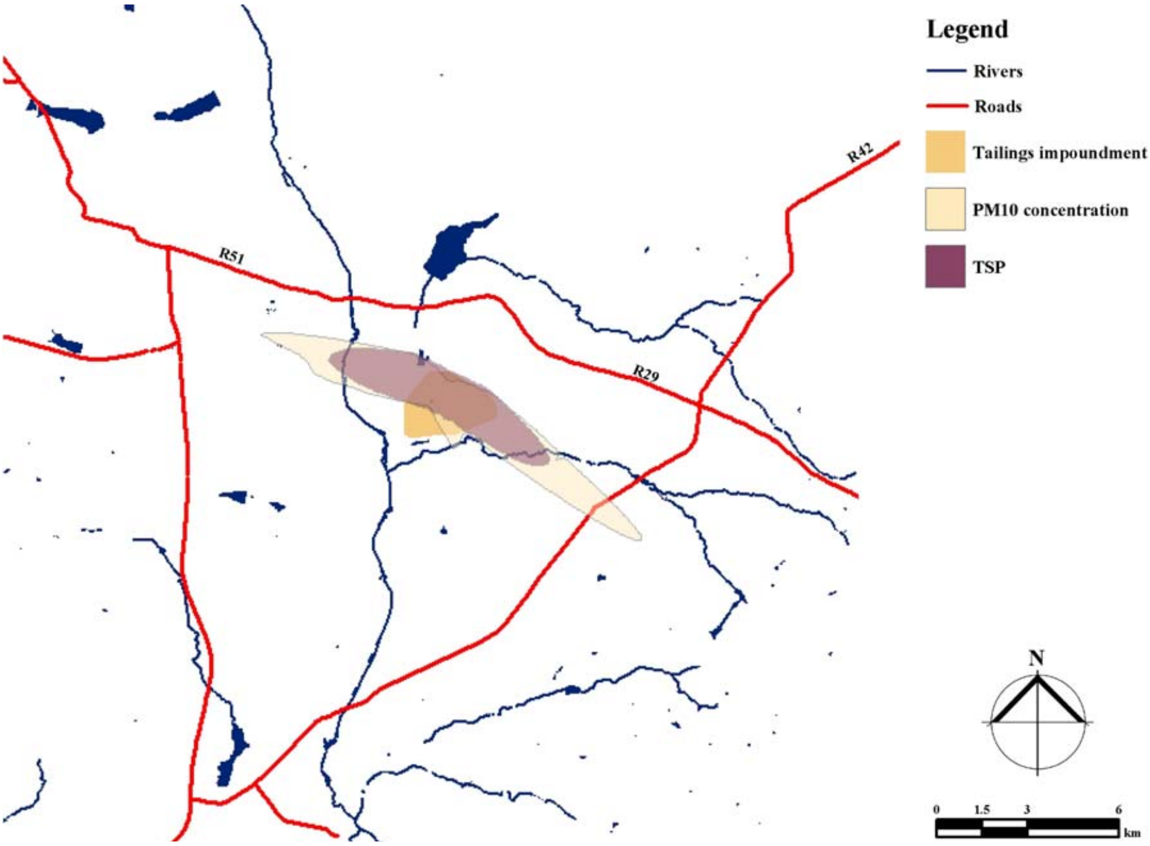


Figure B. 7: *1:6 embankment side slope with 50% control efficiency (AS11)*

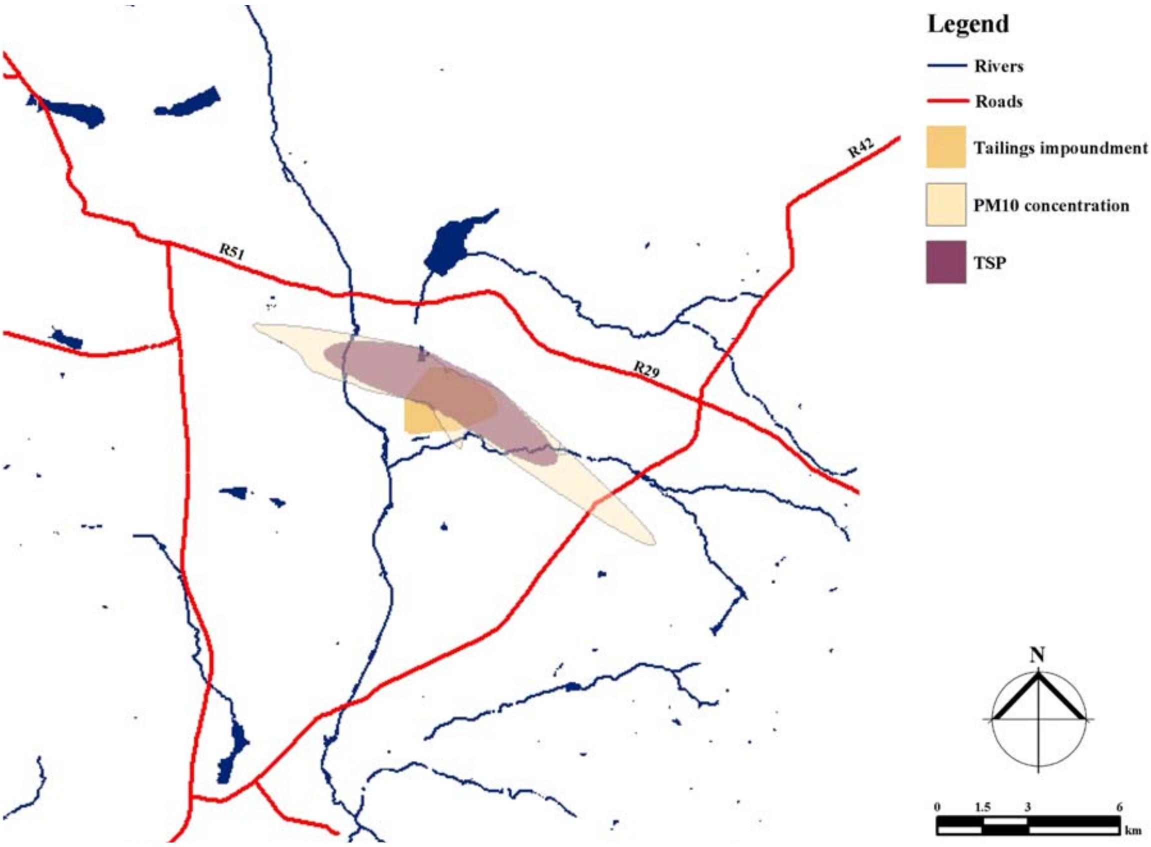


Figure B. 8: *1:9 embankment side slope with 50% control efficiency (AS12)*

