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).

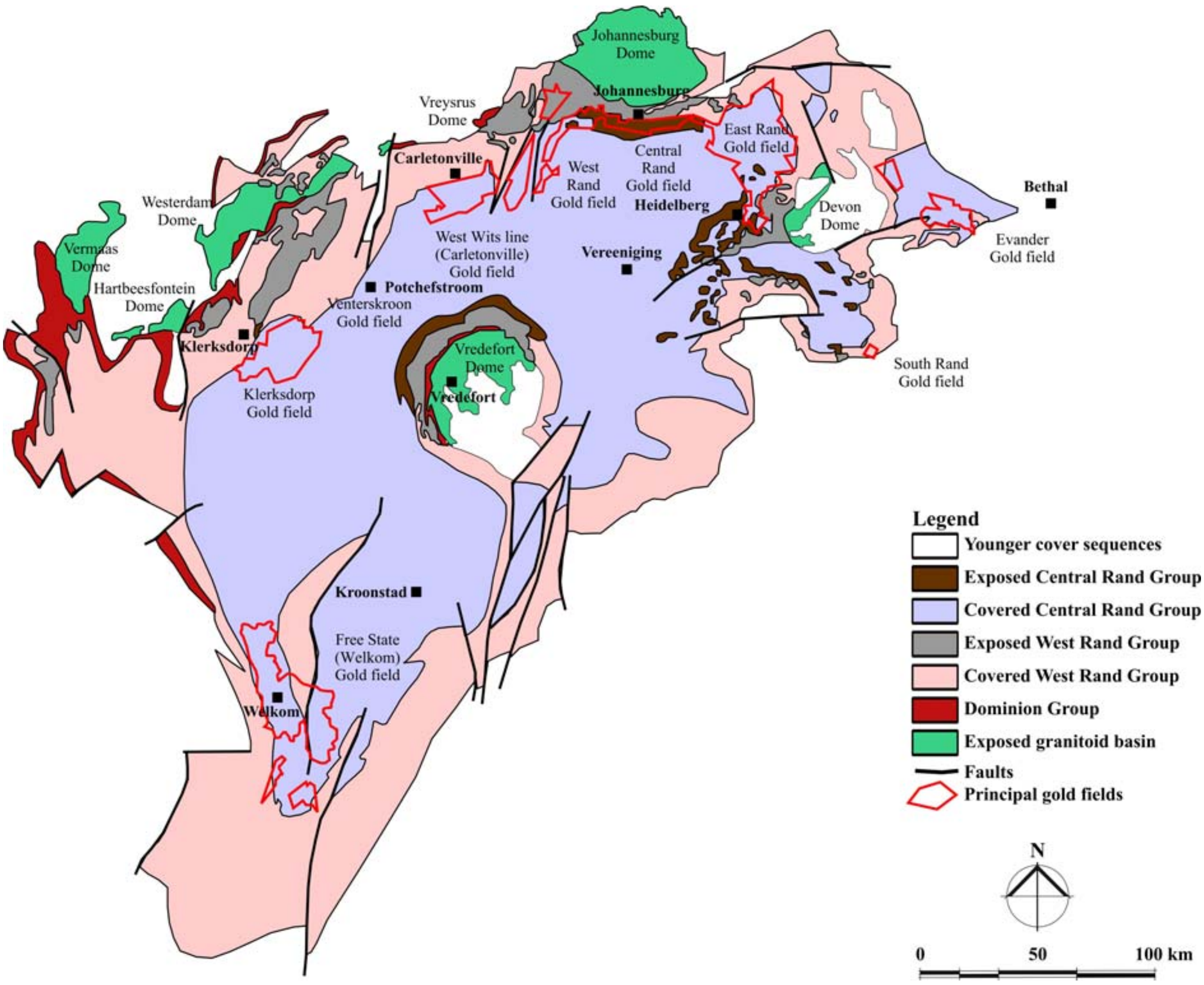


Figure 13: Simplified geological map of the Witwatersrand Basin with the principal gold fields delineated (Robb and Robb, 1998:296).

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.

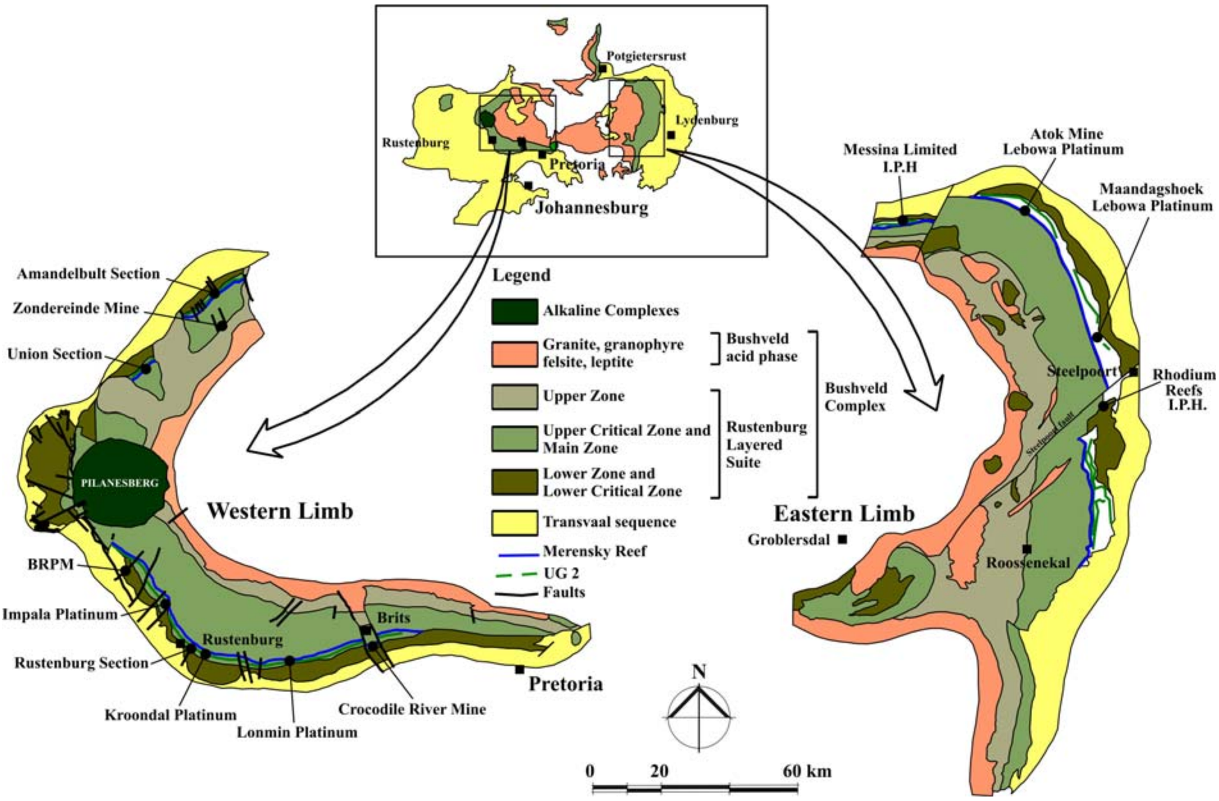
		Production (kg)	
		Gold	**PGM**
Time (years)	**1994**	580 200	183 900
	1995	523 800	183 000
	1996	498 300	188 600
	1997	490 600	196 000
	1998	465 100	199 900
	1999	451 200	216 400
	2000	430 800	206 770
	2001	394 800	228 700
	2002	389 300	236 600
	2003	372 800	266 200
	Total	**4 596 900**	**1 929 300**

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.

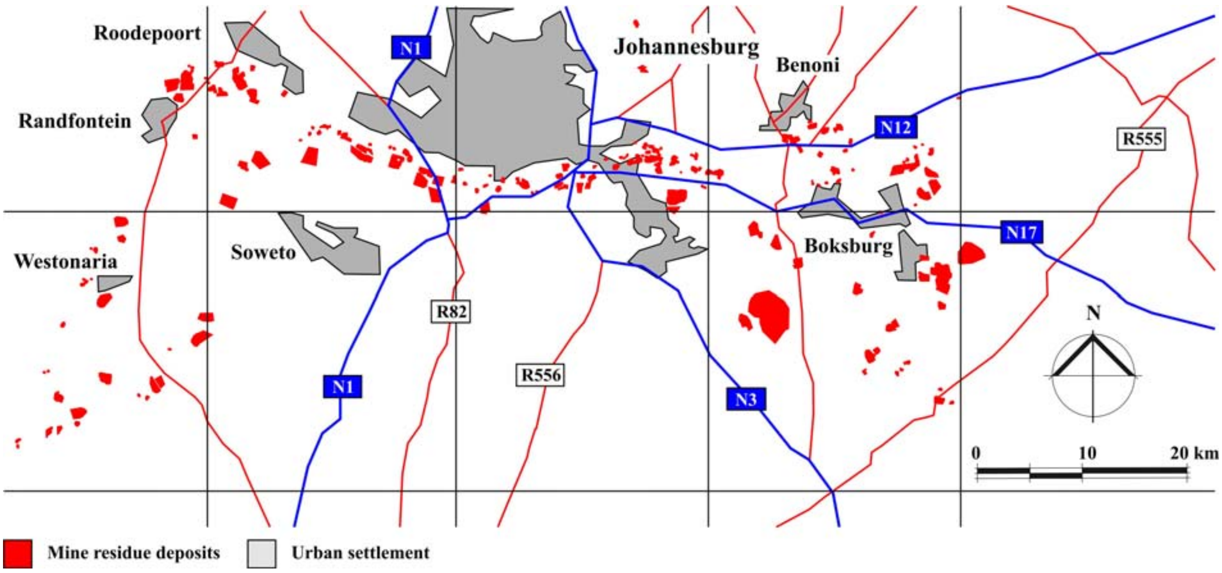


Figure 15: Surface area covered by mining residue deposits within and around Gauteng Province (Rademeyer and van den Berg, 2005).

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?

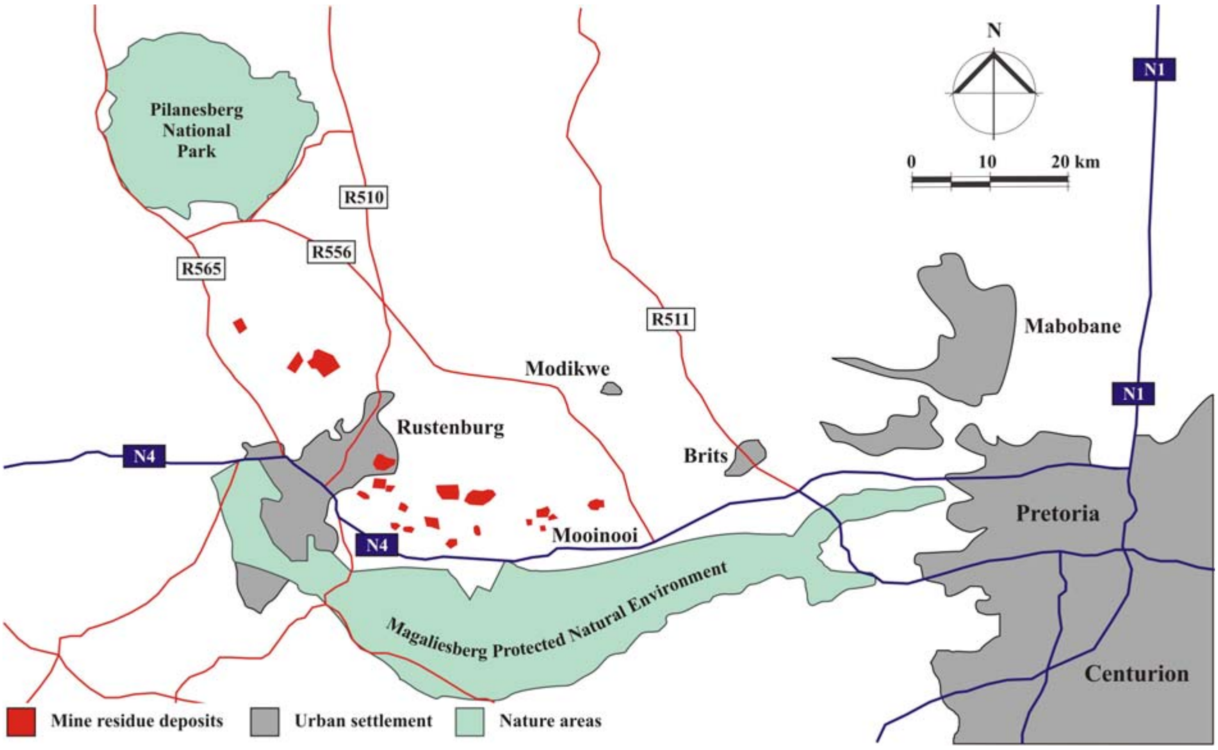


Figure 16: Footprints of mine residue deposits in and around the Rustenburg Region, South Africa.

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).

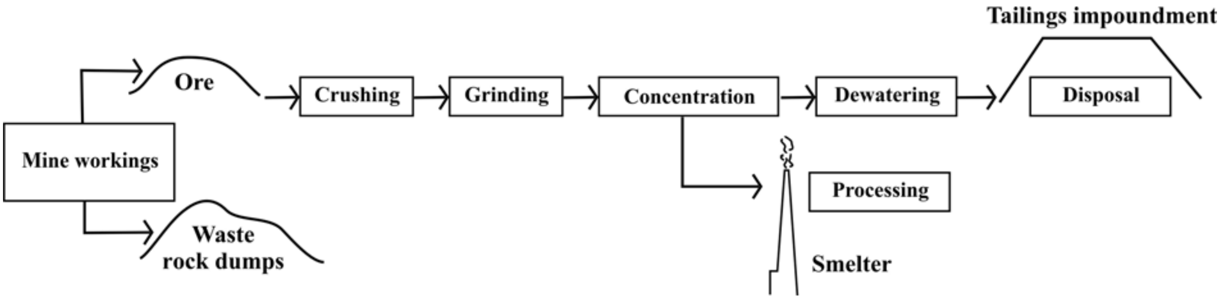


Figure 18: Typical mineral process indicating the context of tailings disposal.

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.

