The Influence of Environmental Impacts on Tailings Impoundment Design

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.

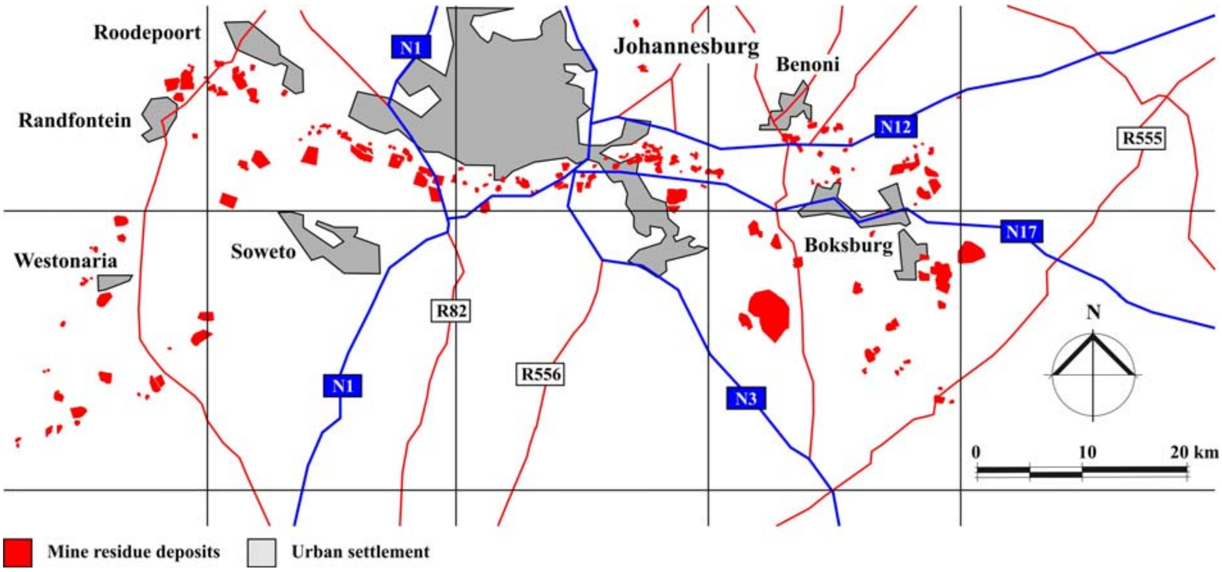

Figure 1: Footprints of mine residue deposits in and around the Gauteng province, South Africa (Rademeyer and van den Berg, 2005).

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.

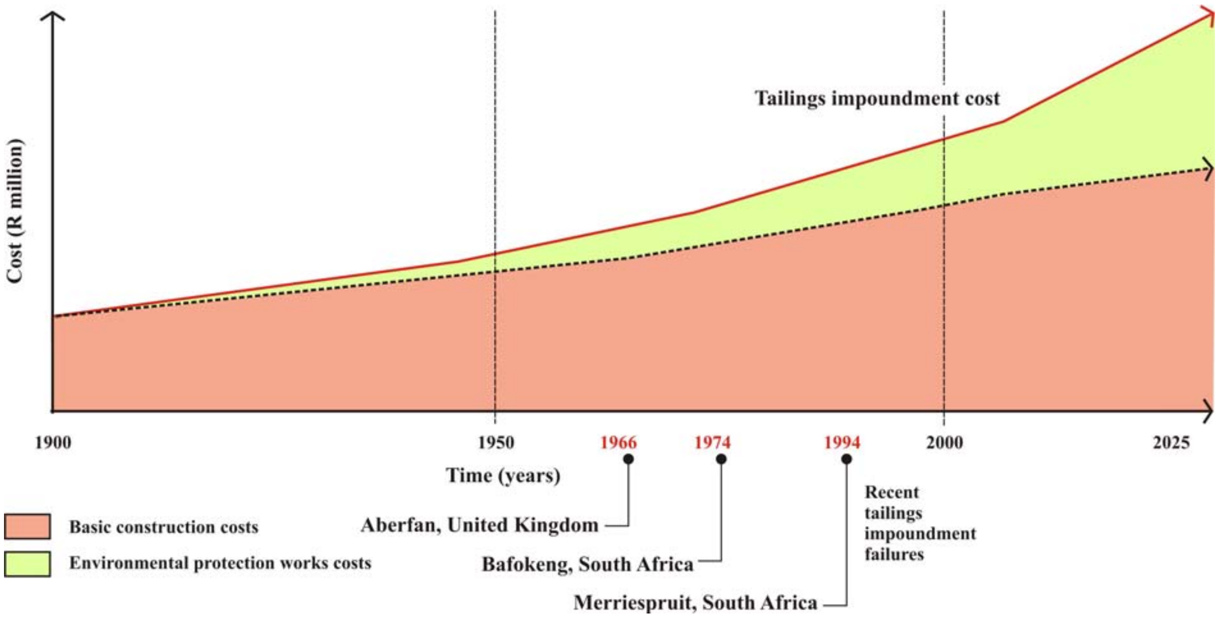

Figure 2: Schematic illustration of perceived increase in tailings impoundment cost over time.