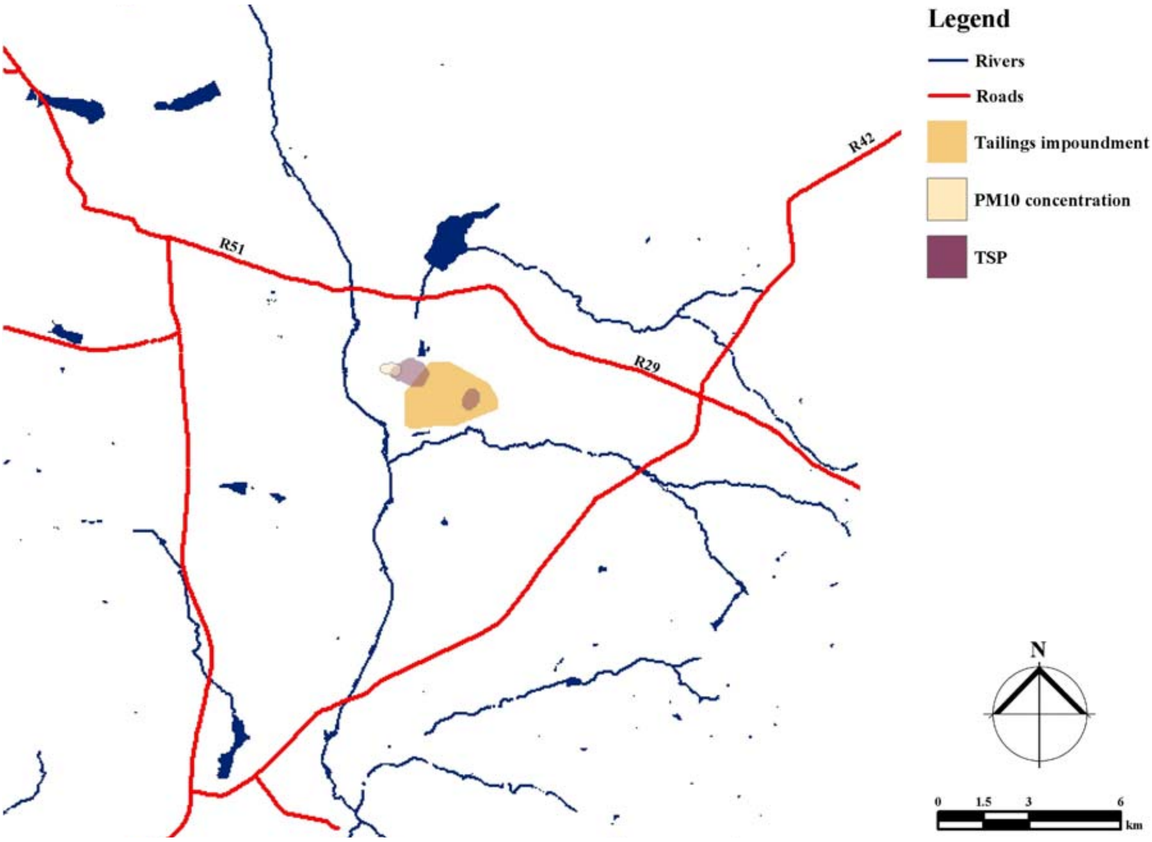


Figure B. 9: 1:1,5 embankment side slope with 80% control efficiency (AS13)

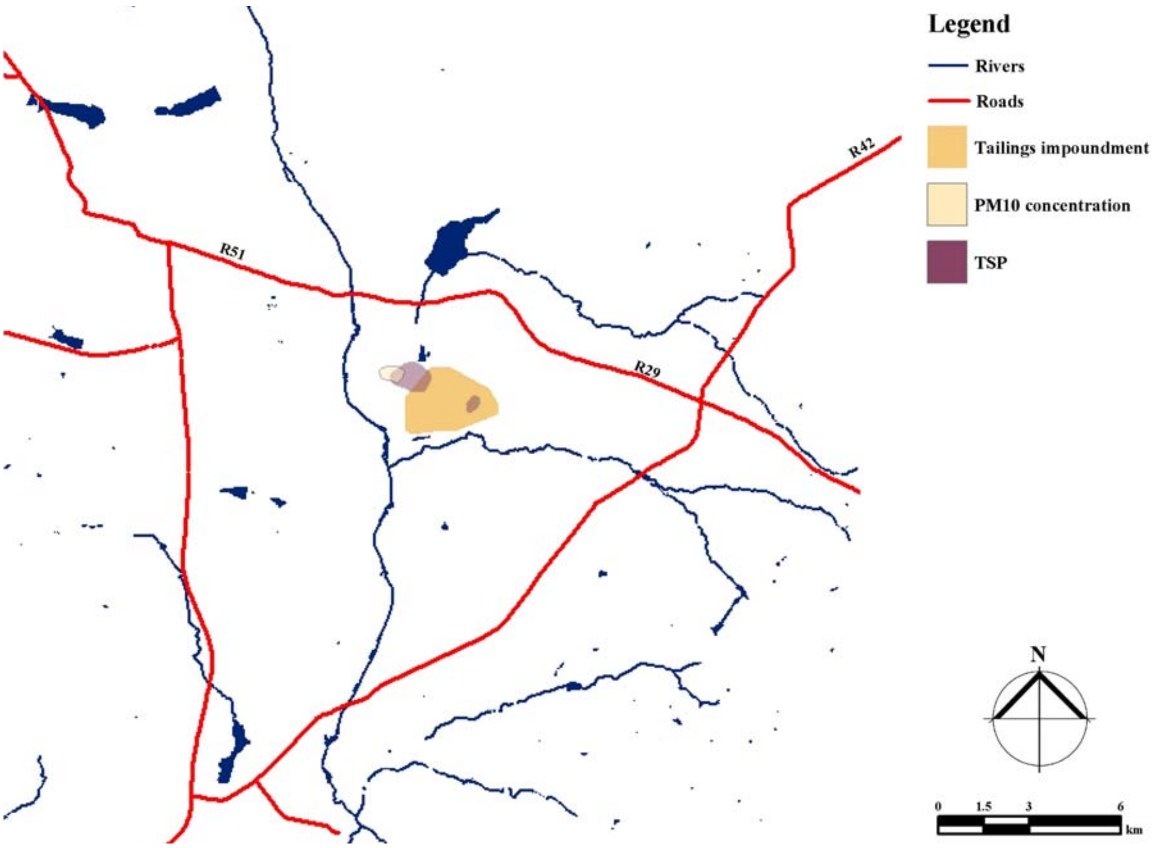


Figure B. 10: 1:3 embankment side slope with 80% control efficiency (AS14)

