CHAPTER THREE: EXPERIMENTAL WORK AND MODELLING

> "There is nothing that is a more certain sign of insanity than to do the same thing over and over and expect the results to be different."
>
> Albert Einstein (Arden, 2003:51)

> "Success is going from failure to failure with no less enthusiasm."
>
> Winston Churchill (Arden, 2003:122)

3.1 Introduction

The purpose of the research is to develop a model that can be used to rationally inform decision making with regard to the sustainable configuration of tailings impoundments. The emphasis is on the post-closure long-term land use of such and to determine the sustainability of various impoundment configurations.

Simplistically the post-closure land use of a facility is controlled by:

- access to the facility which in turn is dependent on the side slope profile;
- the land use as a function of slope; and
- the land use as a function of final cover.

The premise is that by integrating environmental impacts and engineering costs a holistic view of change in impoundment configuration can be accomplished. The engineering model calculates the costs incurred over the life of the facility, i.e. during the design, construction, deposition, decommissioning, closure and post-closure stages and is described in Section 3.7.

There is an apparent drive in industry to flatten the overall impoundment embankment side slopes from say a 1:1,5 to a 1:3 slope during final rehabilitation in order to close the facility. The principle is illustrated in Figure 79, Figure 80 and Table 18 (p. 157). Flattening the overall side slope from 1:1,5 to 1:3 results in step-in side slopes that will vary between 1:1 and 1:2,5 respectively. The flattening of the overall embankments side slope also impacts on the physical extent of the footprint and in certain instances the larger footprint can result in the covering and subsequent decommissioning of existing engineered stormwater runoff and sediment control measures.

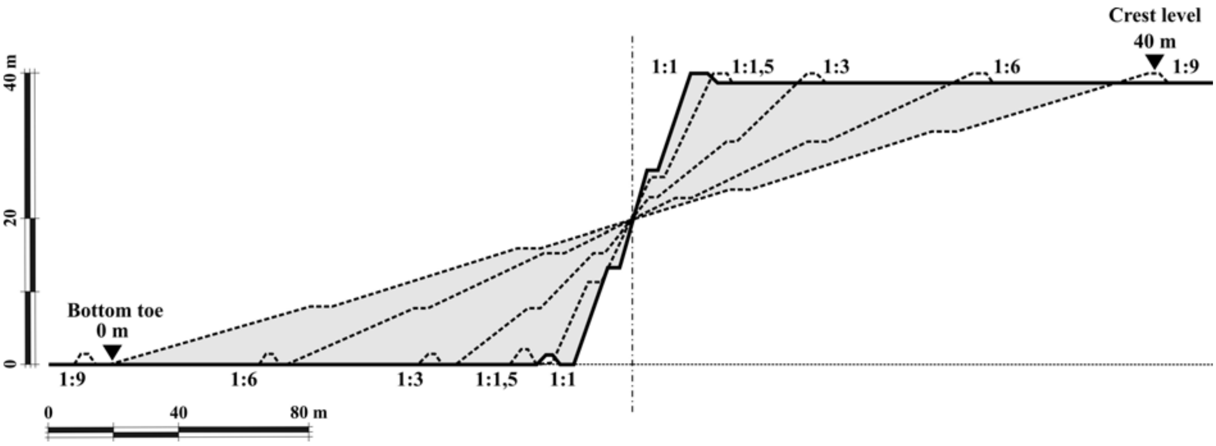
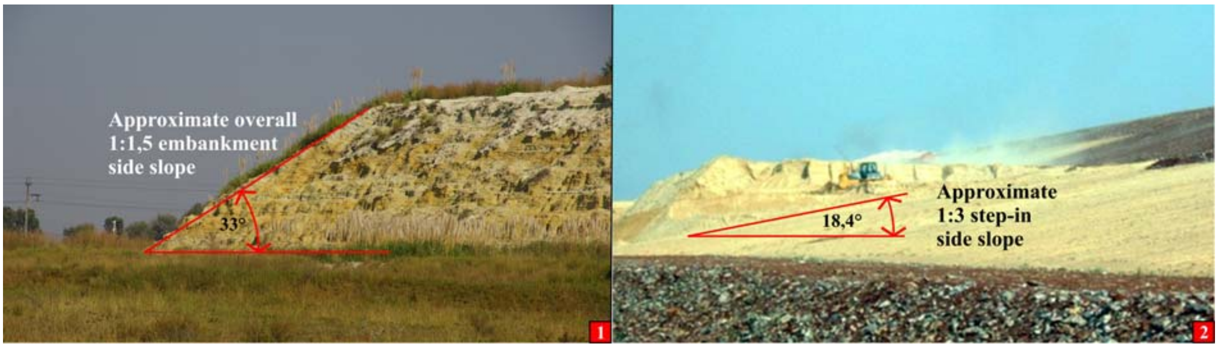