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.

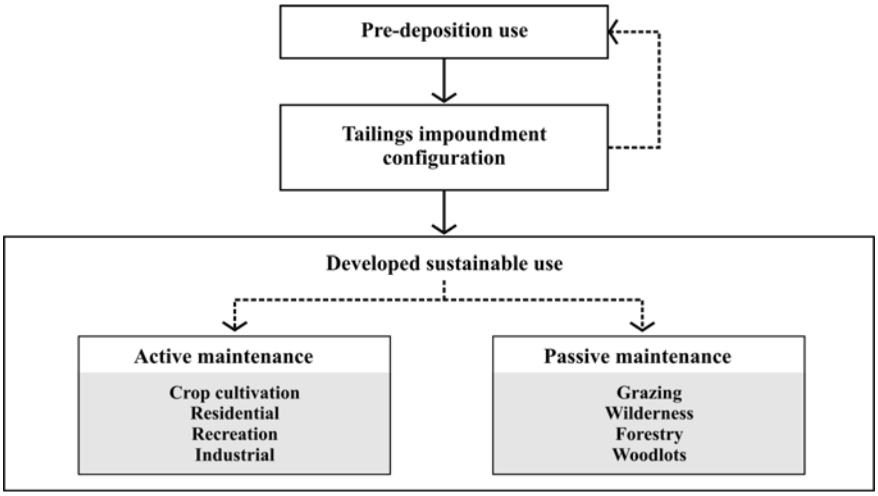

Figure 5: The land use selection process for developed sustainable land use (Roberson et al., 1998a).

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.

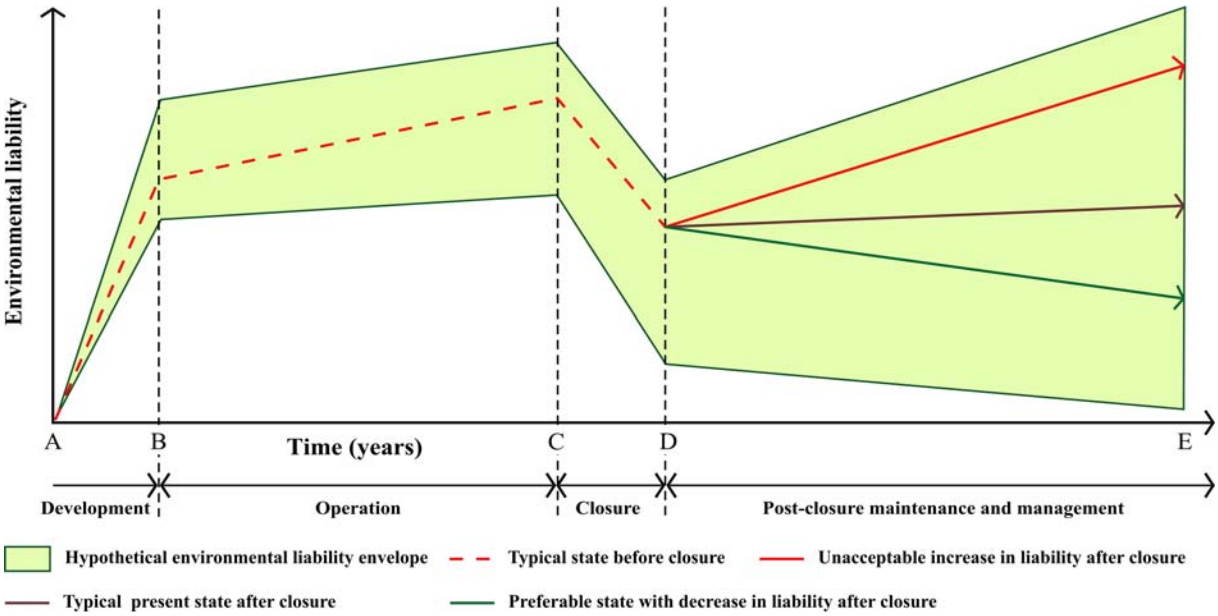

Figure 6: Conceptual environmental liability over the life of an impoundment.

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).