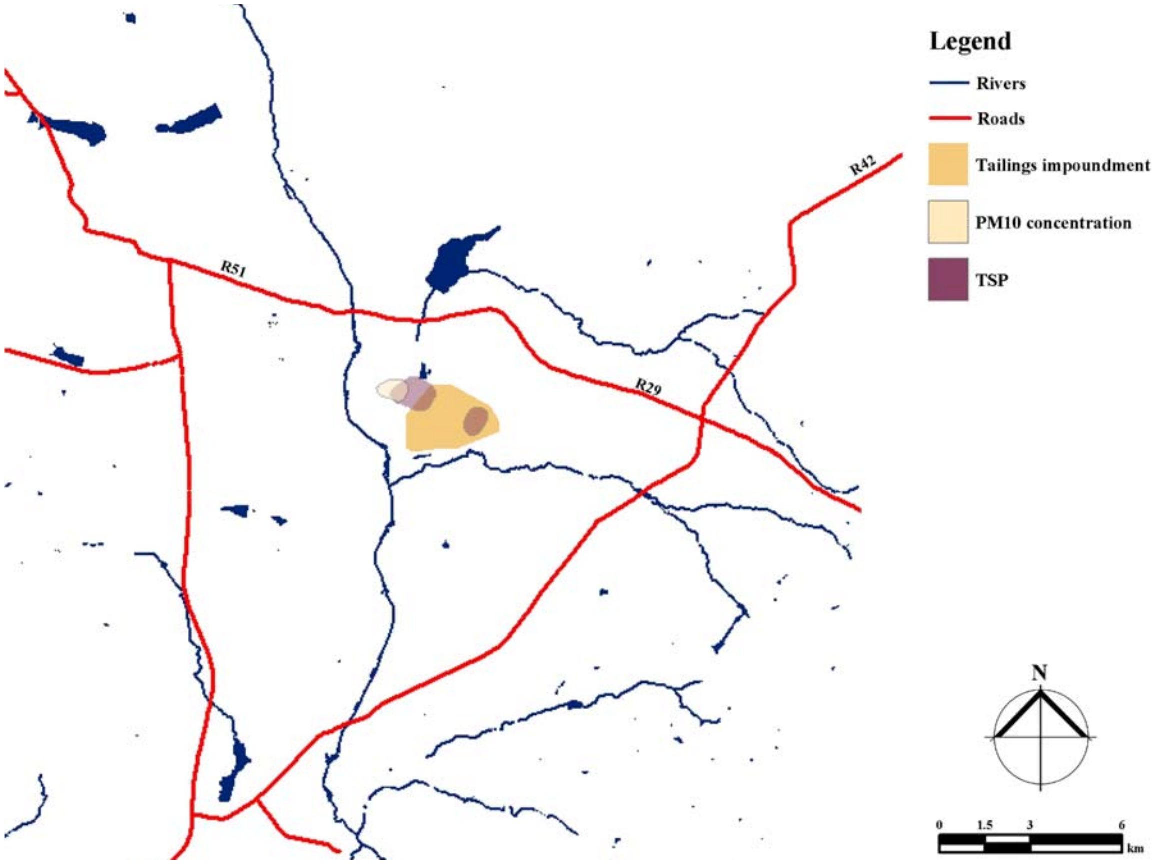


Figure B. 11: 1:6 embankment side slope with 80% control efficiency (AS15)

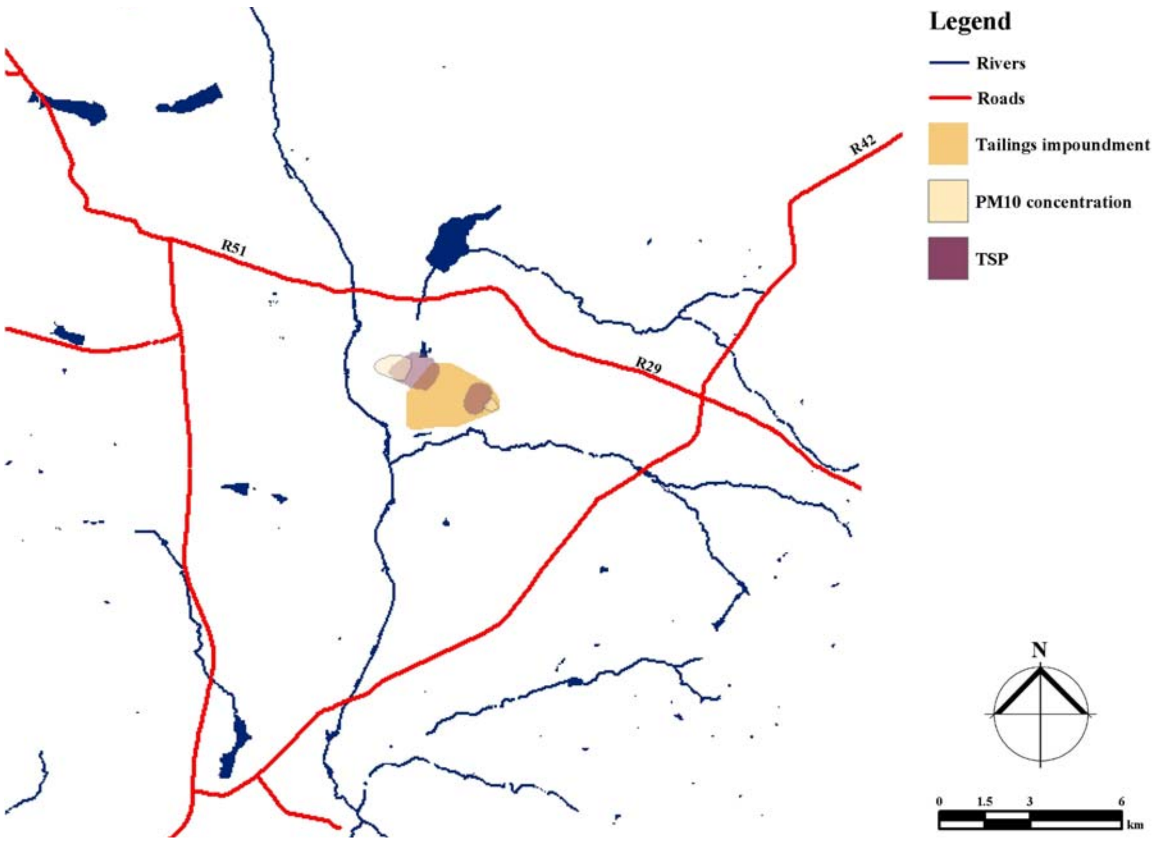


Figure B. 12: 1:9 embankment side slope with 80% control efficiency (AS16)