Figure 79: Schematic illustrating the flattening of the embankment slope of a tailings impoundment.

It is not so much the overall embankment slope as the step-in slope that is important. Although what may be considered to be an acceptable overall embankment slope of 1:3 is achieved the resulting step-in slope is much steeper (1:2,5) and may in certain instances result in excessive erosion or be inaccessible. Table 18 provides typical slope configuration information when flattening the embankment slope by means of mechanical methods and keeping the impoundment height constant.

Table 18: Typical embankment slope configuration when flattening side slopes.

Overall slope ratio	**(V1:?H)**	**1,5**	**3**	**6**	**9**
Overall slope angle	**(°)**	33,7	18,4	9,5	6,3
Intermediate slope ratio	**(1V:?H)**	1	2,5	5,5	8,5
Intermediate slope angle	**(°)**	45	21,8	10,3	6,7



[1] Photograph of a tailings impoundment with an overall embankment side slope of 1:1,5 (33°).

[2] Photograph of the ERGO Daggafontein impoundment embankment being flattened mechanically.

Figure 80: Photographs of impoundment embankment comparing the overall slopes.

The overall environmental aspects framework identifies and contextualises the most important environmental aspects. It is described in Section 2.8. Decision models are used to predict the environmental impacts and estimate the engineering costs in order to determine the overall sphere of influence and are described in detail later on in this section. The ERGO Daggafontein impoundment is used as a case study site for spatial contextualisation and information on this impoundment is provided in Section 3.3.

When changing an impoundment configuration the following typical questions arise:

- should industry continue disposing tailings at steep side slopes – i.e. say overall side slope of between 1:2,5 to 1:3 and do nothing. In many case the slopes are even steeper (1:1,5);
- deposit tailings at a steep overall side slope – i.e. overall side slope of between 1:1,5 to 1:2,5 and suitably cover the facility in order to mitigate some of the environmental impacts;
- pro-actively deposit the impoundment at flattened side slopes from the start ending with an intended and designed overall flatter side slope;
- when flattening the side slopes is it possible to determine what flat enough is or what the ideal side slope is? Is an overall embankment slope of 1:3, 1:6 or 1:9 ideal?
- continue to deposit at say 1:2,5 and then mechanically flatten to 1:3, 1:6 and 1:9 side slopes and do nothing or cover the impoundment surface with rock, or an engineered armoured cover in order to create a suitable growing-medium to sustain vegetation.

3.1.1 Test impoundment site

In order to answer the above the ERGO Daggafontein impoundment site is used to model the various upstream deposited ring-dyke tailings impoundment configurations. General limitations are:

- The ERGO impounded tailings was cycloned and not spigotted – hence a modelled dry density of the placed product of 1,8 t/m^3 and not 1,45 t/m^3. Also a safe rate of rise was fixed at 2,5 m/annum.
- The production is constant at 990 000 t/annum over 16 years with a total storage requirements of 105,6 Mm^3.
- The final height must ideally remain constant – see Table 19 which provides the results using the engineering cost model.
- The overall embankment side slope angles are 1:1,5, 1:3, 1:6 and 1:9. Also, one should be able to specify step-ins and end with and impoundment with say and overall side slop of 1:3 but with steeper step-in side slopes with varying slope angles. Our understanding is that the side slope configuration (i.e. the step-in side slope, length and cover) determines the surface runoff and hence resultant erodibility of the material.

[1] Oblique photograph looking south-west. Photograph with the courtesy of AngloGold Ashanti.