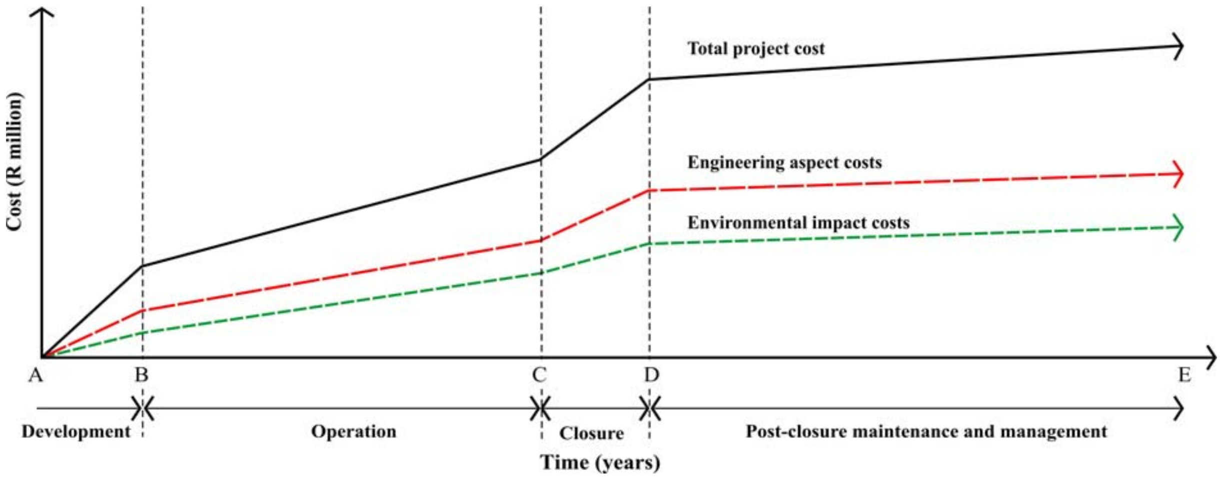

Figure 7: Total tailings impoundment life-cycle costs combining environmental impact costs and engineering aspect costs.

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.

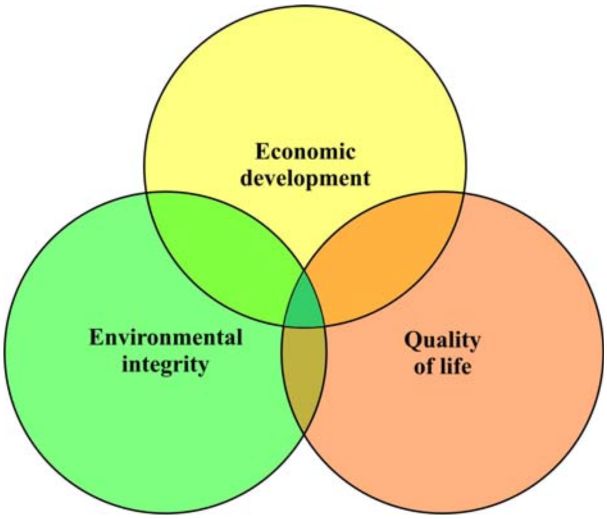

Figure 8: Three components of sustainable development.

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.

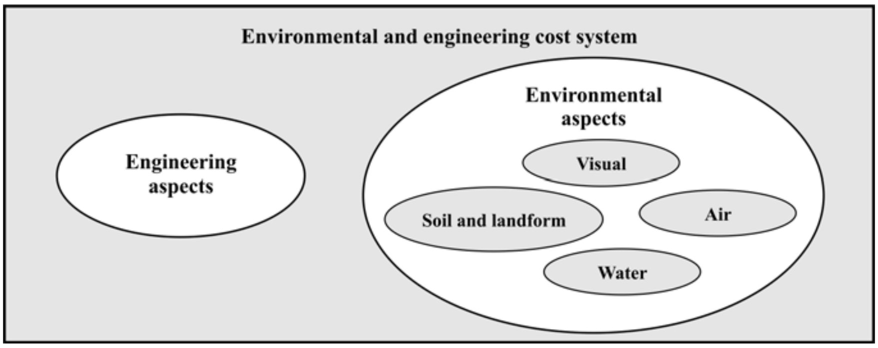

Figure 9: Components of the overall costing system.

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.

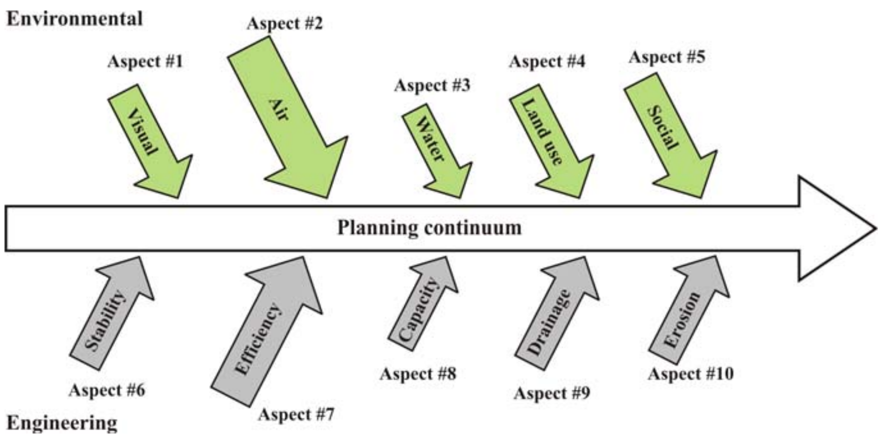

Figure 10: Representation of environmental and engineering aspects in the planning continuum.

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.