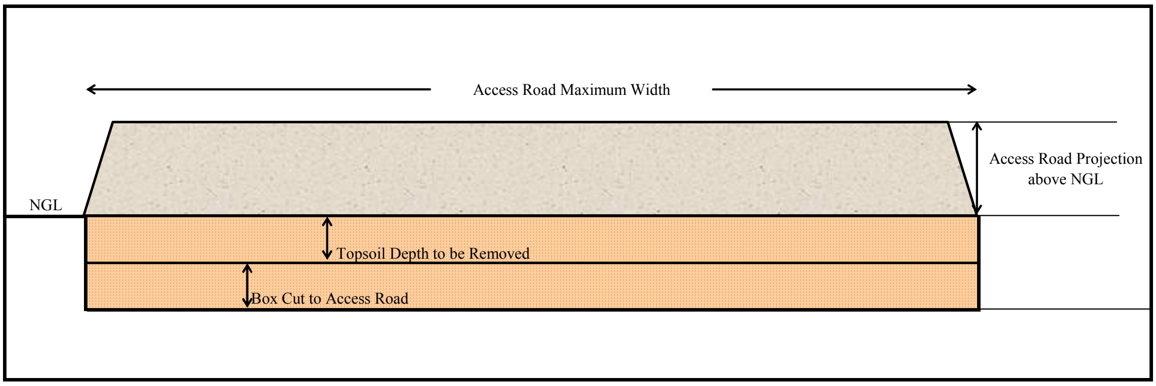
APPENDIX C: ENGINEERING COST MODEL

Appendix C1: Engineering specification sheets

C.1 Access and perimeter roads

SPECIFICATION SHEET FOR ACCESS ROAD CONSTRUCTION

Typical Cross Section through Access Road



Notes and Specifications

1 Access road width is a variable defined by user input, default value of 5.0m
2 Access road length is a variable either defined by user input or calculated by model
3 Topsoil depth to be removed is a variable defined by user input, default value 0.15m
4 Depth of box cut to access road is a variable defined by user input, default value 0.15m
5 Access road projection above NGL is a variable defined by user input, default value of 0.3m
6 Total fill thickness required is a variable dependant on user input, default value of 0.6m defined as depth of topsoil removal (0.15m) + depth of box cut (0.15m) + fill above NGL (0.3m)
7 Clear and grub material to be disposed of within freehaul distance
8 Topsoil to be stockpiled within freehaul distance for re-use
9 Material from box cut excavation to be stockpiled for re-use elsewhere
10 Suitable construction material to be sourced from borrow area **or** ex-excavation **or** ex-stockpile
11 All construction material available within 2km freehaul distance
12 Compaction effort required defined as minimum of four passes with one tonne vibratory roller

Known Dimensions / Parameters and Variables

		Unit	Quantity
1	Access road width	m	5.00
2	Access road length	m	2000.00
3	Access road depth of topsoil to be removed	m	0.15
4	Access road depth of box cut	m	0.15
5	Access road fill above NGL thickness	m	0.30

C.2 Tailings delivery, ring main and distribution pipelines

SPECIFICATION SHEET FOR DELIVERY AND DISTRIBUTION PIPING

Notes and Specifications

1	Delivery pipeline diameter is a variable defined by user input, default value of 250NB
2	Delivery piping specification; Grade B 6mm thick steel piping, rubber lined (6mm), in standard 9.144m lengths flanged at both ends
3	Delivery pipelines number of is a variable defined by user input, default value of 2No
4	Delivery pipeline route length is a variable defined by user input
5	All delivery pipeline specials and non standard lengths are to be rubber lined
6	Delivery pipeline plinths have dimensions 1.25m width x 0.75m height x 0.3m thickness. Rate to include for excavation, formwork, concrete (Class 15Mpa), float finish, backfill and cast in items (16mm diameter mild steel guide rods 600mm long and skid plates, 80 x 4 flat bar 1.0m long)
7	Spacing between delivery pipeline plinths is a variable defined by user input, default value of 3.05m
8	Delivery piping number of specials (bends, T-pieces) is a variable defined by user input, default value of 10No. Rate to be indicative only
9	Delivery piping number of non-standard lengths is a variable defined by user input, default value of 20No. Rate to be indicative only
10	Valves are specified as ATVAL Type KE pinch valve (closed body) with diameter equal to delivery pipeline diameter, rate to include for the supply and installation of hydraulic pack
11	Valves number of is a variable defined by user input default value of 10No
12	Distribution pipeline diameter is a variable defined by user input, default value of 250NB
13	Distribution piping specification; Grade B 6mm thick steel piping, unlined, in standard 9.144m lengths flanged at both ends with 75mm stub ends at 2.5m centers (defined)
14	Distribution pipeline route length is a variable defined by user input, default value equal to tailings dam perimeter
15	Distribution piping number of specials (bends, T-pieces) is a variable defined by user input, default value of 20No. Rate to be indicative only
16	Distribution piping number of non-standard lengths is a variable defined by user input, default value of 40No. Rate to be indicative only
17	Starter wall length, average height and inner slope gradient are variables either defined by user input or calculated by model
18	Layflat hosing is specified as 75mm diameter, length of hosing required is calculated by model

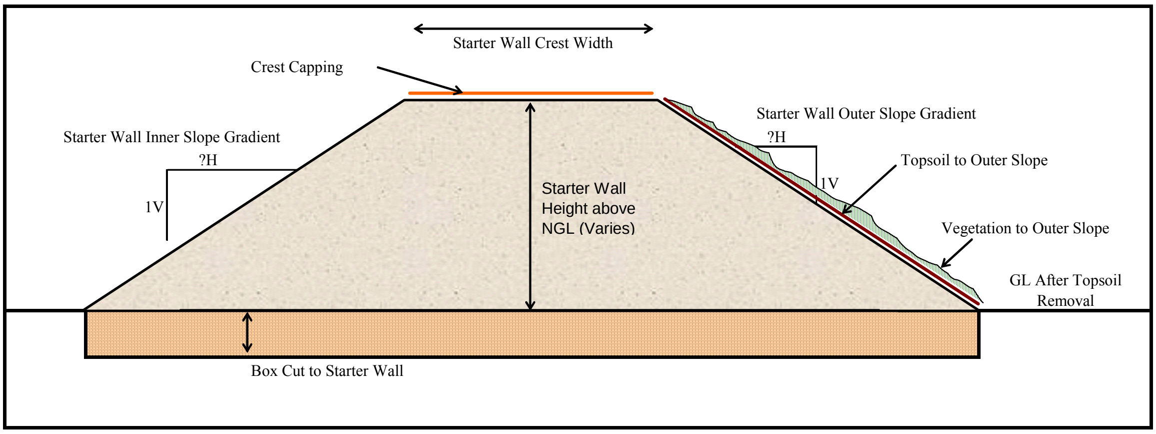
Known Dimensions / Parameters and Variables