[2] Oblique photograph at the southern corner also referred to as 'Windy Corner'. Photograph with the courtesy of AngloGold Ashanti.

Figure 81: Views of the ERGO Daggafontein tailings impoundment.

3.1.2 Spatial overlay of environmental aspects considered in this study

Figure 82 illustrates the concept of total sphere of influence by overlaying of the different environmental aspect zones of influence for a specific impoundment configuration.

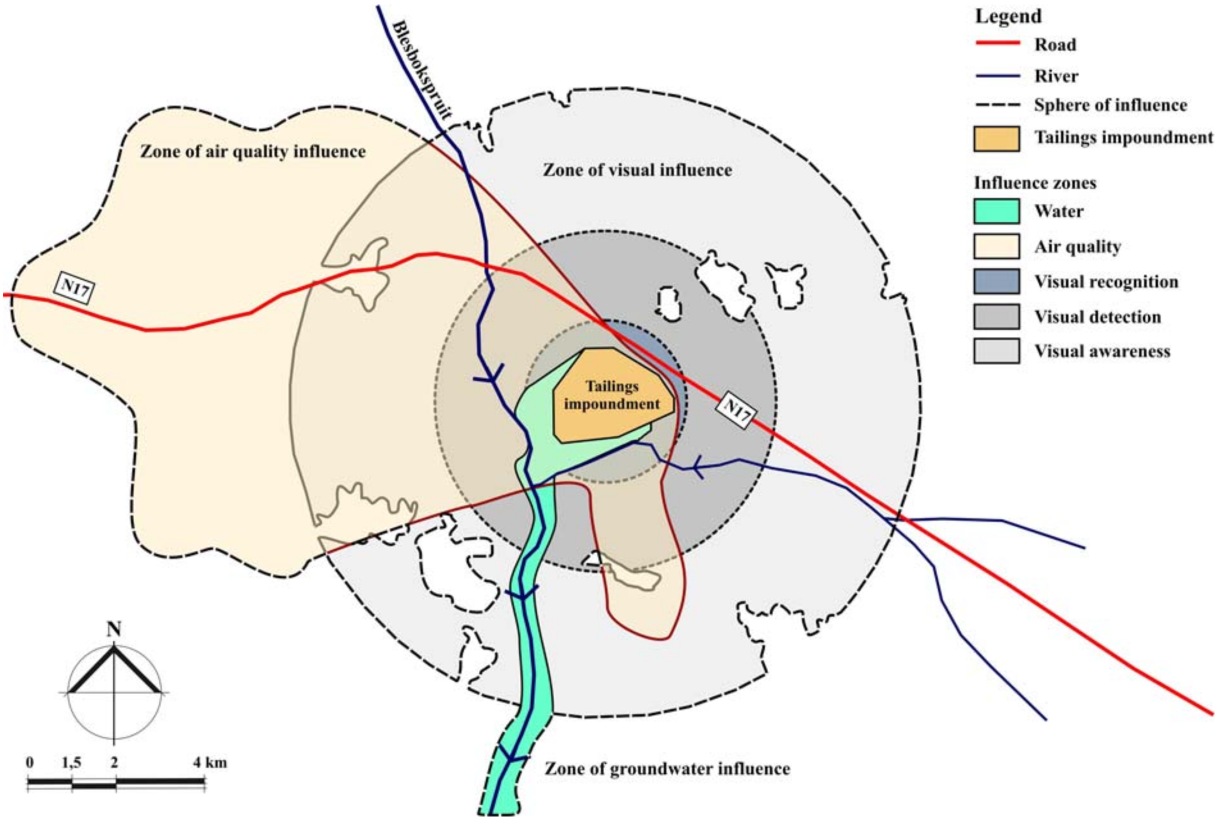


Figure 82: Total environmental sphere of influence anticipated as an outcome of this study.

Figure 82 indicates the total sphere of influence for a particular impoundment configuration. The total cost for this specific configuration could be the sum of the:

- engineering costs to construct, operate, and close such a facility;
- permanent or temporary take of land by the impoundment footprint;
- value of property sterilised for future use;
- direct costs as a result of the impact on health (inhalable particulates causing ill-health effects);
- costs to treat polluted groundwater or having to purchase replacement water;
- mitigation costs; and
- long-term post-closure maintenance costs.