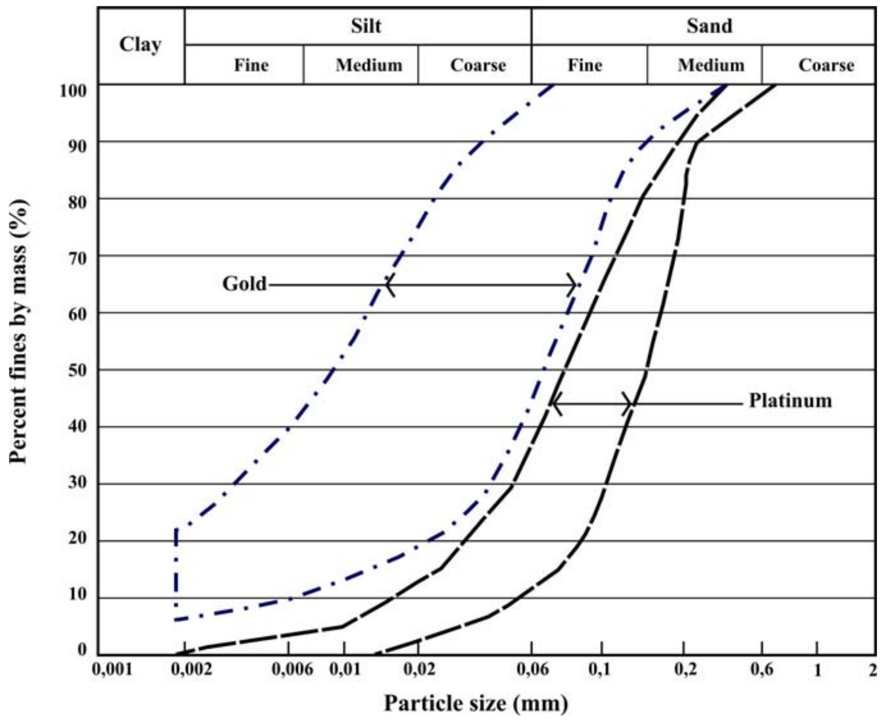


Figure 19: Typical particle size envelopes for gold and platinum tailings (CM, 1996:19).

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.

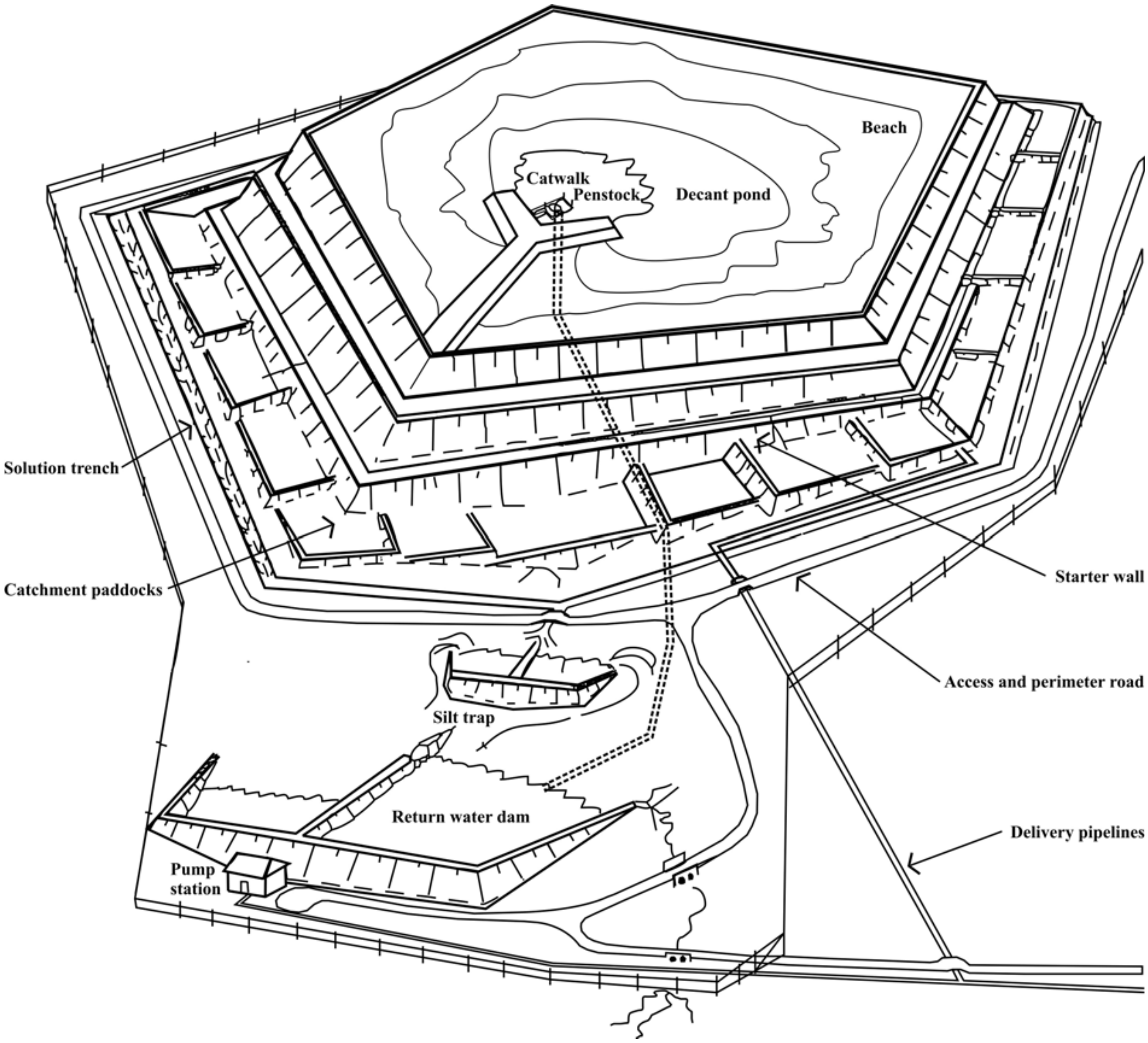


Figure 20: Schematic of upstream deposited ring-dyke tailings impoundment (CM, 1996:169).

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.

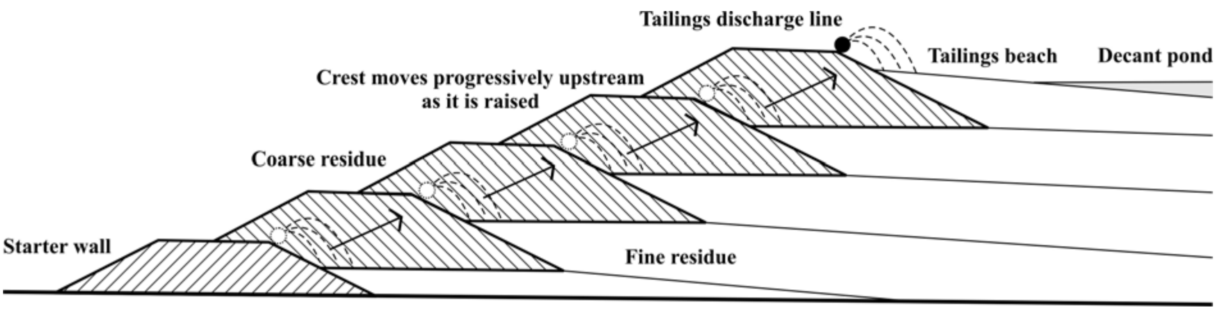


Figure 21: Cross-section through an upstream deposited ring-dyke impoundment embankment.

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.

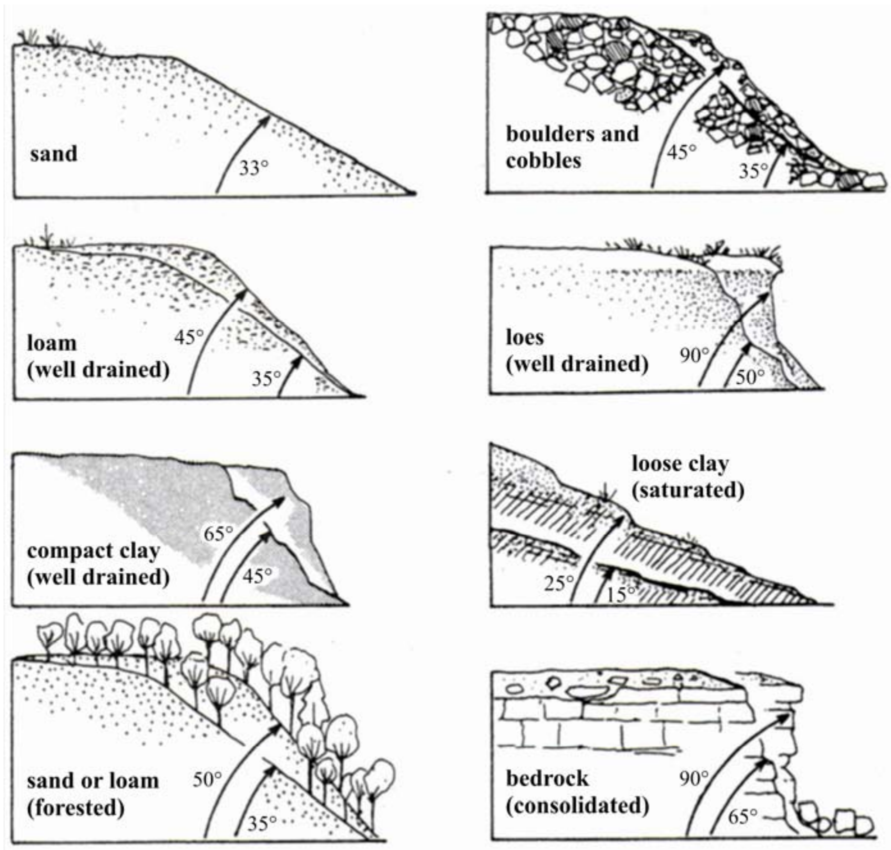


Figure 22: Angles of repose for various types of slope materials (Marsh, 1997:81).

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.

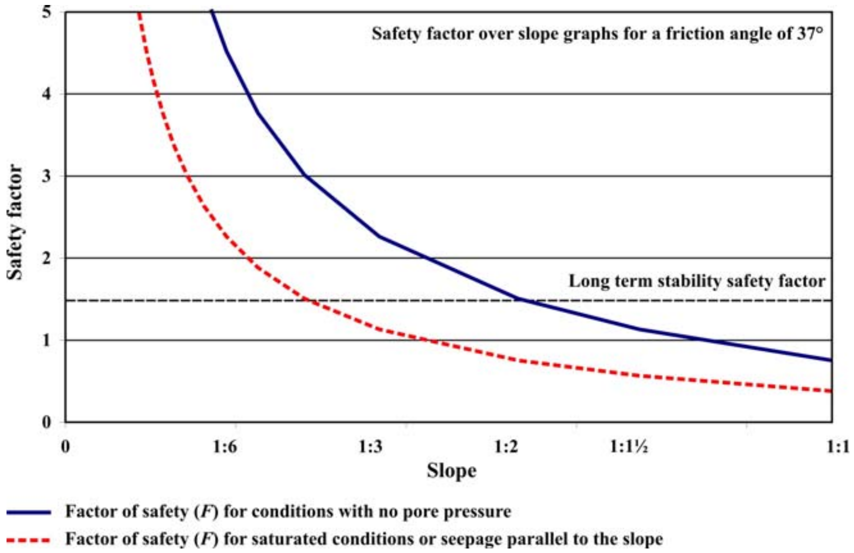


Figure 23: Typical slope safety factors for various slopes given a critical state parameter for the tailings of 37°.

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.

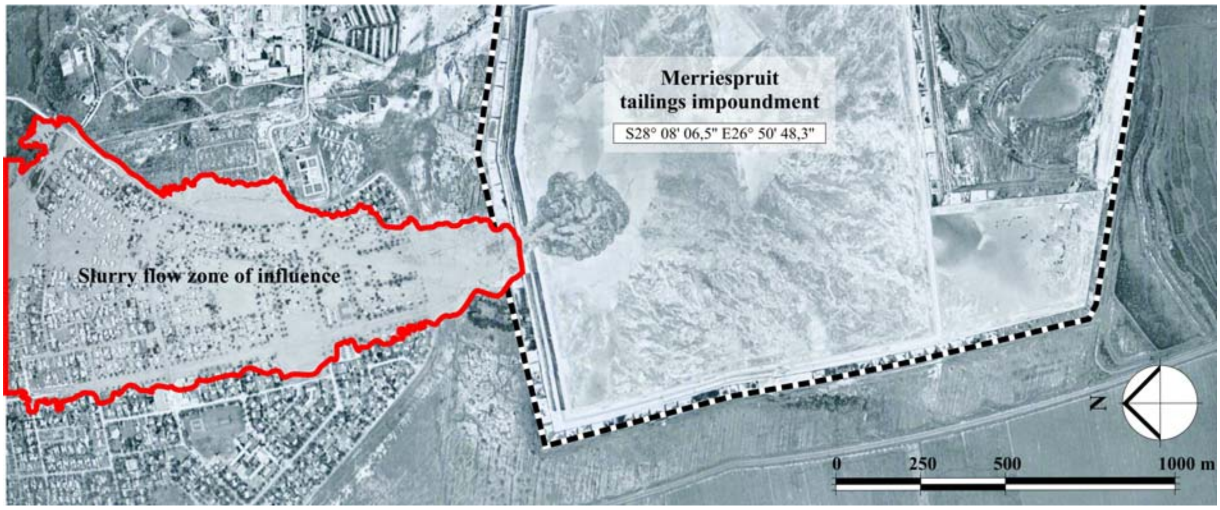
It appears that the Bafokeng impoundment failed as a result of overtopping that was triggered by a form of erosion failure caused by either:

- 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.