		Unit	Quantity
1	Delivery pipeline number of	No	2.00
2	Delivery pipeline route length	m	2000.00
3	Delivery pipeline specials (bends, T-pieces etc) number of per pipeline	No	10.00
4	Delivery pipeline non standard lengths number of per pipeline	No	20.00
5	Delivery pipeline spacing between plinths	m	3.05
6	Distribution piping route length	m	2000.00
7	Distribution piping spacing between spigots	m	2.50
8	Starter wall length	m	1000.00
9	Starter wall average height	m	7.00
10	Starter wall inner slope gradient (1V :?H)	Ratio	2.00
11	Layflat hosing average length per spigot	m	15.65
12	Distribution piping specials (bends t-pieces) number of	No	20.00
13	Distribution piping non standard lengths number of	no	40.00
14	Valves number of	No	10.00

C.3 Starter wall

SPECIFICATION SHEET FOR STARTER CONSTRUCTION

Typical Cross Section through Starter Wall



Notes and Specifications

1. Starter wall crest width is a variable defined by user input, default value of 5m
2. Starter wall length is a variable either defined by user input or calculated by model
3. Starter wall depth of box cut is a variable defined by user input, default value 0.15m
4. Starter wall inner slope gradient is a variable defined elsewhere by user input
5. Starter wall outer slope gradient is a variable defined elsewhere by user input

6. Starter wall height above NGL varies according to user input defined elsewhere; total fill volume, base area and outer side slope area are calculated by model
7. Starter wall crest capping thickness is a variable defined by user input, default value of 0.2m
8. Starter wall topsoil to outer slope thickness is a variable defined by user input, default value 0.15m
9. Starter wall cladding to outer slope thickness is a variable defined by user input, default value of 0.2m
10. Material from box cut excavation to be stockpiled for re-use as fill material
11. Suitable construction material to be sourced from borrow area **or** ex-excavation **or** ex-stockpile
12. All construction material available within 2km freehaul distance
13. Compaction effort required, defined as minimum of six passes with suitable vibratory roller

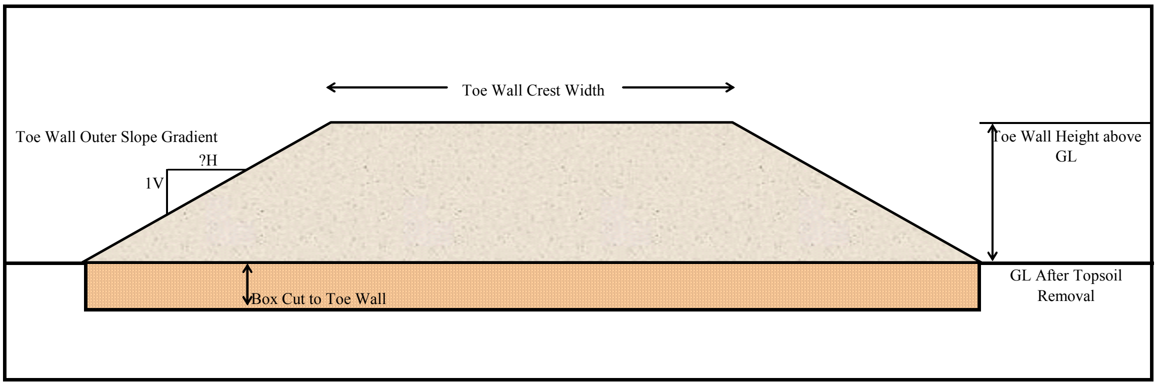
Known Dimensions / Parameters and Variables

		Unit	Quantity
1	Starter wall crest width	m	5.00
2	Starter wall length	m	1000.00
3	Starter wall depth of box cut	m	0.15
4	Starter wall fill volume (above GL)	m^3	150000.00
5	Starter wall base area	m^2	12000.00
6	Starter wall crest capping thickness	m	0.20
7	Starter wall outer slope area	m^2	15000.00
8	Starter wall topsoil to outer slope thickness	m	0.15
	OR		
	Starter wall cladding to outer slope thickness	m	0.20

C.4 Toe wall

SPECIFICATION SHEET FOR TOE WALL CONSTRUCTION

Typical Cross Section through Toe Wall



Notes and Specifications

1. Toe wall crest width is a variable defined by user input, default value of 2m
2. Toe wall length is a variable either defined by user input or calculated by model
3. Topsoil depth to be removed is a variable defined by user input, calculated elsewhere, default value 0.15m
4. Toe wall depth of box cut is a variable defined by user input, default value 0.15m
5. Toe wall height above GL is a variable defined by user input, default value of 1.0m
6. Toe wall outer slope gradient is a variable defined by user input, default value of 1V : 2H
7. Material from box cut excavation to be stockpiled for re-use as fill material
8. Suitable construction material to be sourced from borrow area **or** ex-excavation **or** ex-stockpile
9. All construction material available within 2km freehaul distance
10. Nominal compaction effort required, defined as minimum of two passes with light vibratory roller

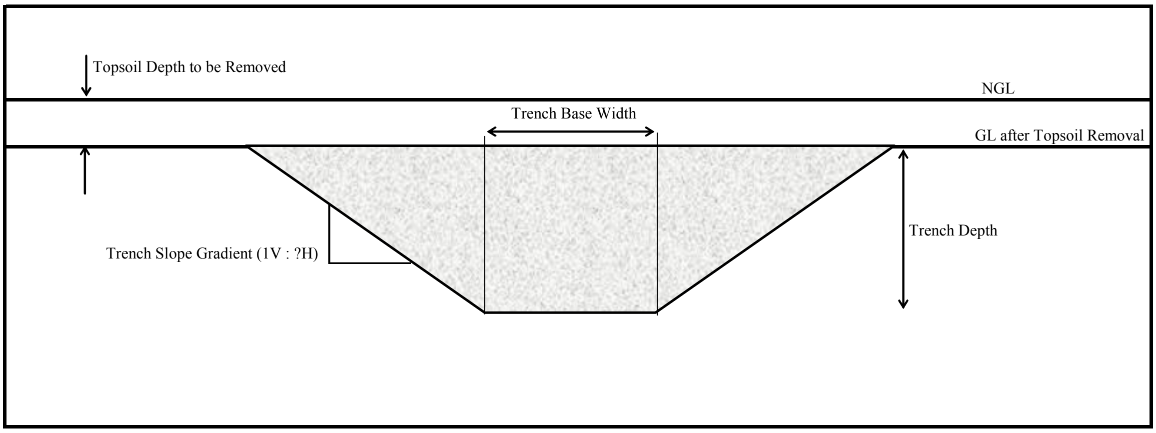
Known Dimensions / Parameters and Variables