3.2 Configurations modelled

Configuration is the term used to describe the combination of geometry and cover, whereas geometry is a function of height, side slope and volume. Side slope is a function of slope length and gradient. Slope gradient is usually the determining factor when considering various land use options and can restrict development and should be carefully considered during the design of the tailings impoundment in order to increase the range of future land use options. Figure 83 provides maximum slope gradients for various land uses. A wider range of land uses can be accommodated by lower slope gradients.

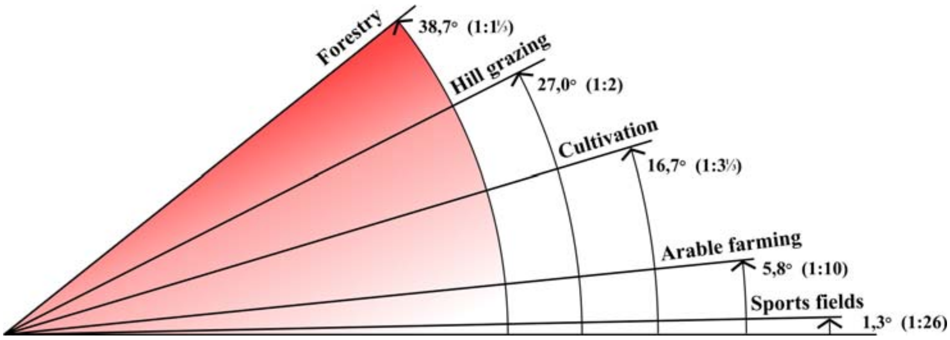


Figure 83: Typical land uses as a function of maximum slope gradients.

3.2.1 Geometry

Table 19 indicates the different overall slope profiles modelled in this study. Although the overall embankment slopes are indicated and used in the modelling of the respective environmental aspects, the engineering cost model optimises the slope length and angle for each step-in. The engineering model also allows for the bench width to be included in the calculations. This is important as the overall impoundment embankment is a combination of the step-ins and although the modelling of the key environmental aspects are undertaken for an overall embankment slope configuration only. Future refinement of the environmental models should allow for the inclusion of such detail.

Table 19: Embankment slope configurations modelled. Production and height are kept constant.

		Configurations			
		S1	**S2**	**S3**	**S4**
Overall slope ratio	**1V:?H**	**1,5**	**3**	**6**	**9**
Production	tpm	990 000	990 000	990 000	990 000
Dry density of placed product	t/m^3	1,8	1,8	1,8	1,8
Life of facility	years	16	16	16	16
Step-in width	m	4	4	4	4
Geometric volume	m^3	105 600 000	105 600 000	105 600 000	105 600 000
Impoundment height	m	37,28	37,28	37,28	37,28
Rate of rise at closure	m/annum	2,5	2,7	3,2	3,9
Step-in side slope angle	°	45	21,8	10,3	6,7
Top surface area	m^2	2 640 000	2 444 444	2 062 500	1 692 308
Footprint length	m	2 204	2 271	2 399	2 516
Footprint width	m	1 377	1 419	1 499	1 572
Footprint surface area	m^2	3 035 257	3 223 056	3 596 259	3 955 614

Table 19 provides the slope configurations used in the engineering cost model to calculate life-cycle costs. The same configurations are used when modelling the environmental impacts for the various environmental aspects in this study. A comparison of the engineering costs and the environmental impacts will be made for the status quo (i.e. depositing at steep embankment slopes and during the closure stage flatten the embankment mechanically to the final configuration) and the pro-active deposition of flatter slopes during the operation stage.

3.2.2 Covers

During rehabilitation the final impoundment material layer can consist of the following:

- tailings in situ (no cover);
- soil (imported soil suitable to sustain plant growth);
- rock cladding; and
- armouring (cover consisting of a 60 % rock and 40 % topsoil mixture).

The vegetation cover on tailings impoundment could consist of:

- nothing;
- grass cover; and
- diversity of vegetation species.

Tailings cover is the in situ tailings material and is representative of many tailings impoundments where no rehabilitation has taken place.