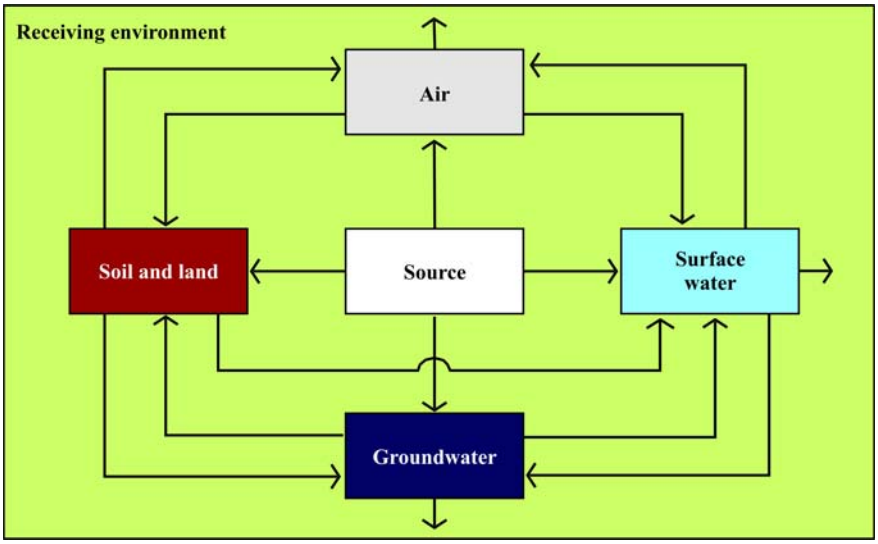


Figure 26: Biophysical environmental aspect pathways.

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.

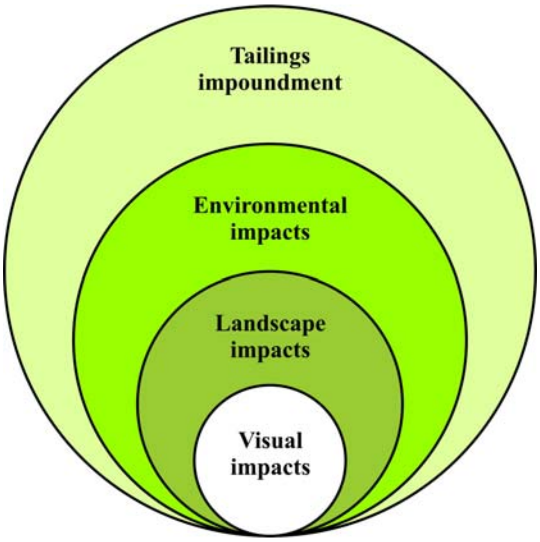


Figure 27: A tailings impoundment impacts the environment resulting in landscape impacts and finally leading to visual impacts (Turner, 1998:34).

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.

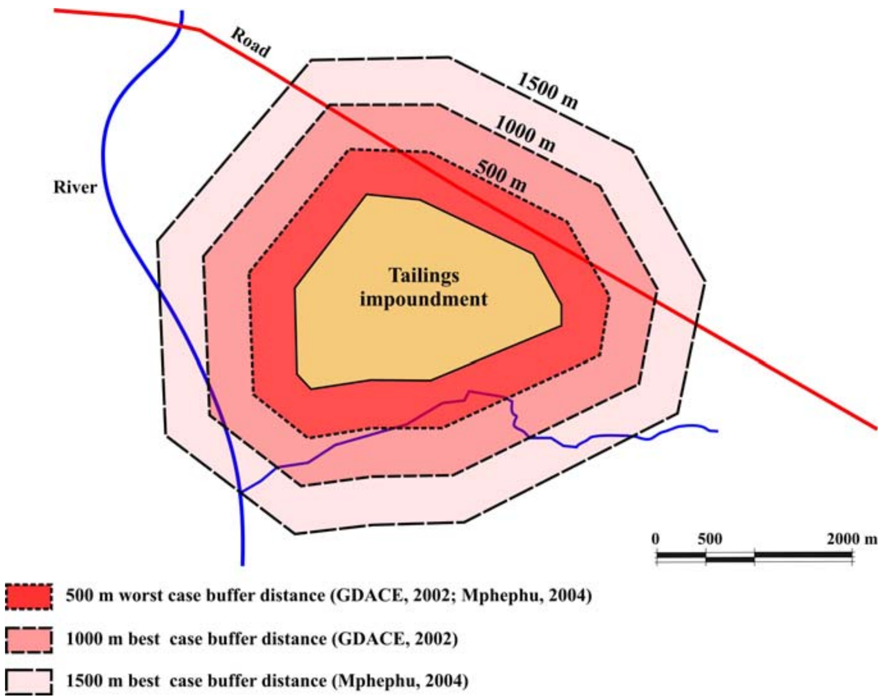


Figure 28: Schematic representation of typical buffer distances.

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.

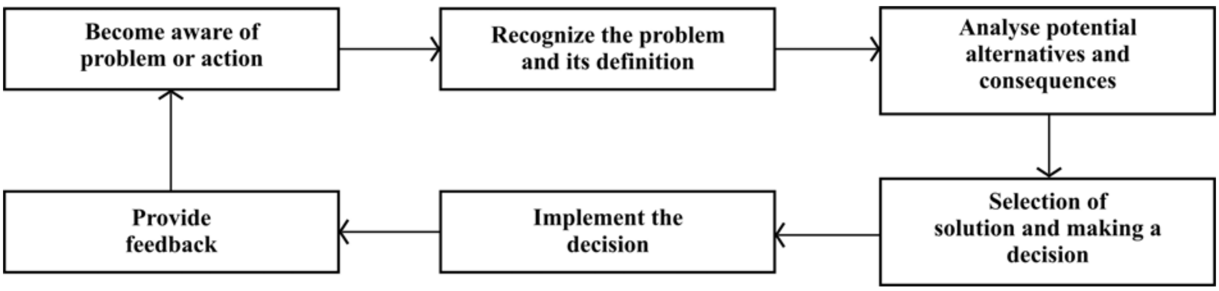


Figure 29 Closed loop decision-making process comprising typical steps common to most decision-making circumstances (Moody, 1983:1).

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.

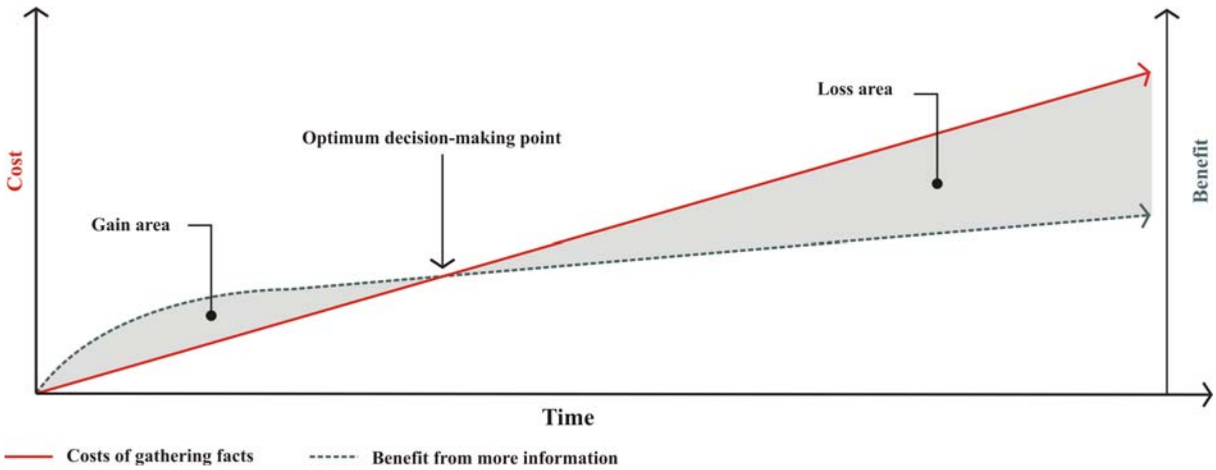


Figure 30: The theoretical optimum decision-making point lies at the cross over point of cost and benefit (Moody, 1983:5).

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?"

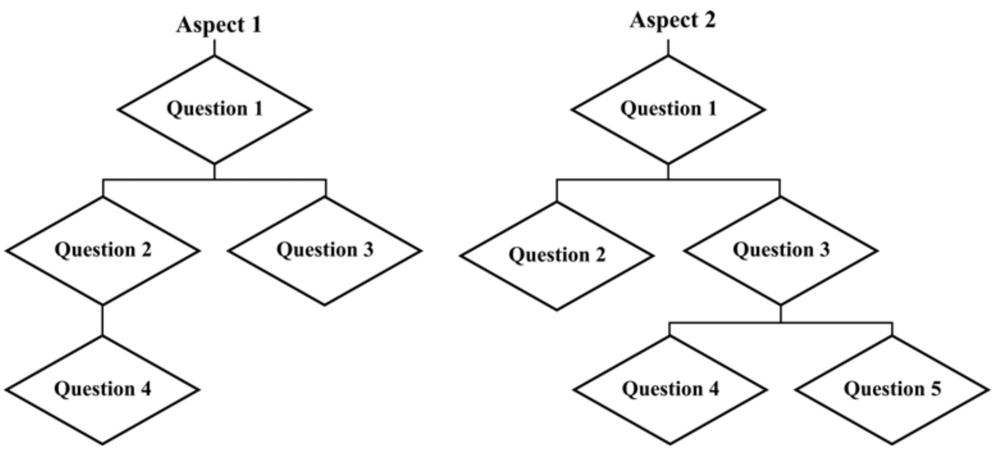


Figure 31: Top down structure of questions for the environmental aspects being considered.

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.

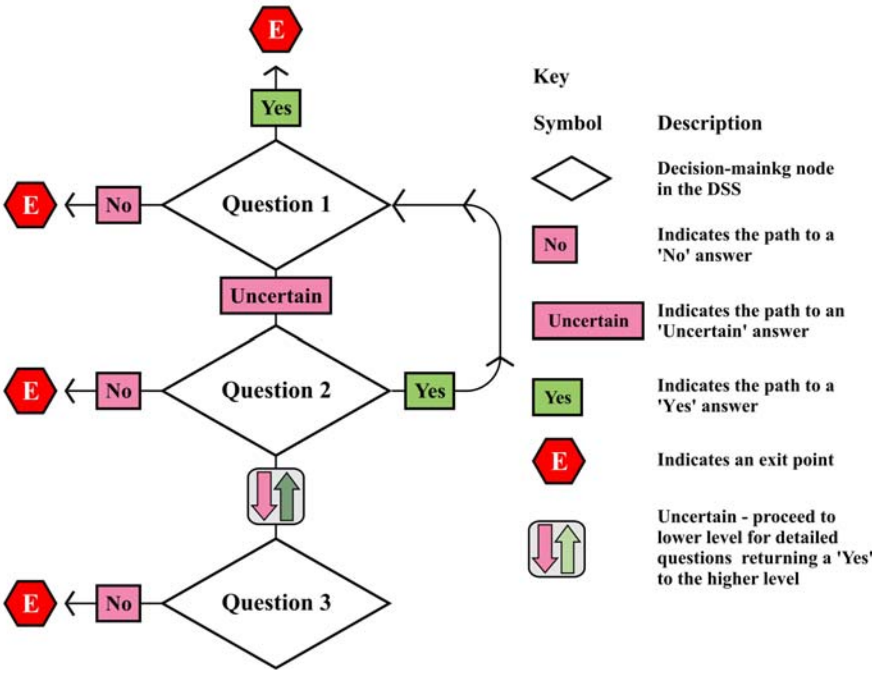


Figure 32: Conceptual DSS framework indicating decision-making paths (Rademeyer et al., 2007).

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).

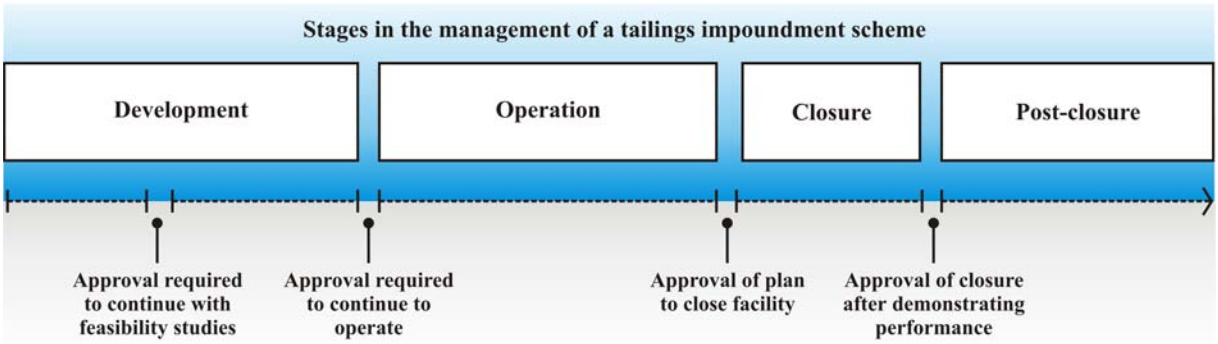


Figure 33: Important decision-making points during tailings impoundment configuration (Rademeyer et al., 2007).

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).

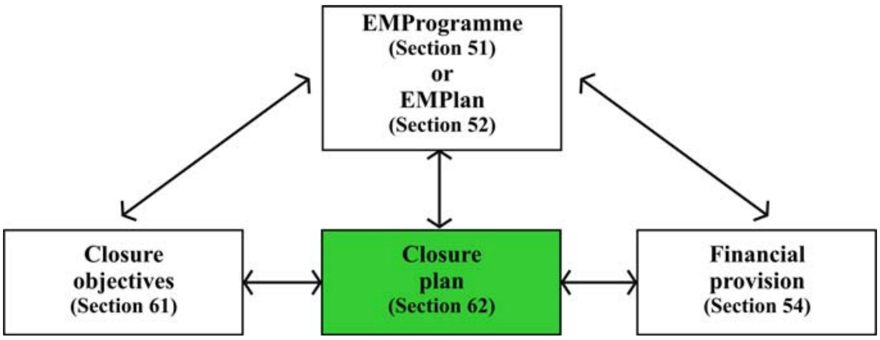


Figure 34: MPRDA closure planning process.

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.