		Unit	Quantity
1	Toe wall crest width	m	2.00
2	Toe wall length	m	1000.00
3	Toe wall depth of box cut	m	0.15
4	Toe wall height above GL	m	1.00
5	Toe wall outer slope gradient (1V :?H)	Ratio	2.00

C.5 Solution trench

SPECIFICATION SHEET FOR CONSTRUCTION OF SOLUTION TRENCH

Typical Cross Section through Solution Trench



Notes and Specifications

1. Length of solution trench is calculated by model
2. Solution trench depth is a variable defined by user input, default value 1m
3. Solution trench base width is a variable defined by user input, default value 1m
4. Solution trench side slope gradient is a variable defined by user input, default value 1V : 2H
5. Clear and grub material to be disposed of within freehaul distance (quantified elsewhere)
6. Topsoil to be stockpiled within freehaul distance for re-use (quantified elsewhere)
7. Material from excavation to be stockpiled for re-use as fill material

Known Dimensions / Parameters and Variables

		Unit	Quantity
1	Solution trench length	m	1000.00
2	Solution trench depth	m	1.00
3	Solution trench base width	m	1.00
4	Solution trench side slope gradient (1V : ?H)	Ratio	2

Quantification

		Unit	Quantity
1	Solution trench excavation *Calculation [solution trench sectional area x length of solution trench]*	m^3	5000.00

Base Rates

		Unit	Rate
1	Solution trench excavation	R/m^3	5

Applicable CPI Factors to Base Rates

		Unit	CPI Factor
1	Rate for solution trench excavation	Factor	1.1

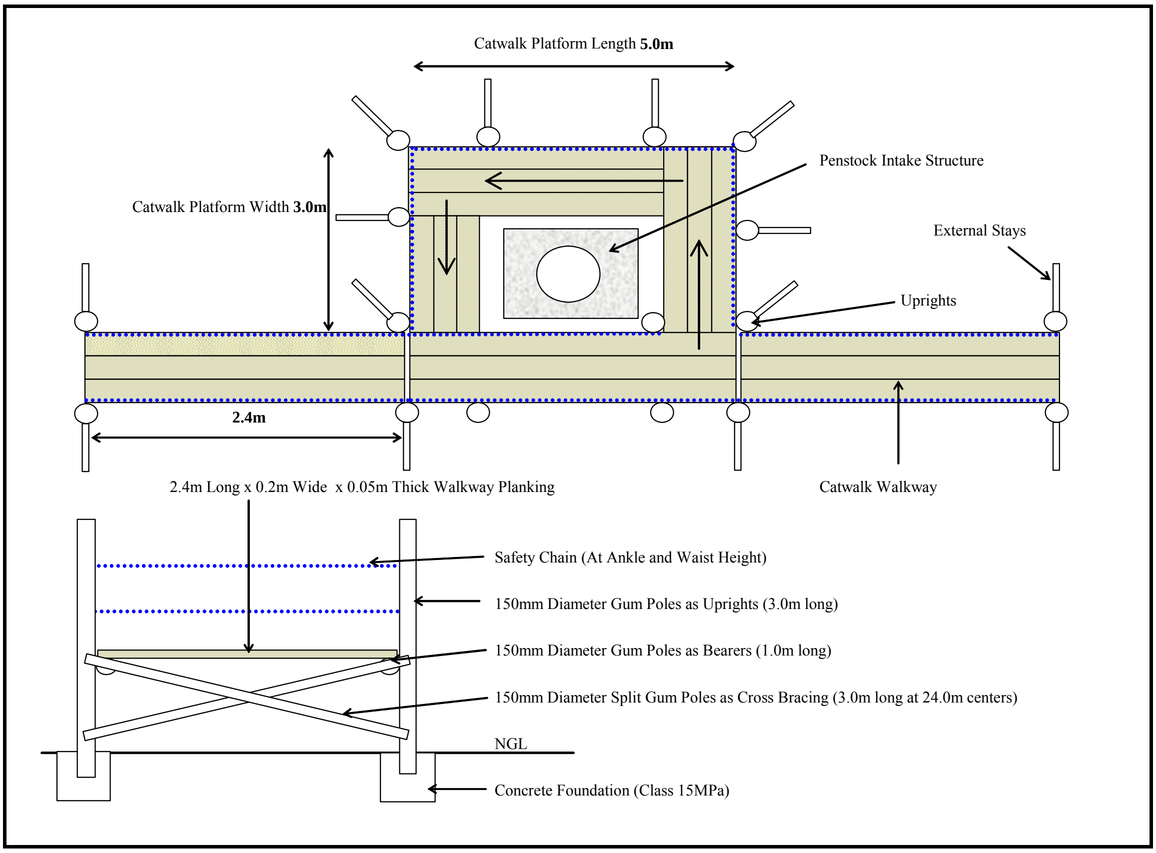
Final Rates for Construction of Solution Trench

		Unit	Final Rate
1	Solution trench excavation	R/m^3	7.7

C.6 Catwalk

SPECIFICATION SHEET FOR INSTALLATION OF CATWALK WALKWAY AND PLATFORMS

Typical Sections through Catwalk Installation



Notes and Specifications

1. Catwalk length is a variable defined by user input, default value equal to penstock pipeline length
2. Catwalk platforms number of is a variable defined by user input, default value of 4No
3. All timber is to be Tanolith treated prior to delivery to site
4. Installation rate is to be all inclusive for materials (timber, concrete, safety chain, nuts, bolts etc), excavation, fixing and backfill

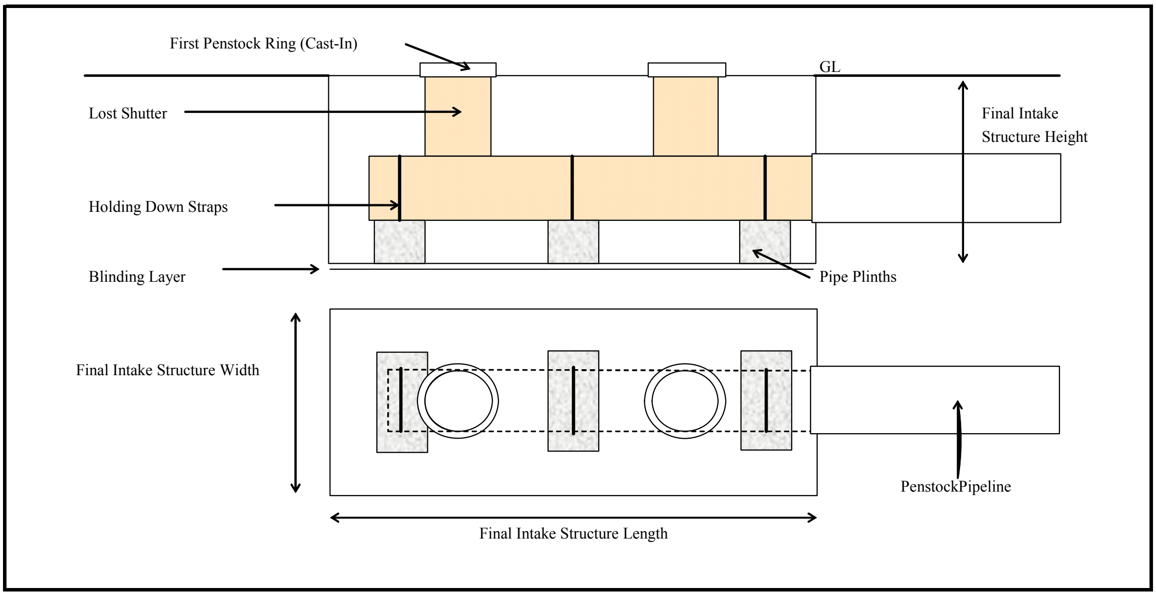
Known Dimensions / Parameters and Variables