A rock cladding or riprap cover is often applied in order to reduce the surface erodibility potential. The rock is usually sourced from rock dumps in close proximity. The colour of rock can vary considerably. In this study, photographs were taken from a nearby rock dump and used as reference for further photo manipulation.

Re-vegetation of the tailings impoundment with grass is common practice and for this reason the ERGO Daggafontein site is considered typical of the other impoundments that have been grassed.

Establishment of diversity of vegetation on an impoundment could be regarded as the ultimate in rehabilitation. Even though this may not yet be a common approach, it is important to demonstrate the relevance and possible success of this approach.

The overall 1:1,5 through 1:3 (vertical to horizontal) slope configuration is the status quo scenario for most impoundments. The 1:6 through 1:9 slope configurations were selected as flatter side slopes are occasionally applied to enhance vegetation establishment. There is also common perception that flatter side slope configurations may reduce the overall visual impact.

3.2.3 Defining the scenarios modelled in the study

The purpose of this section is to model different tailings impoundment embankment scenarios using a set of tools which comprise:

- a visual (visual perception) model;
- a air (dust) model;
- a water (sulphate flux) model; and
- an engineering cost model.

The ERGO Daggafontein tailings impoundment site is used to provide context to the modelling and demonstration of the approach. Also, for the purpose of this research the modelling is undertaken for a very large impoundment with a tailings production of 990 000 tpm with a life of facility taken as 16 years and a tailings placed dry density of 1,80 t/m^3. The amount of tailings placed over the life of the impoundment and the final height of the impoundment is kept constant. Other parameters are included in Table 19, p. 160. Table 20 to Table 23 provide descriptive codes used for the various aspects modelled. For continuity and ease of reference it is necessary to use the codes throughout the study.

Table 20: Engineering scenarios modelled.

	Modelled Engineering Configurations			
	Slope 1	**Slope 2**	**Slope 3**	**Slope 4**
Engineering costs of placing material at the following side slopes with no further flattening				
Covers	**1:1,5**	**1:3**	**1:6**	**1:9**
Tailings in situ (no cover)	ES1	ES2	ES3	ES4
Rock cladding (300 mm)	ES5	ES6	ES7	ES8
Grassed armouring	ES9	ES10	ES11	ES12
Diverse vegetation	ES13	ES14	ES15	ES16
Engineering costs to construct at steep (i.e. 1:1,5 overall) side slope and flattening such to 1:3, 1:6 and 1:9				
Covers	-	**1:3**	**1:6**	**1:9**
Tailings in situ (no cover)	-	ES17	ES18	ES19
Rock cladding (300 mm)	-	ES20	E21	E22
Grassed armouring	-	ES23	ES24	ES25
Diverse vegetation	-	ES26	ES27	ES28

Table 21: Visual perception configuration scenario modelling codes and buffer distances.

	Overall side slope	**Buffer distances for levels of visual perception**			
Covers	**1:3**	**Recognition**	**Detection**	**Awareness**	**10 000 m limit of ZVI**
Tailings in situ (no cover)	VS1	R-1645	D-5490	A-2865	-
Rock cladding (300 mm)	VS3	R-1890	D-4085	A-4025	-
Grassed armouring	VS5	R-975	D-2745	A-3530	O-2750
Diverse vegetation	VS7	R-180	D-855	A-3655	O-5300
Covers	**1:6**				-
Tailings in situ (no cover)	VS2	R-4145	D-4695	A-1160	-
Rock cladding (300 mm)	VS4	R-1890	D-5245	A-2865	-
Grassed armouring	VS6	R-1645	D-2625	A-2430	O-3300
Diverse vegetation	VS8	R-180	D-855	A-3165	O-5800

Table 22: Air quality modelling scenarios and area of influence codes for the isopleths.