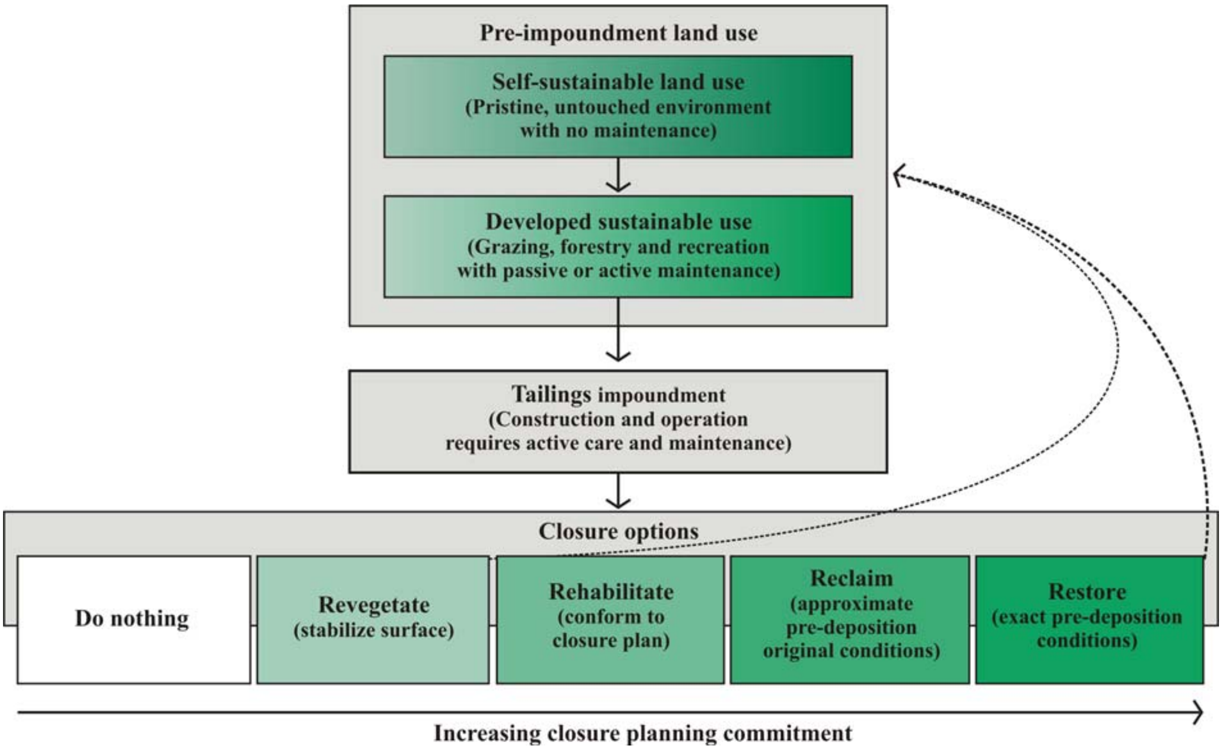


Figure 35: Closure options (Robertson, Devenny and Shaw, 1998b).

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.

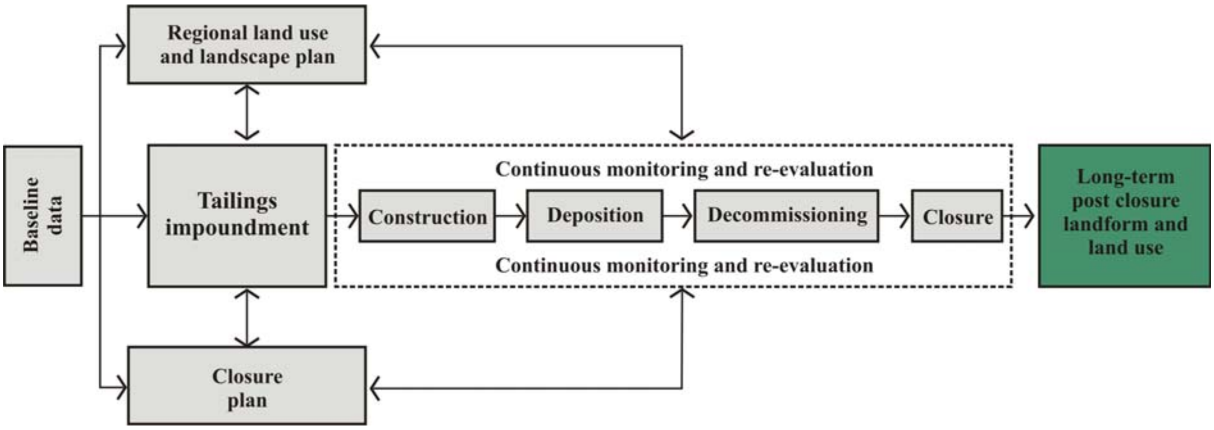


Figure 36: Integrated impoundment environmental planning and design process (Rademeyer and van den Berg, 2005).

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).

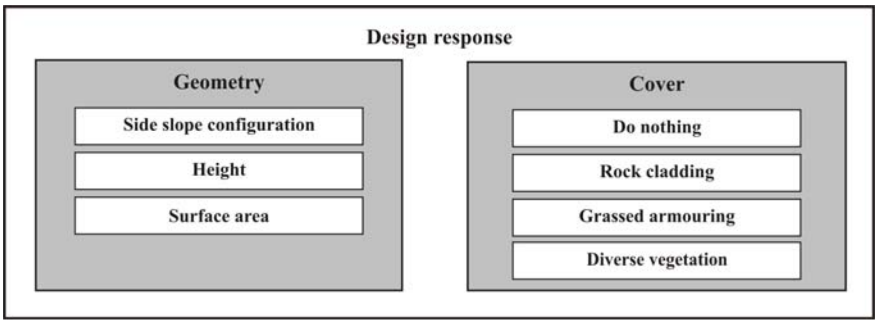


Figure 37: Context of design (Rademeyer and van den Berg, 2005).

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.

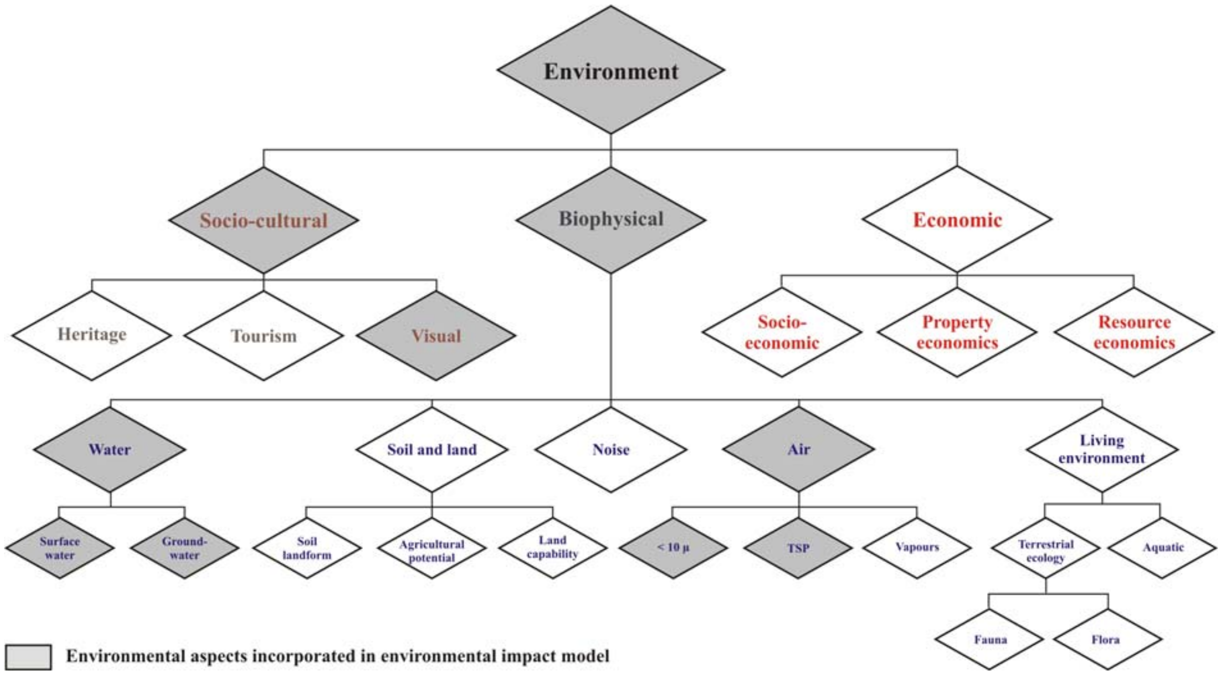


Figure 38: Overall simplified environmental aspects diagram. Highlighted blocks indicate the environmental aspects that must be built into the initial model.

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).

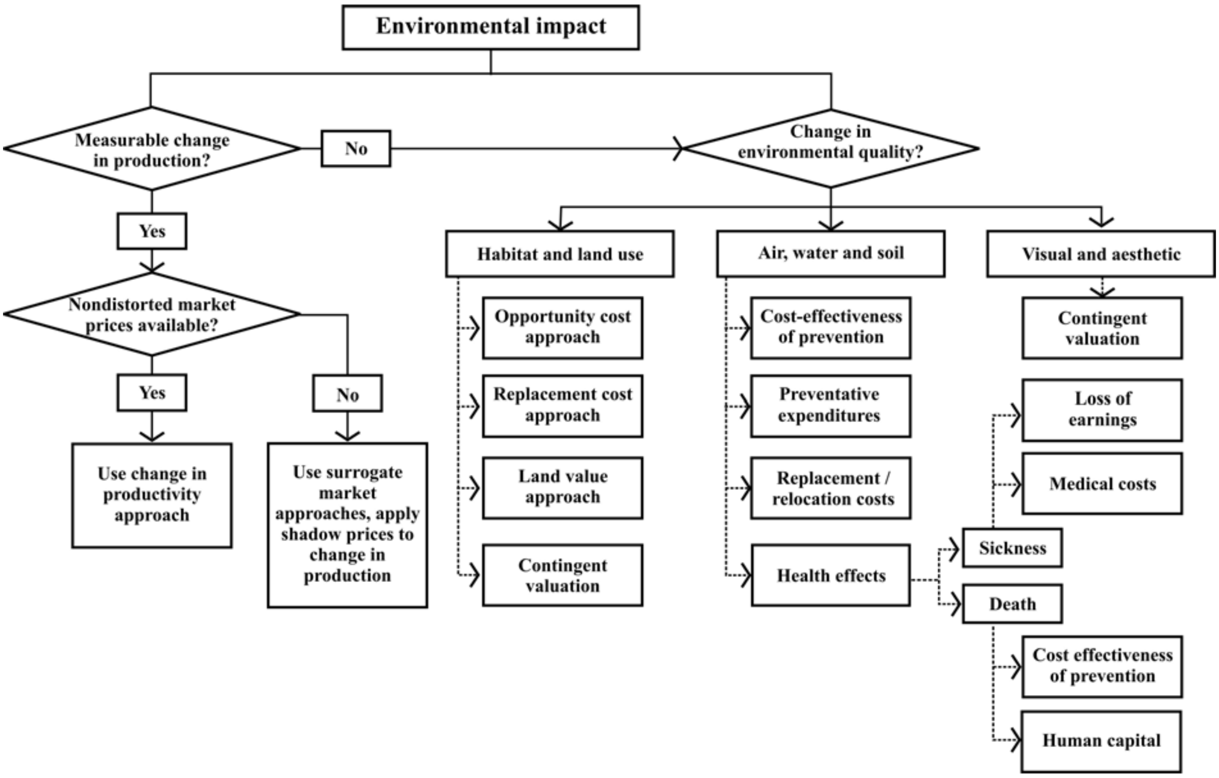


Figure 39: Simplified valuation flowchart for environmental impacts (Adapted from Dixon and Sherman, 1990).

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.

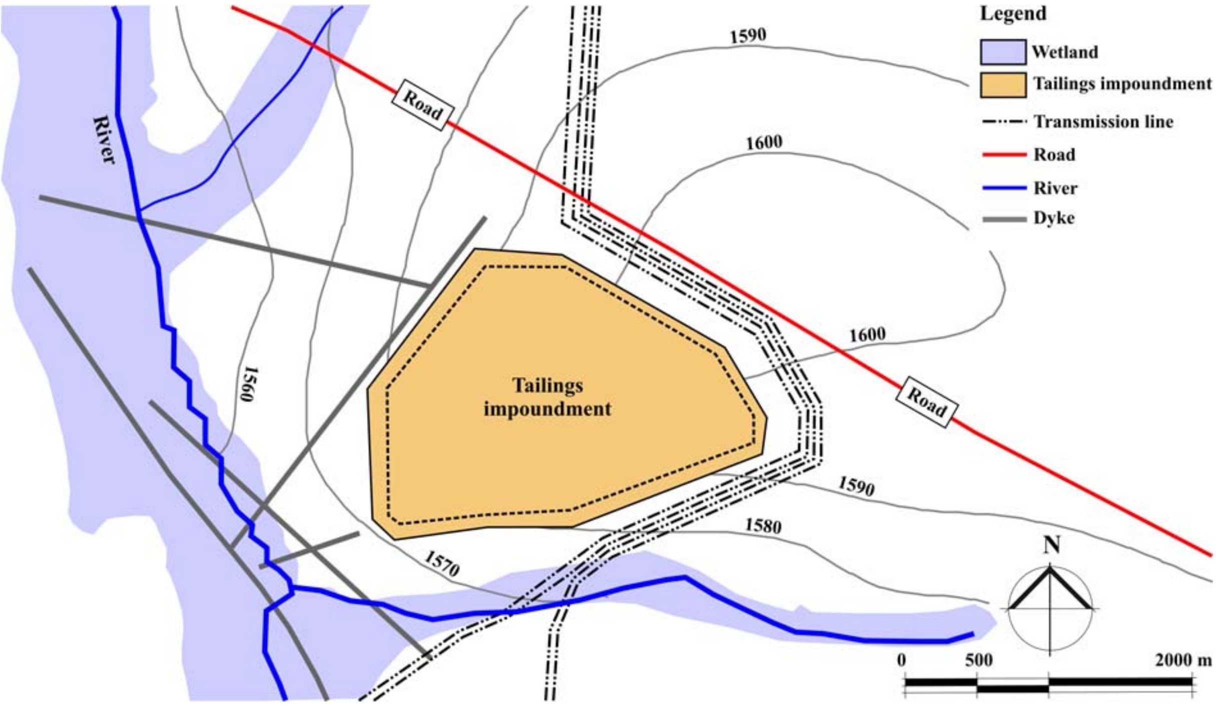


Figure 40: Simplified illustration of boundaries limiting tailings impoundment locality.

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.