		Unit	Quantity
1	Catwalk length	m	300.00
2	Catwalk number of platforms	m	4.00

C.7 Penstock

SPECIFICATION SHEET FOR CONSTRUCTION OF FINAL INTAKE STRUCTURES

Typical Cross Section through Final Intake Structures



Notes and Specifications

1 Number of final penstock intake structures is a variable defined by user input, default value of 1No
2 Final penstock structure excavation width is a variable defined by user input, default value of 2.0m
3 Final penstock structure excavation length is a variable defined by user input, default value of 3.0m
4 Final penstock structure height is a variable defined by user input, default value of 1.2m
5 Final penstock structure width is a variable defined by user input, default value of 1.5m
6 Final penstock structure length is a variable defined by user input, default value of 2.5m
7 Number of pipe plinths is a variable defined by user input, default value of 3No. Dimensions 800 x 200 x 200, rate to be all inclusive

8 Number of penstock rings per structure is a variable defined by user input, default value of 2No. Rings to be SABS approved with 510mm diameter
9 Blinding thickness is a variable defined by user input, default value of 75mm
10 Anchor straps to be 80 x 5 mild steel, rate to include for HD bolts and is indicative only

11 Lost shutter to be manufactured with 3mm mild steel with dimensions to suit inner diameter of penstock pipeline and penstock rings, rate to be indicative only
12 All excavated material to be retained for backfill or disposed of within construction area
13 Blinding layer to be constructed with 15Mpa / 19mm concrete
14 All concrete is specified as Class 30Mpa / 19mm
15 Compaction effort required defined as minimum of four passes with one tonne vibratory roller

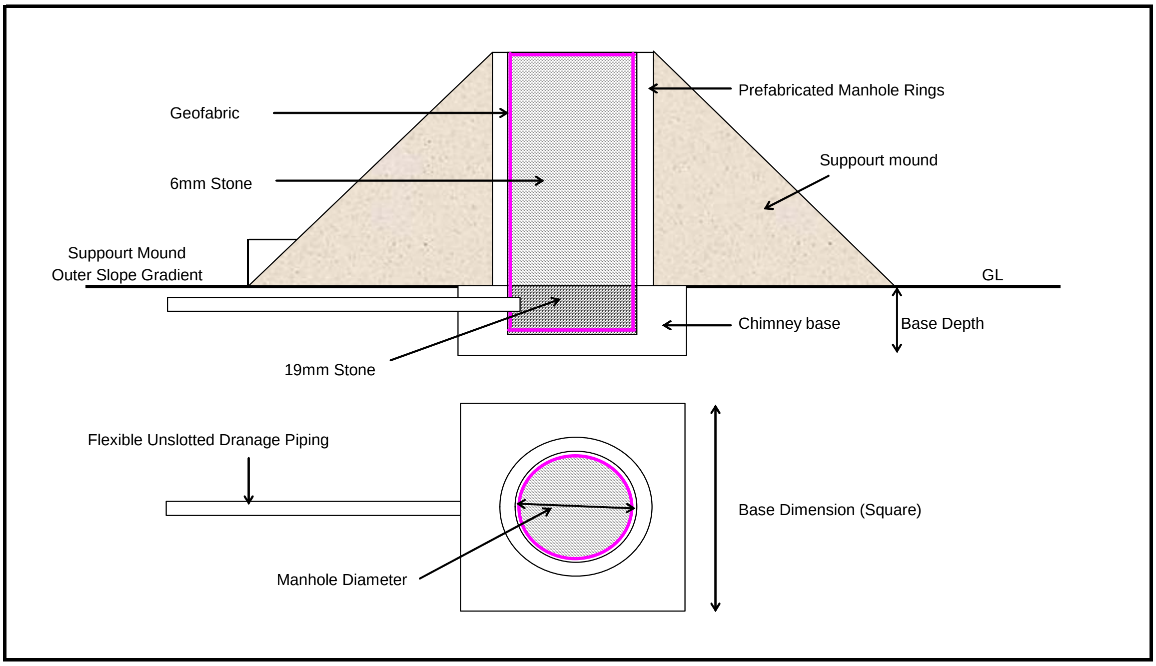
Known Dimensions / Parameters and Variables

		Unit	Quantity
1	Penstock final intake number of	No	1.00
2	Penstock final intake structure excavation width	m	2.00
3	Penstock final intake structure excavation length	m	3.00
4	Penstock final intake structure height	m	1.20
5	Penstock final intake structure width	No	1.50
6	Penstock final intake structure length	m	2.50
7	Penstock final intake structure blinding thickness	m	0.075
8	Penstock final intake structure plinths number of	m	3.00
9	Penstock final intake structure number of penstock rings per structure	m	2.00

C.8 Drains

SPECIFICATION SHEET FOR CONSTRUCTION OF ELEVATED DRAIN CHIMNEYS

Typical Cross Section through Elevated Drain Chimney



Notes and Specifications

1 Elevated drain length that requires chimney outlets is a variable defined by user input or calculated by model, default value of length of starter wall
2 Spacing between elevated drain chimneys is a variable defined by user input, default value of 50m
3 Number of elevated drain chimneys is calculated by model

4 Elevated drain chimneys average height is a variable defined by user input or calculated by model, default value of maximum height of starter wall
5 Elevated drain chimney base has dimensions 1.5 x 1.5 x 0.35, rate to include for formwork, concrete (Class 25MPa), float finish and cast-in unslotted Drainex coupling (160mm diameter)
6 Elevated drain chimney to be constructed with pre-fabricated manhole rings 1.0m diameter, first ring to be cast into base
7 Height of 6mm stone drainage layer is equal to chimney height
8 Thickness of 19m stone drainage layer is equal to base internal height defined as 0.25m
9 Drainage piping is specified as 160mm diameter 'Drainex' flexible HDPE unslotted piping, but is quantified elsewhere
10 Geofabric is specified as Bidum A4
11 6mm stone is to be washed and must meet the following grading criteria