	Overall side slope	**Air quality isopleths**	
Covers	**1:1,5**	**PM$_{10}$ (µg/m^3)**	**TSP (mg/m^2)**
Tailings in situ (no cover) 0% efficiency	AS1	AS1_10day	AS1_DDday
Rock cladding (300 mm) 100% efficiency	AS5[1]	no emissions	no emissions
Grassed armouring 50% efficiency	AS9	AS9_10day	AS9_DDday
Diverse vegetation 80% efficiency	AS13	AS13_10day	AS13_DDday
Covers	**1:3**		
Tailings in situ (no cover) 0% efficiency	AS2	AS2_10day	AS2_DDday
Rock cladding (300 mm) 100% efficiency	AS6[1]	no emissions	no emissions
Grassed armouring 50% efficiency	AS10	AS10_10day	AS10_DDday
Diverse vegetation 80% efficiency	AS14	AS11_10day	AS12_DDday
Covers	**1:6**		
Tailings in situ (no cover) 0% efficiency	AS3	AS3_10day	AS3_DDday
Rock cladding (300 mm) 100% efficiency	AS7[1]	no emissions	no emissions
Grassed armouring 50% efficiency	AS11	AS11_10day	AS11_DDday
Diverse vegetation 80% efficiency	AS15	AS15_10day	AS15_DDday
Covers	**1:9**		
Tailings in situ (no cover) 0% efficiency	AS4	AS4_10day	AS4_DDday
Rock cladding (300 mm) 100% efficiency	AS8[1]	no emissions	no emissions
Grassed armouring 50% efficiency	AS12	AS12_10day	AS12_DDday
Diverse vegetation 80% efficiency	AS16	AS16_10day	AS16_DDday

[1] AS5 through AS8 is included in the table although not modelled during the study. The 100% control efficiency implies that there will be no emissions from the impoundment.

Table 23: Groundwater quantity and quality modelling scenarios.

	Side slope configuration			
Covers	**1:1,5**	**1:3**	**1:6**	**1:9**
Tailings in situ (no cover)	WS1	WS2	WS3	WS4
Rock cladding (300 mm)	WS5	WS6	WS7	WS8
Grassed armouring	WS9	WS10	WS11	WS12
Diverse vegetation	WS13	WS14	WS15	WS16

3.3 Study site

East Rand Gold and Uranium Company Limited (ERGO) was established in 1977 to reclaim and retreat gold residue deposits on the East Rand, in Gauteng, South Africa. In 1985, following an agreement with East Daggafontein Mines Limited, a 1 Mtpm carbon-in-leach (CIL) plant was completed for this purpose. The plant recovered approximately 3700 kg of gold per annum, depositing the tailings at the ERGO Daggafontein site at an average rate of 1,37 Mtpm. Active deposition of reworked tailings onto the impoundment ceased during December 2001 after about 200 Mt had been deposited during the 15 years.

The ERGO tailings facility is located in the Ekurhuleni Metropolitan Municipality, Gauteng Province, South Africa. Springs lies approximately 5 km West and Nigel approximately 15 km North East of the impoundment (Figure 84). It covers a total area of approximately 600 ha, whereas the footprint of the impoundment covers 435 ha – one of the largest of its kind in the world.