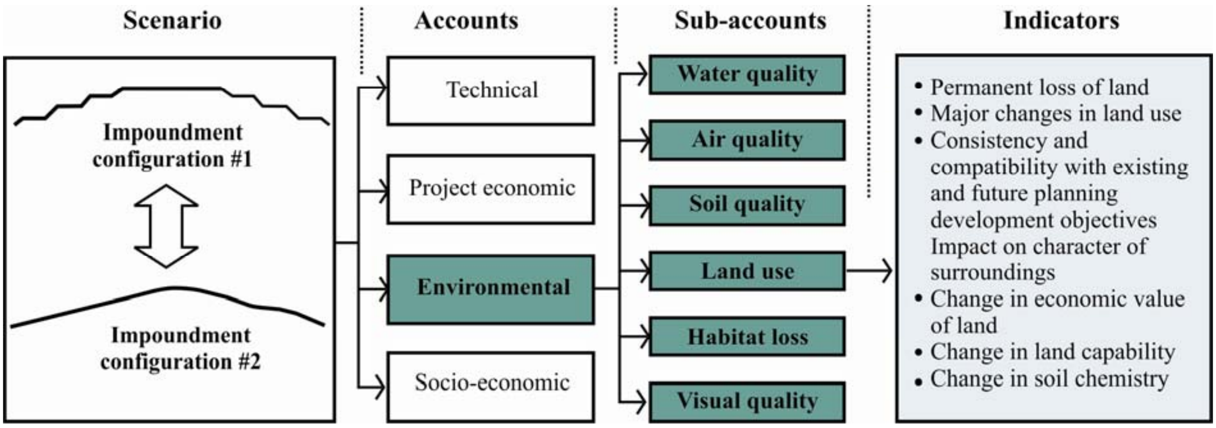


Figure 41: Fundamental accounts for comparing configurations using the MAA methodology.

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).

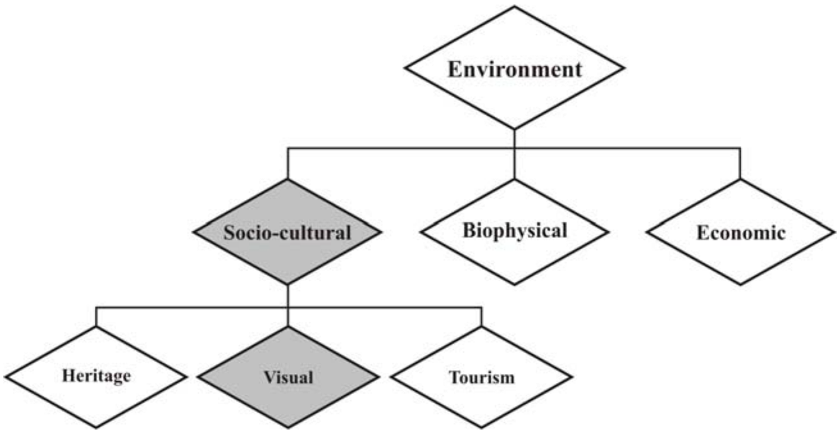


Figure 42: Simplified environmental aspects flow-diagram indicating the context of visual quality.

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.

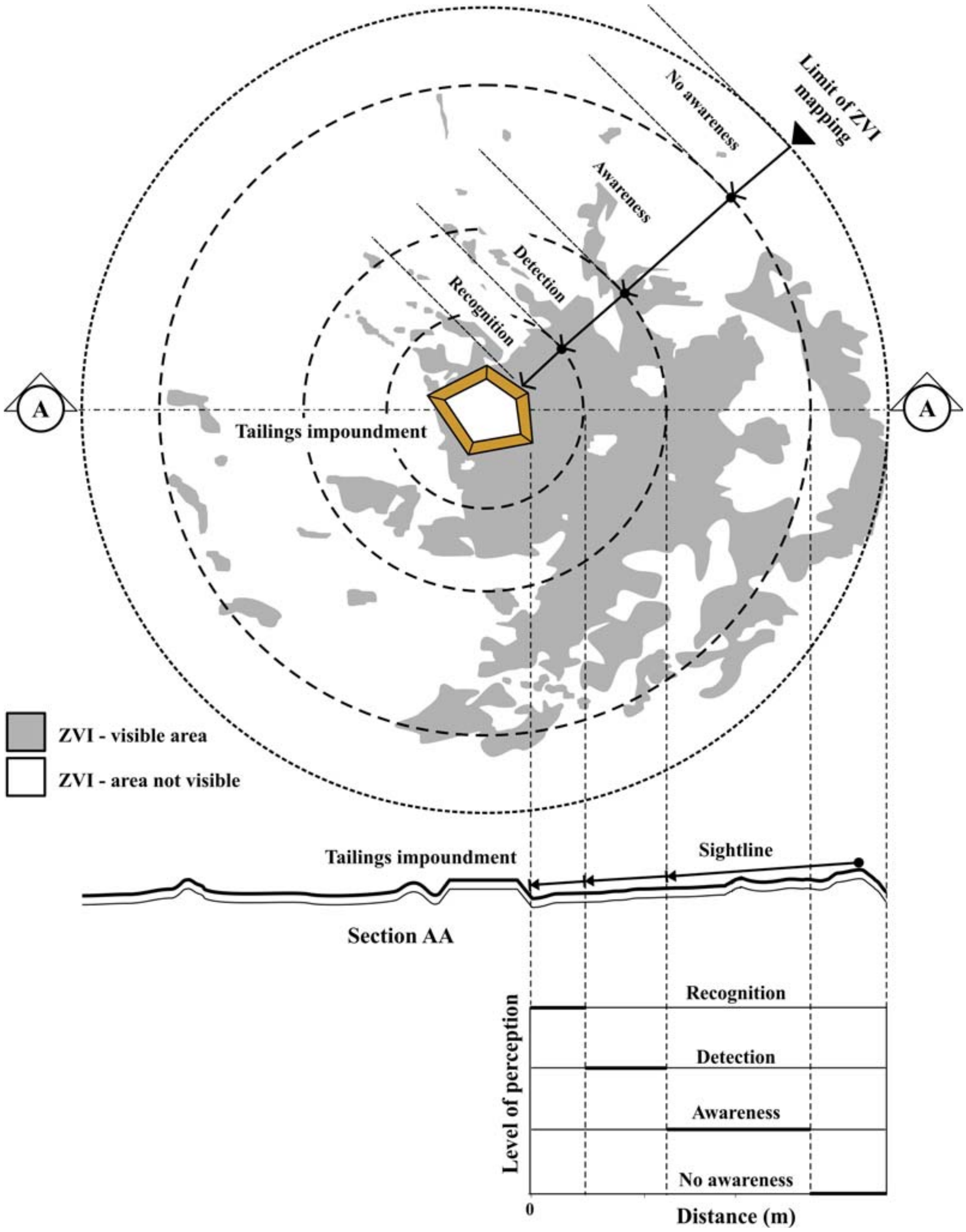


Figure 43: Zone of visual influence terminology and concepts.

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.

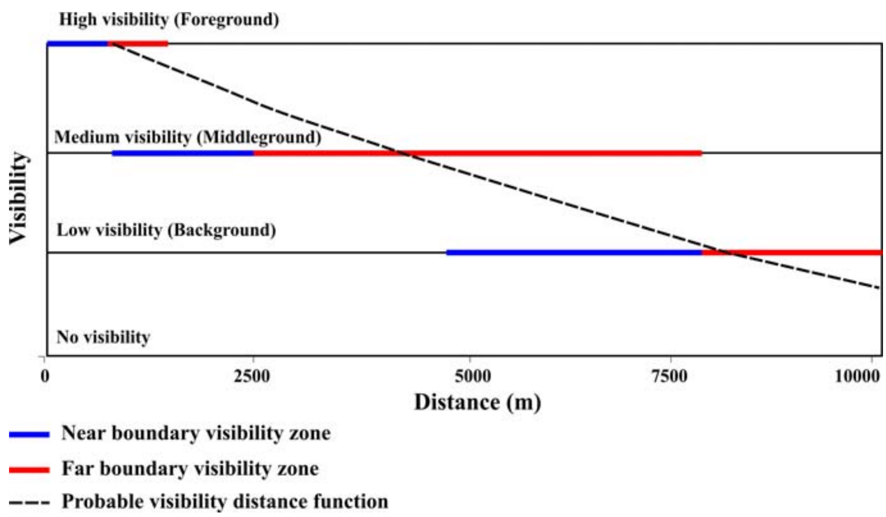


Figure 44: Subdivision of zone of visual influence into visibility distance zones.

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.

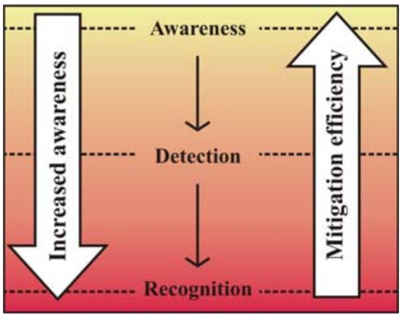


Figure 46: Visual perception thresholds (Shang and Bishop, 2000:126).

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.

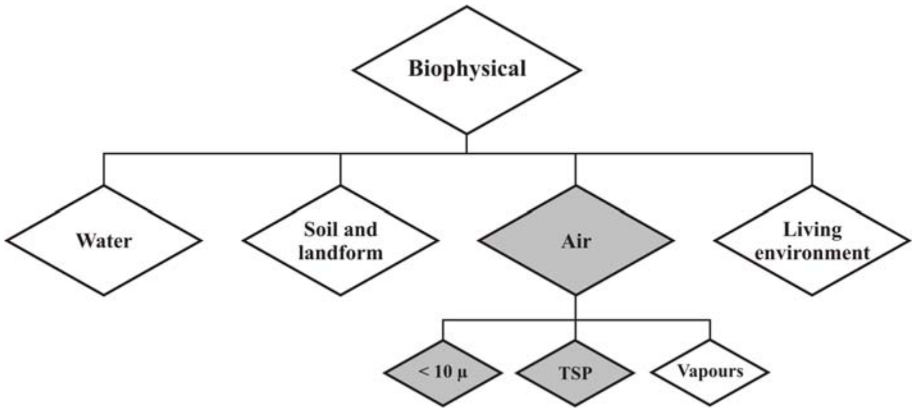


Figure 47: Simplified environmental aspects flow-diagram. The highlighted blocks indicate the context of the air quality aspects relevant to most tailings impoundments.

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):

- <u>Total suspended particulates (TSP)</u>, 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.

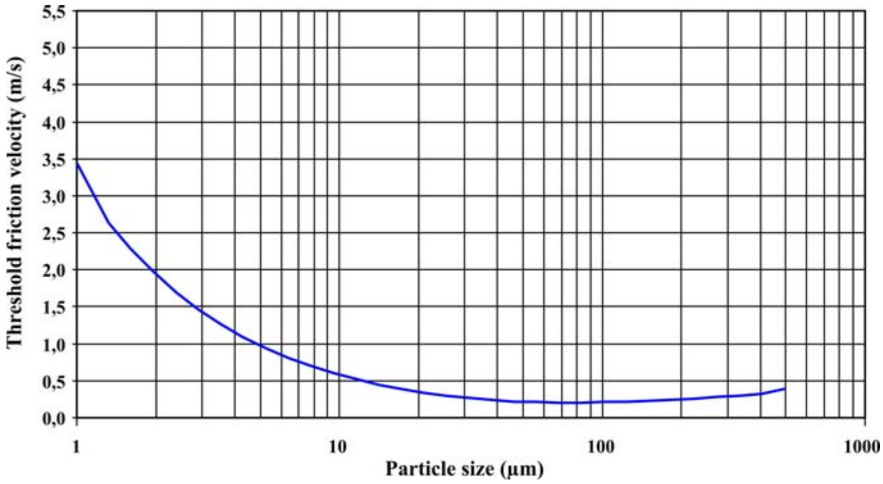


Figure 50: Relationship between particle size and threshold friction velocity using the calculation method proposed by Marticorena and Bergametti (1995).

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)

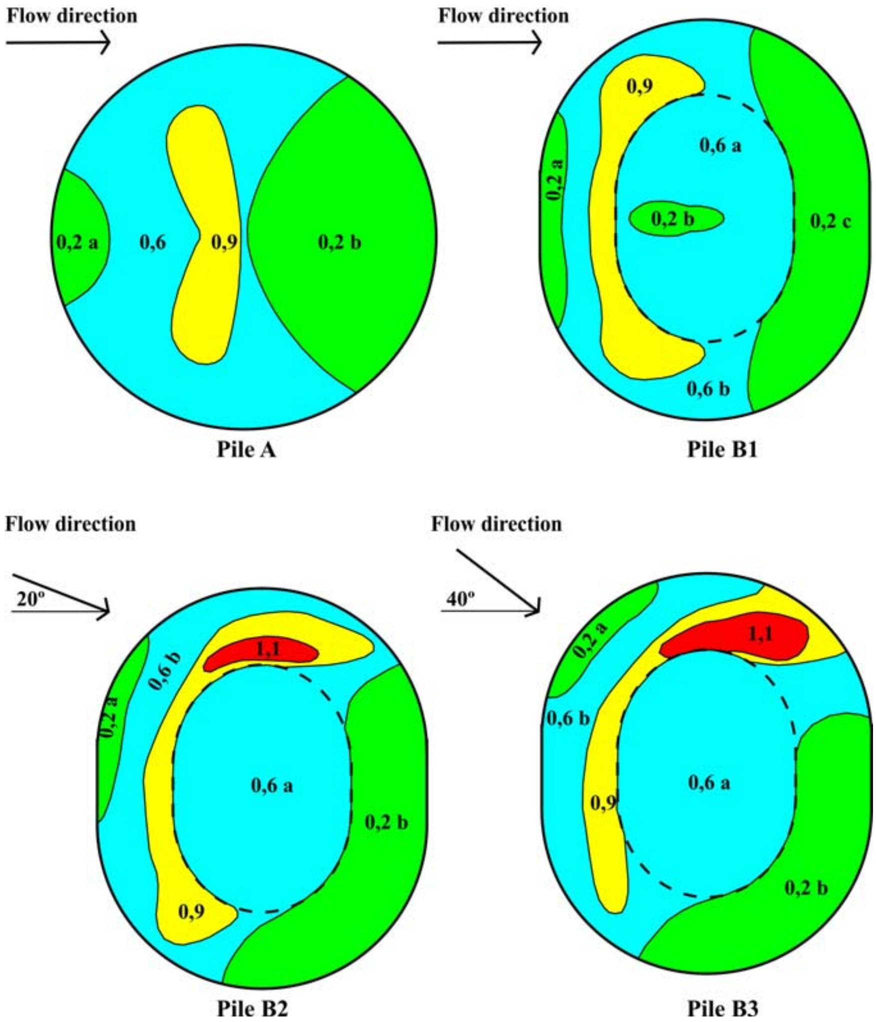


Figure 51: Contours of normalised surface wind speeds (US EPA, 1996).