Sieve size (mm)	Percentage passing
9.50	100
6.70	85 - 100
4.75	0 - 30
3.35	0 - 5
Dust	Nil

12 19mm stone is to be washed and must meet the following grading criteria

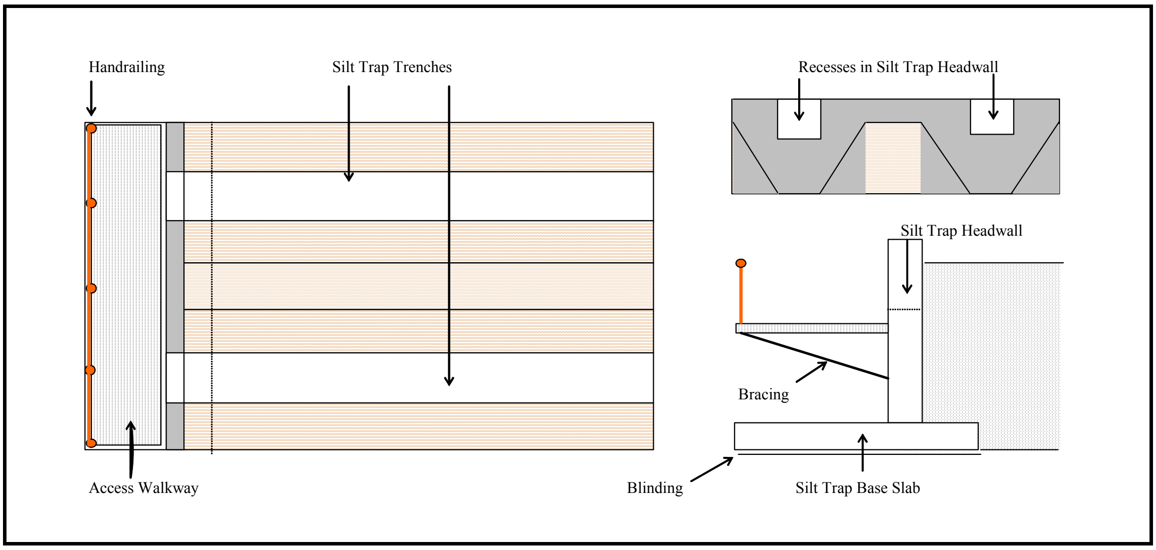
Sieve size (mm)	Percentage passing
26.50	100
19.00	85 - 100
13.20	0 - 30
9.50	0 - 5
Dust	Nil

13 All excavated material to be stockpiled for re-use

C.9 Silt trap

SPECIFICATION SHEET FOR CONSTRUCTION OF SILT TRAP HEADWALL AND TRENCHES

Typical Cross Sections through Silt Trap



Notes and Specifications

1 Silt trap topsoil depth to be removed is a variable defined by user input, default value of 0.15m
2 Silt trap headwall length is a variable defined by user input, default value of 20m
3 Silt trap headwall height is a variable defined by user input, default value of 1.7m
4 Silt trap headwall thickness is a variable defined by user input, default value of 0.3m
5 Silt trap base width is a variable defined by user input, default value of 1.2m
6 Silt trap base thickness is a variable defined by user input, default value of 0.3m
7 Silt trap recess to headwall have dimensions 1.0 x 1.0m
8 Silt trap trench length is a variable defined by user input, default value of 20m
9 Silt trap trench base width is a variable defined by user input, default value of 2.0m
10 Silt trap trench side slope gradient is a variable defined by user input, default value of 1V : 2H
11 Silt trap trench depth is a variable defined by user input, default value of 1.5m
12 Silt trap length of handrailing is calculated by model, specified as mild steel galvanised tubular 2 rail type. Hand rail size 34 x 2.5, ball type stanchion type 43 x 3.0, all connections to be welded. Rate to be indicative only
13 Silt trap walkway flooring width is defined as 1.0m, specified as light duty galvanised 40 x 4.5 gratings to be connected to walkway frame constructed out of 80 x 80 x 8 L section beams with bracing at both ends and at 1.2m intervals. Rate to be indicative only
14 Clear and grub material to be disposed of within construction area
15 Topsoil removed is to be stockpiled for re-use within freehaul distance
16 All excavated material to be retailed for use as backfill or disposed of within the construction area
17 Blinding layer to be constructed with 15Mpa / 19mm concrete, thickness specified as 0.150m
18 All concrete is specified as Class 30Mpa / 19mm
19 Mass of rebar per volume of concrete is a variable defined by user input, default value of 120kg/m3
20 Compaction effort required defined as minimum of four passes with one tonne vibratory roller

Known Dimensions / Parameters and Variables

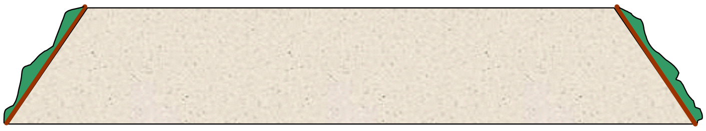
		Unit	Quantity
1	Silt trap topsoil depth to be removed	m	0.15
2	Silt trap headwall length	m	20.00
3	Silt trap headwall height	m	1.70
4	Silt trap headwall thickness	m	0.30
5	Silt trap base width	m	1.20
6	Silt trap base thickness	m	0.30
7	Silt trap recess to headwall dimensions (square)	m	1.00
8	Silt trap trench length	m	20.00

C.10 Cover

SPECIFICATION SHEET FOR CLADDING OF TAILINGS DAM OUTER SLOPES

Typical Cross Section through Tailings Dam

Option One: Topsoil and Vegetate



Option Two: Clad with Rockfill

Notes and Specifications

1 Tailings dam outer slope are is calculated by model elsewhere

2 Topsoil depth is a variable defined by user input, default value of 0.15m. Rate to be based on collection of topsoil from stockpile within 2 km's

3 Vegetation of outer slopes is to be achieved by hand planting, species mix is as follows

Species	Common Name	Variety	Rate (kg/Ha)
Cenchrus ciliaris	Blue buffalo grass	Molopo	5
Chloris gayana	Rhodes grass	Katambora	3
Cynodon dactylon	Kweek	Bermuda	10
Digitaria eriantha	Smuts finger grass	Irene	5

4 Rockfill cladding thickness is a variable defined by user input, default value of 0.3m. Rate to be based on the free supply of material to be collection from within a 2 km radius

Known Dimensions / Parameters and Variables

		Unit	Quantity
1	Tailings dam outer slope area	m^2	80000.00
2	Tailings dam topsoil cladding thickness	m	0.15
3	Tailings dam rockfill cladding thickness	m	0.30