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/s^2)
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:

- <u>tailings material physical characteristics</u> - the particle mass fraction or particle size distributions of material, material threshold friction velocity (m/s), particle density (g/cm^3), bulk density of the material (kg/m^3), the roughness height (m) and average moisture content (%), percent clay fraction – i.e. particles < 2 µm (%).
- <u>dimensions of the impoundment</u> – 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.
- <u>receiving environment information</u> – 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 $\mu g/m^3$ 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).

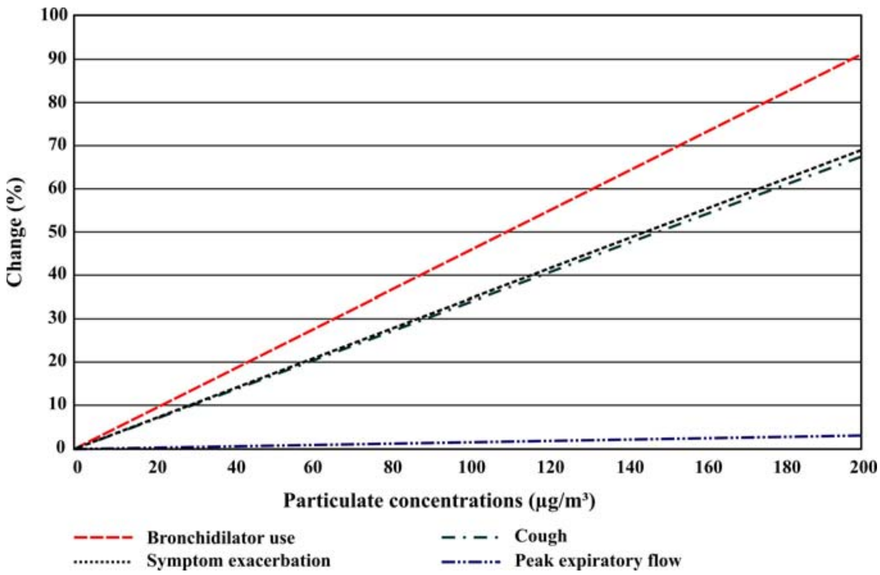


Figure 52: Percentage change in the occurrence of various health endpoints as a result of changes in ambient PM_{10} concentrations (WHO, 2000).

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/m³).

Health effect	Function	Population sector	Source
Asthma attacks	$6{,}50\times10^{-3}$	Asthmatics	Maddison (1997)
Cardiovascular hospital admission – daily exposure	$1{,}01\times10^{-7}$	All persons	Dockery et al. (1989)
Chronic bronchitis – annual exposures	$1{,}61\times10^{-3}$	Children <5 years	Dockery et al. (1989)
Chronic bronchitis – annual exposures	$4{,}90\times10^{-5}$	Adults >20 years	Dockery et al. (1989)
Emergency room visits – annual change	$2{,}35\times10^{-6}$	All persons	Ostro (1994)
Respiratory hospital admissions – daily exposures	$1{,}20\times10^{-5}$	All persons	Ostro (1994)
Respiratory symptoms	$1{,}83\times10^{-1}$	All persons	Ostro (1994)
Restricted activity days – annual average	$5{,}75\times10^{-2}$	Adults	Ostro (1994)

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

$$dH_i = b_i . POP_i . dA \tag{10}$$

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 $\mu g/m^3$ 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.

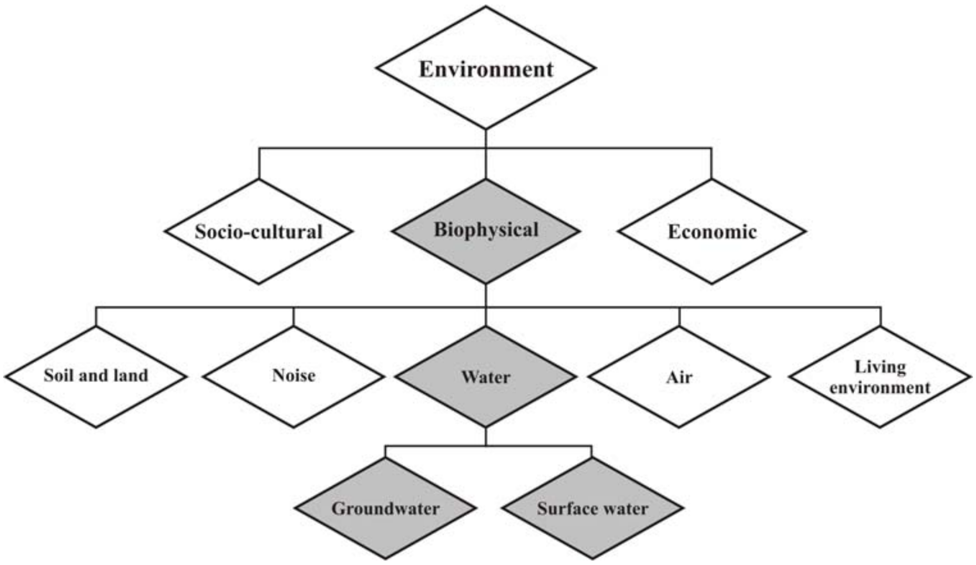


Figure 53: Simplified environmental aspects flow-diagram indicating the context of the water sub-account.

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.

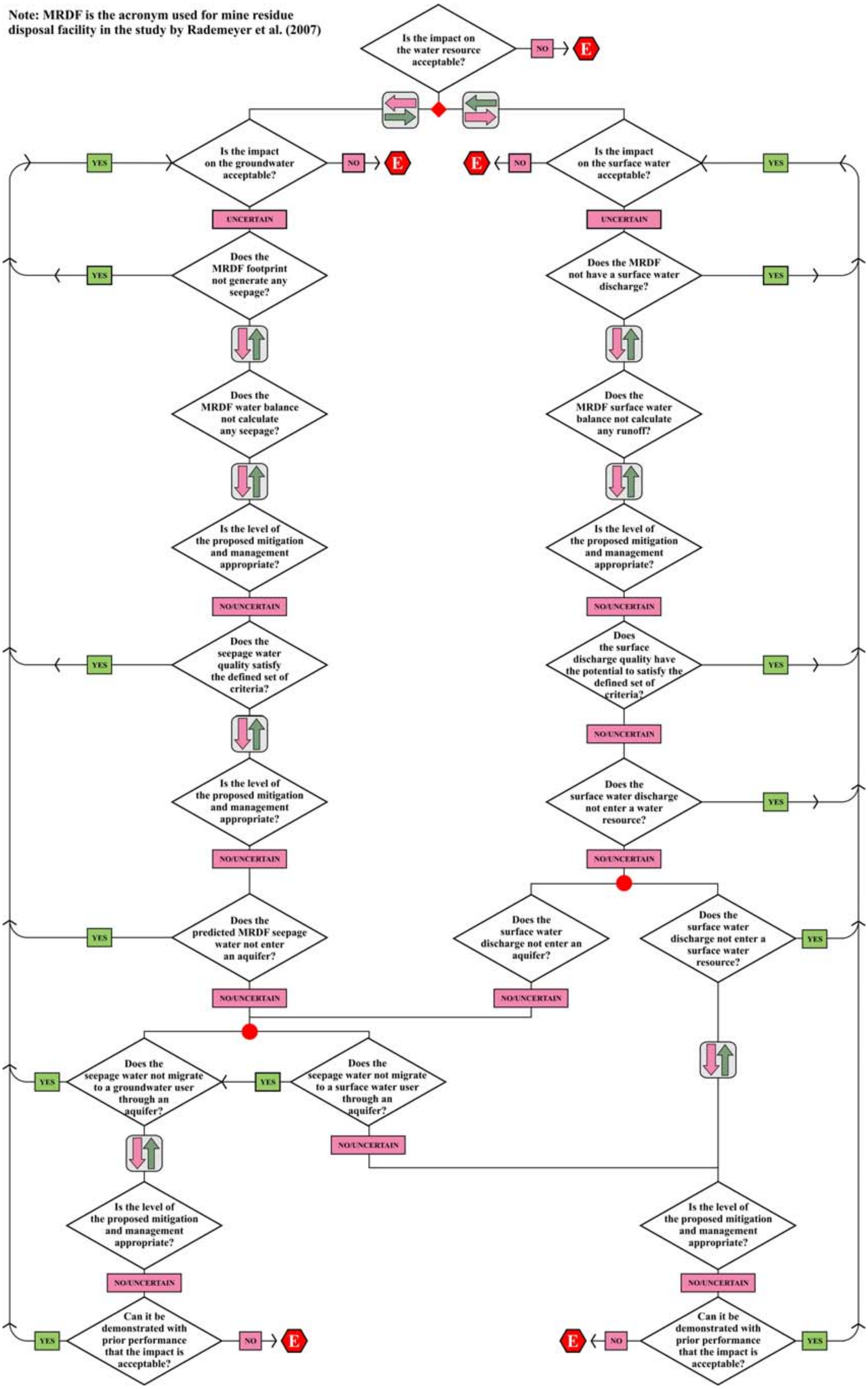


Figure 54: Water quantity and quality decision framework (Rademeyer et al., 2007).

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:

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

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

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

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:

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

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:

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

$Fe(OH)_3$ 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):

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

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

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

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:

$$p_1 = \frac{k_1(d_0 + d_1 + d_2 + d_3)}{d_1\left[\frac{k_2 k_3}{k_3 d_2 - k_2 d_3} + \frac{k_1}{d_1}\right]} \tag{18}$$

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

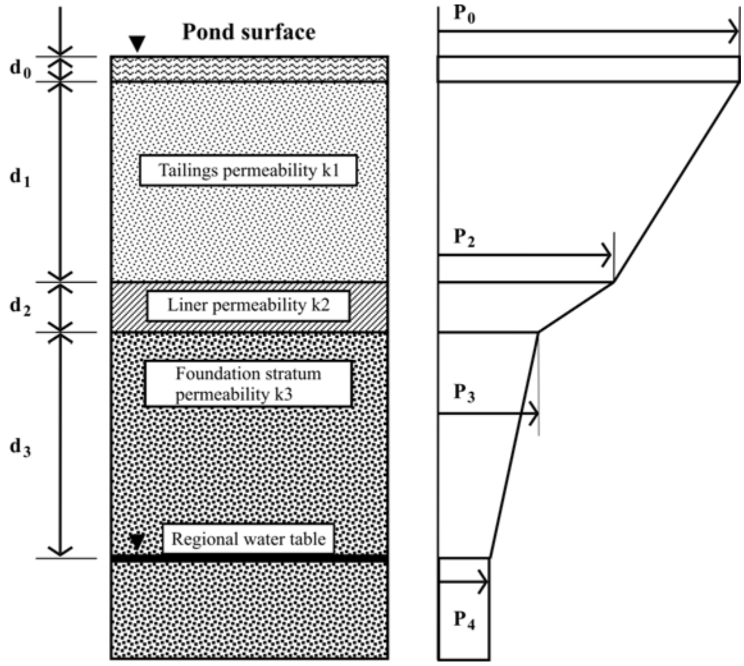


Figure 56: Schematic representation of information required to calculate seepage potential (CM, 1996:136).

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).

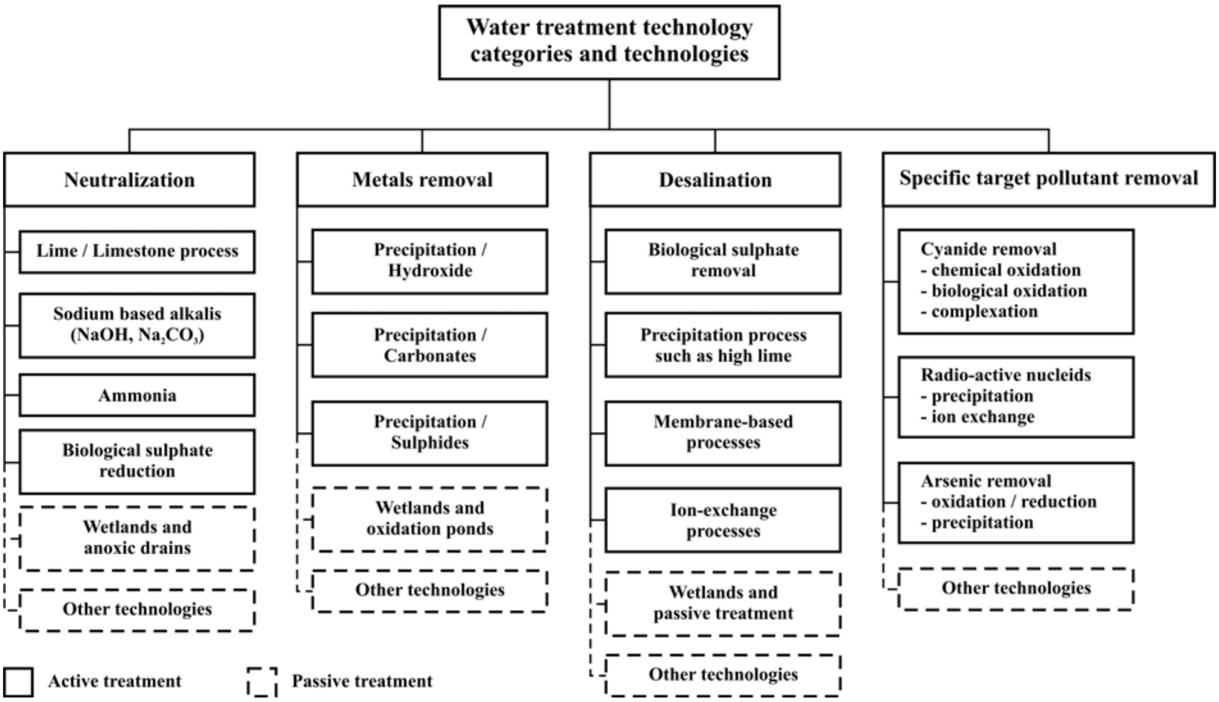


Figure 57: Generic range of mine water treatment technologies (van Niekerk, 2005).

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.

$$SO_4^{2-} \rightarrow H_sS \rightarrow S^0(elemental) \tag{25}$$

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).

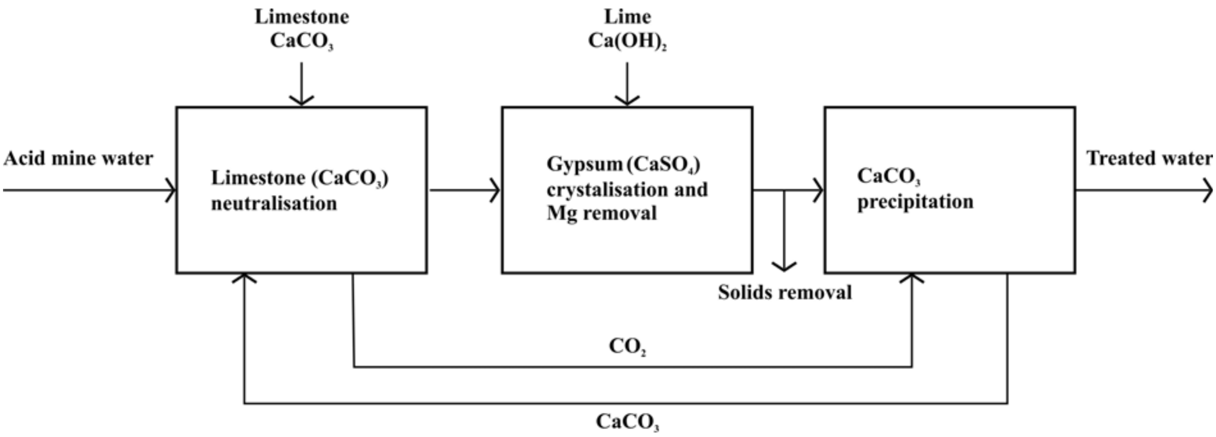


Figure 58: Simplified schematic of the integrated limestone/lime treatment process.

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).

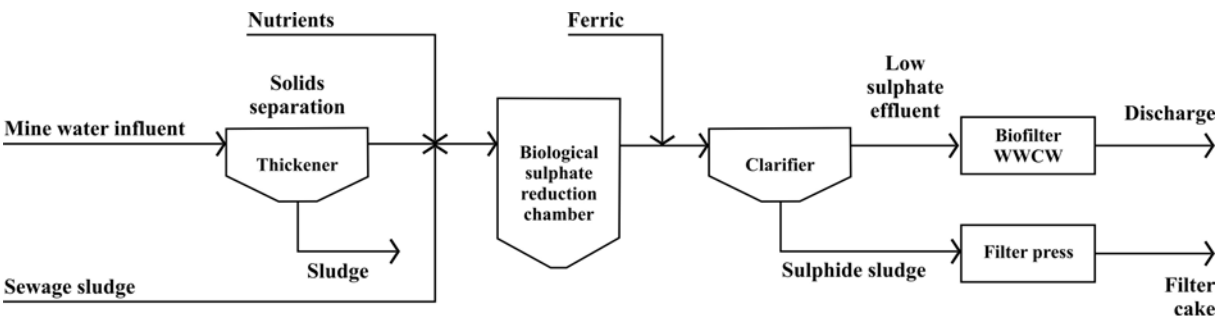


Figure 60: Simplified schematic of the BioSure® process.

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).

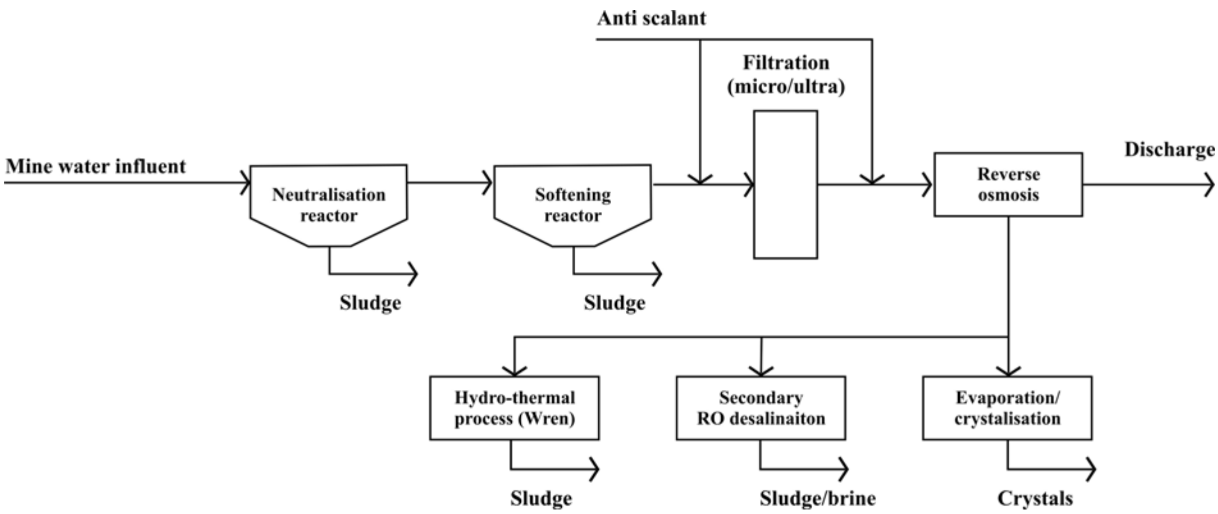


Figure 61: Simplified schematic of a desalination membrane-based process.

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.

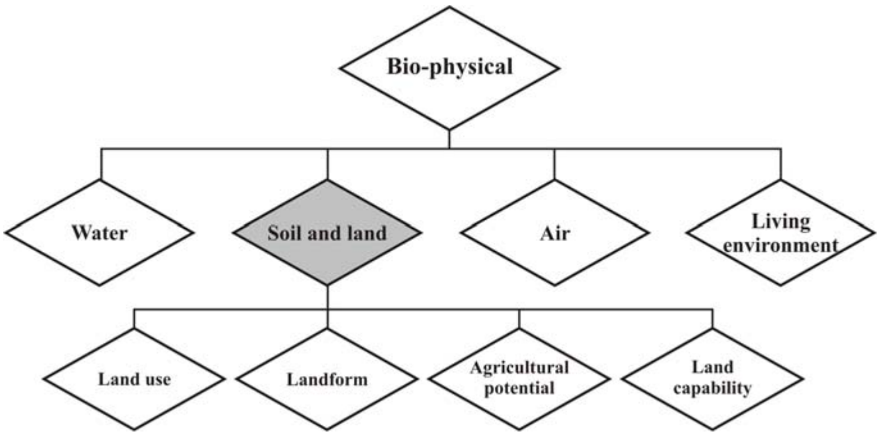


Figure 62: Simplified soil and land environmental aspects diagram.

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.

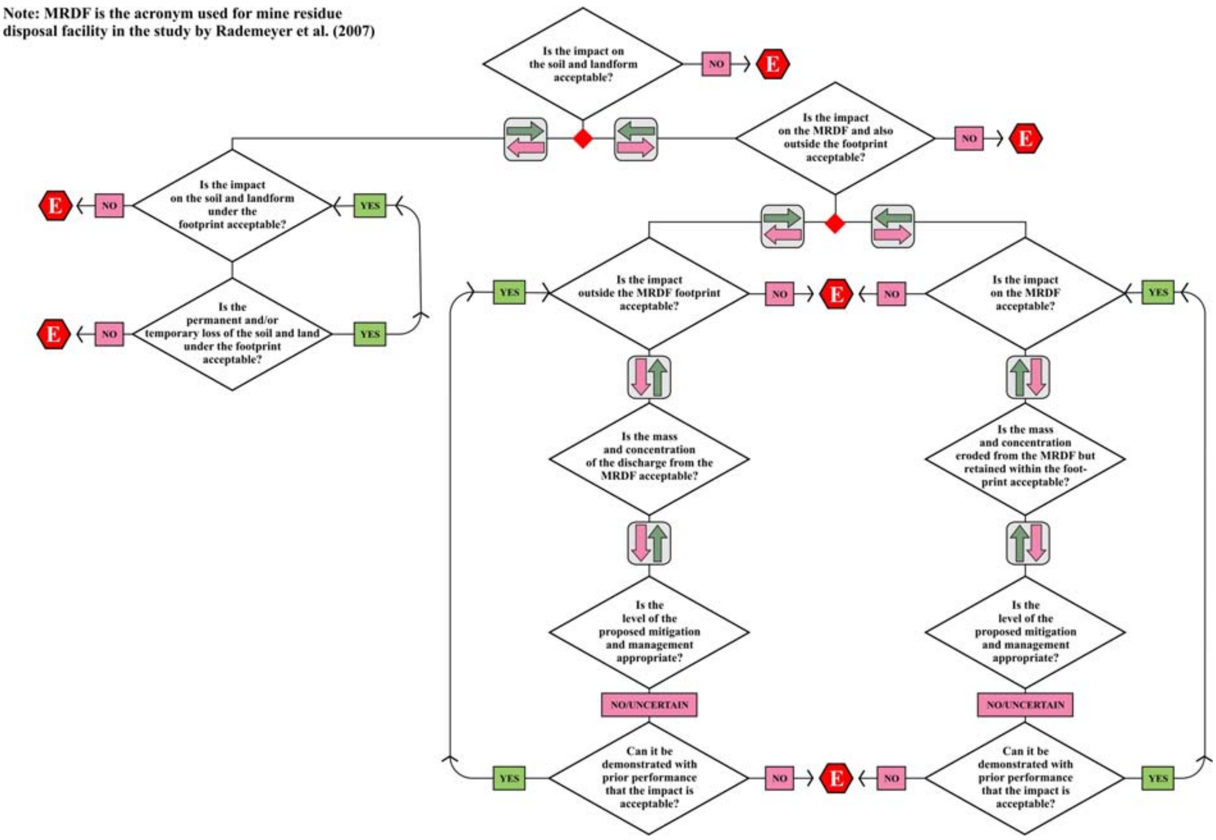


Figure 64: Surface stability decision framework (Rademeyer et al., 2007).

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.

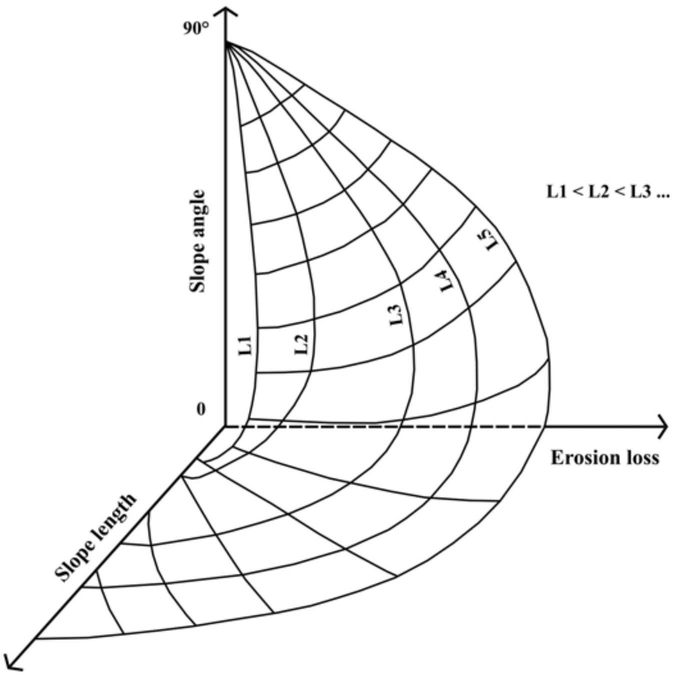


Figure 65: The erosion rate surface showing the effects of slope length and slope angle on rates of erosion from the outer slopes of tailings impoundments (Blight and Amponsah-Da Costa, 1999).

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.

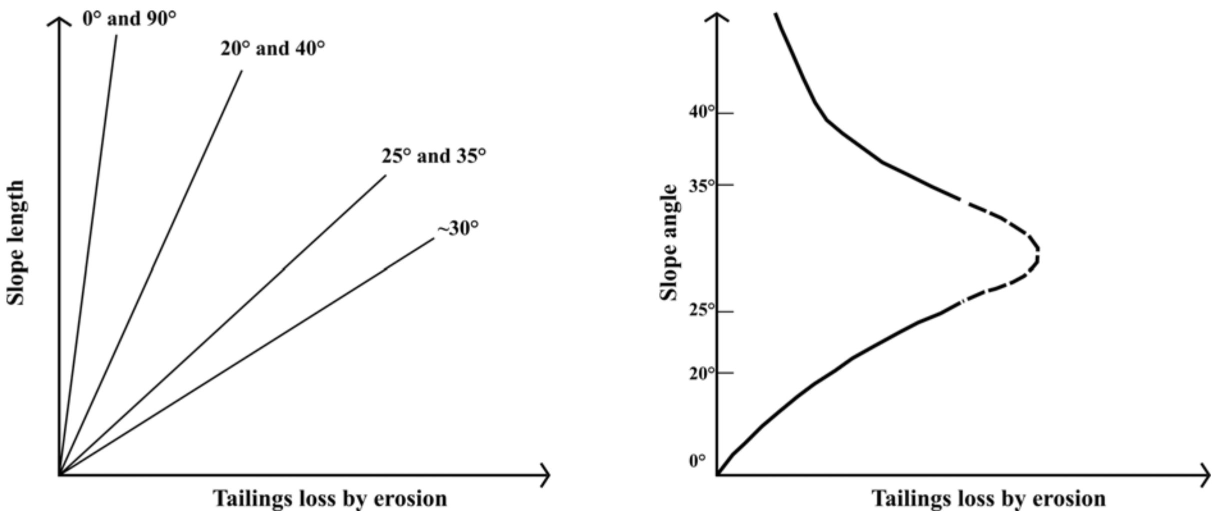


Figure 66: Effect of slope length and slope angle on rates of erosion from the outer slopes of tailings impoundments (CM, 1996).

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.

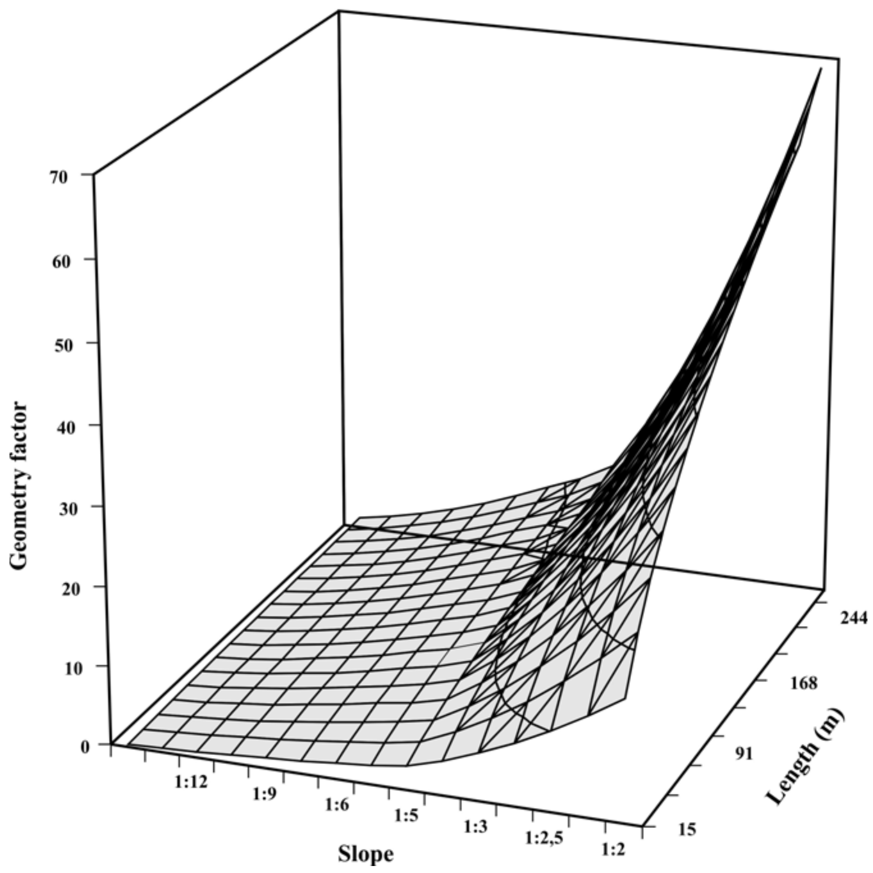


Figure 67: Slope geometry factor based on steepness and length.

- 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.

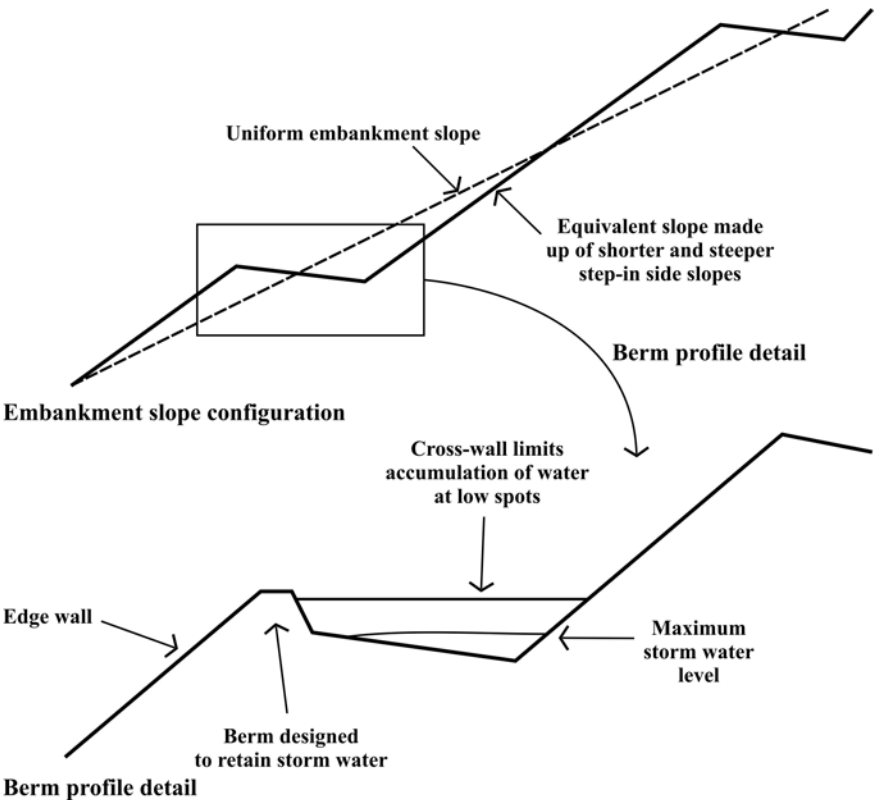


Figure 68: Tailings impoundment embankment side slope and berm details (CM, 1996).

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.

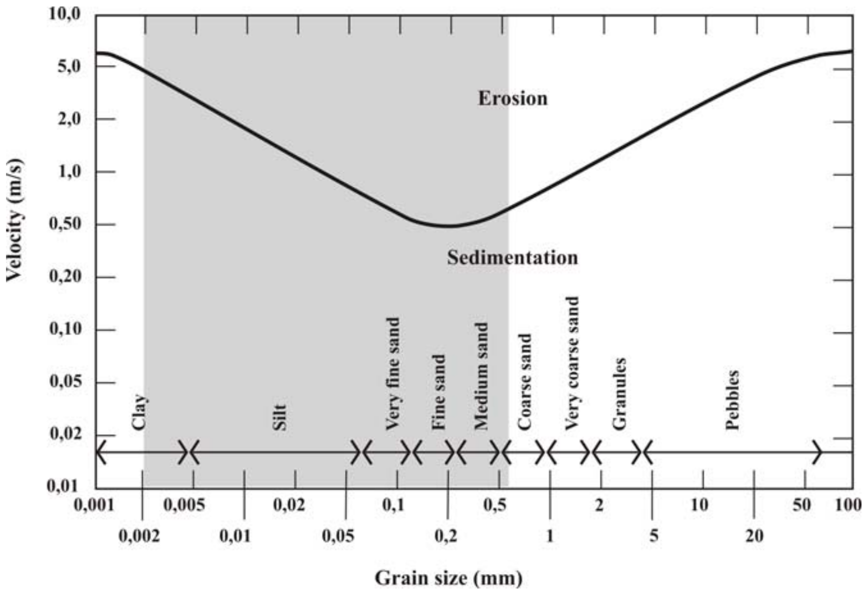


Figure 70: Water erosion thresholds for natural soil particles with the shaded section indicating the area where it is expected that tailings anthropogenic soils would fit (Marsh, 1997:231).

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).

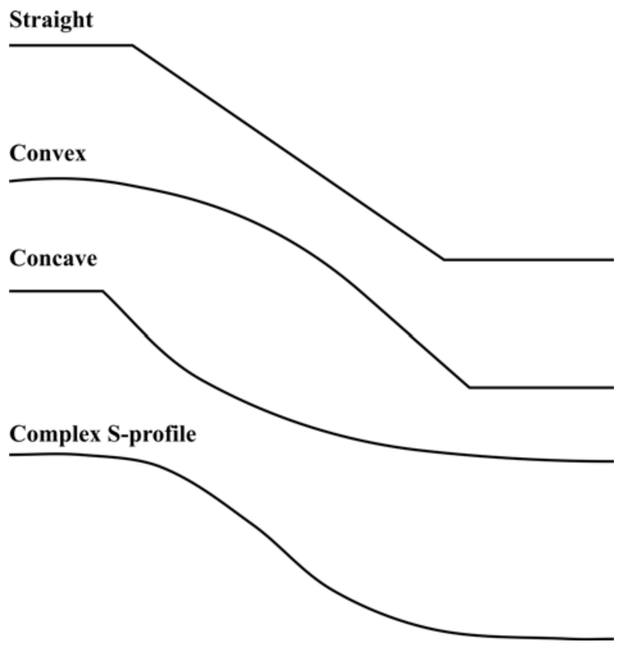


Figure 71: Basic slope profiles.

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.

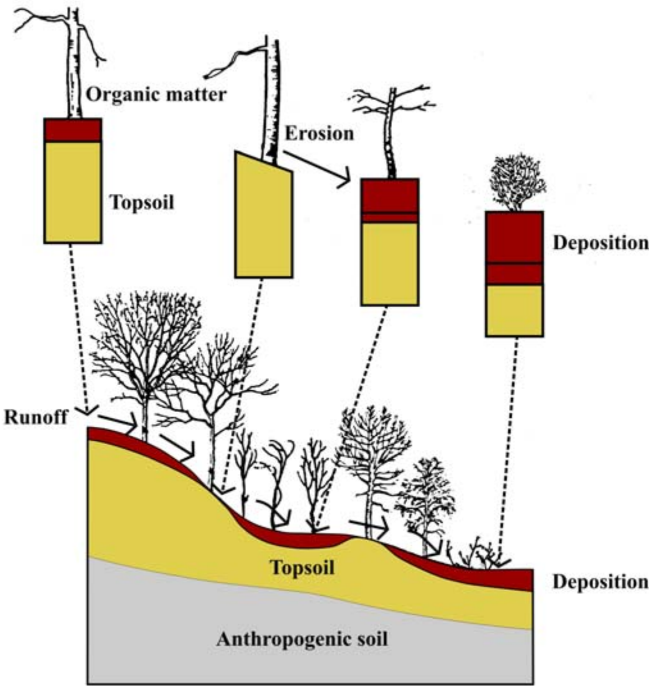
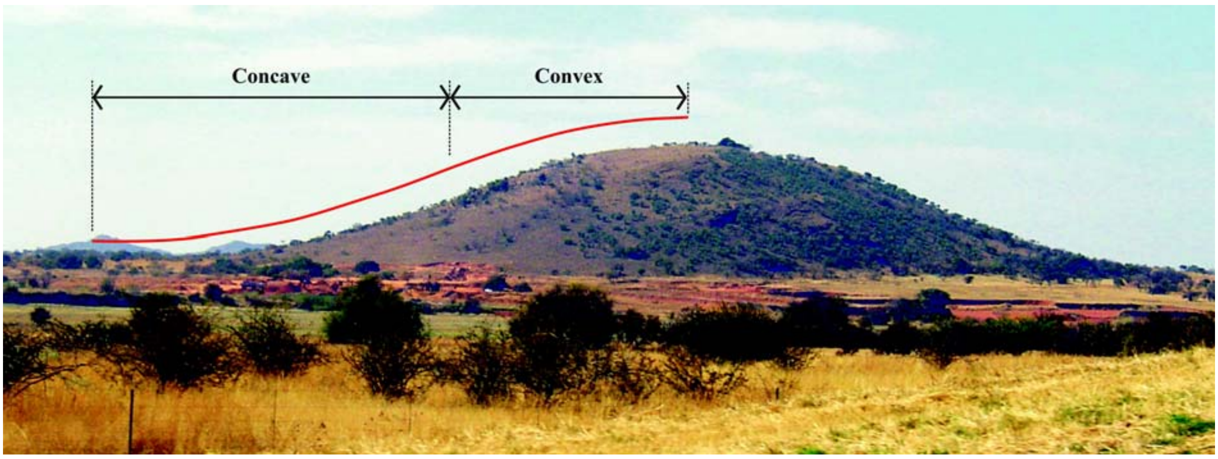


Figure 72: Effects of erosion and deposition (Marsh, 1997:102).

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.

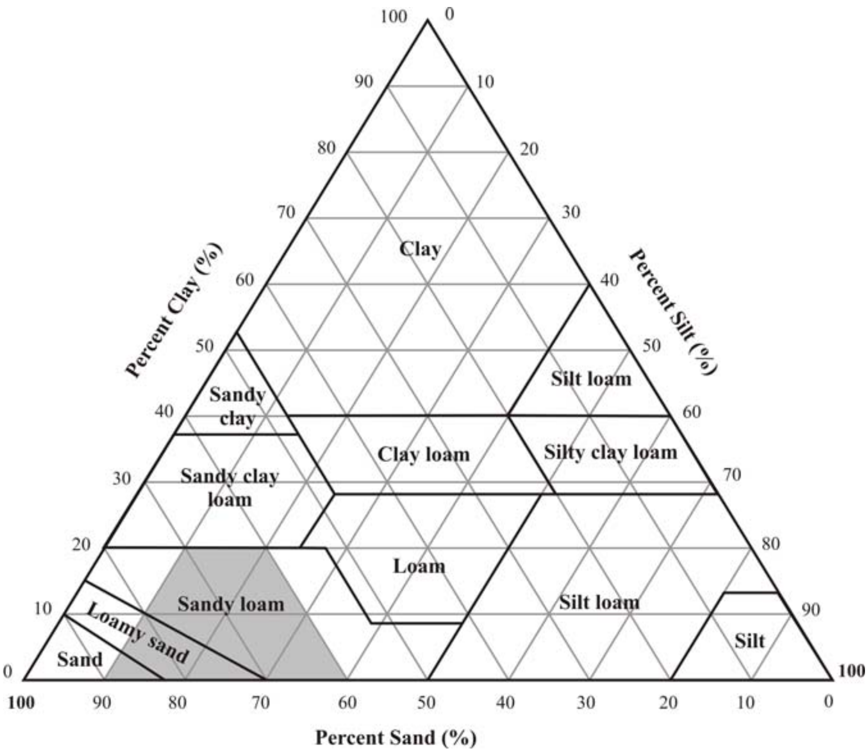


Figure 75: Shaded section indicates area where it is expected that tailings anthropogenic soils would fit if the soil texture triangle for natural soils is applied (Marsh, 1997:96).

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.

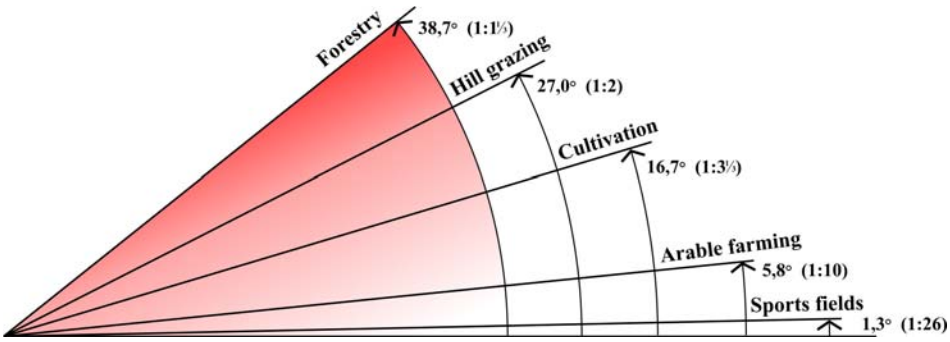


Figure 77: Typical land uses as a function of slope steepness.

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.