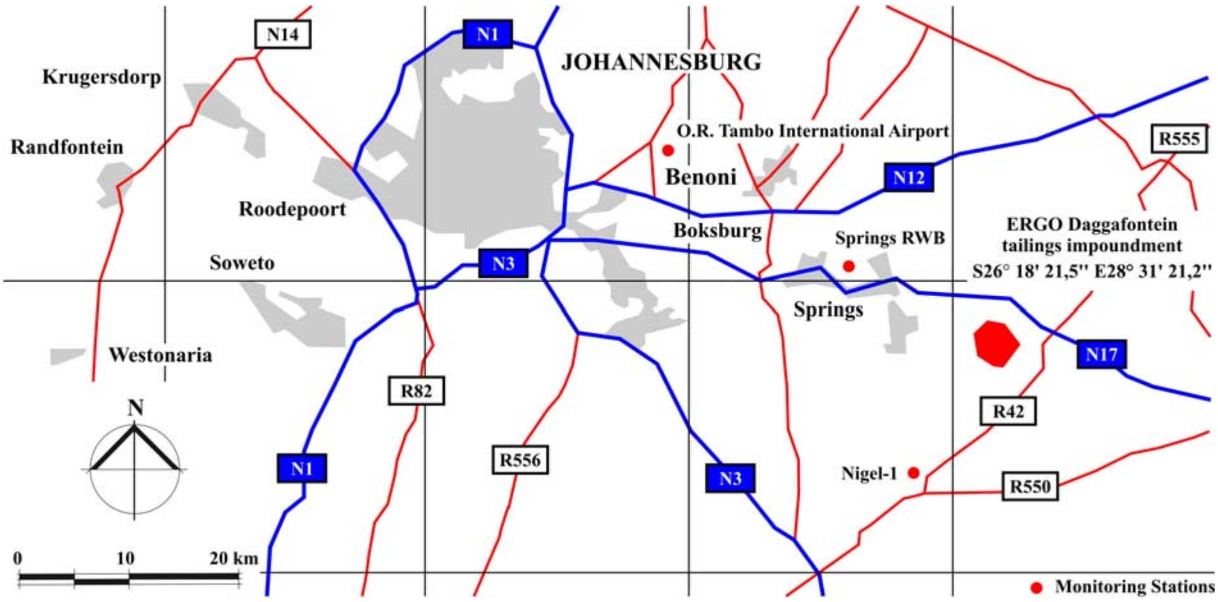


Figure 84: Regional locality map of the ERGO Daggafontein tailings impoundment.

The reclamation of old mine residue deposits predominantly take place by means of hydraulic monitoring methods. High pressure water jets are directed onto the face of the deposit, breaking up the material and turning it into slurry. The slurry flows to a pump station located at a low point on the site, which is then pumped to a process plant for treatment and subsequent disposal on an impoundment.

The ERGO Daggafontein tailings impoundment was designed as a free-standing upstream deposited ring-dyke impoundment with the outer perimeter wall built from coarse cycloned underflow impounding the fine tailings overflow. The lowest point of the tailings impoundment is at the south-western corner at about 1578 m.a.s.l. with a maximum height of about 68 m (Figure 86).

Aerial photograph downloaded from GoogleEarth.com.

Figure 85: ERGO Daggafontein tailings impoundment aerial photograph.

The impoundment is currently in various stages of rehabilitation for a wilderness end land use (Wates, Sabbagha, Geldenhuys, and Steenkamp, 2001) through:

- the mechanically flattening of the embankment step-in side slopes varying between 18° and 20° with 13 m vertical steps and 7 m wide benches – this results in an overall side slope of less than 18°;
- the placing of an armouring consisting of a 40 % topsoil and 60 % rock mixture;
- providing lateral drainage in order to route stormwater collected on the benches to concrete stormwater chutes spaced at 200 m intervals; and
- planting grass on the embankment slopes.

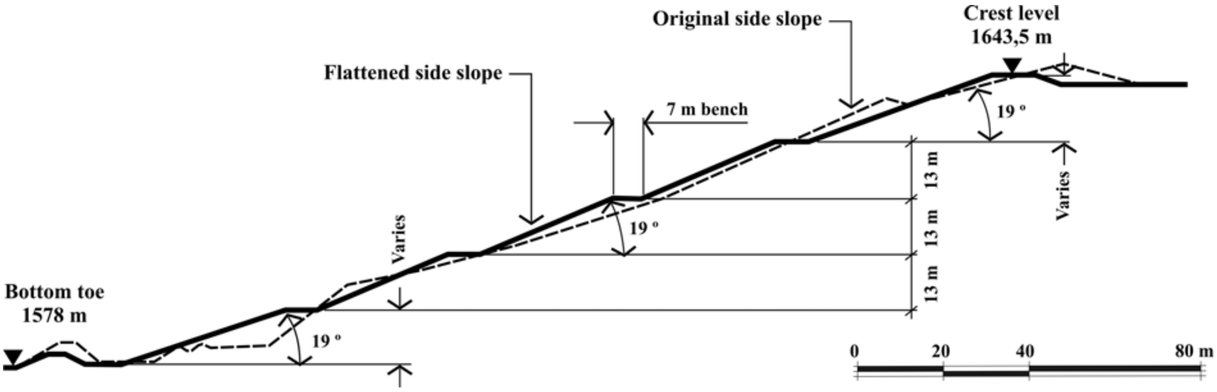


Figure 86: Typical section through ERGO Daggafontein tailings impoundment embankment.

The area has a rural character and the impoundment lies within the highveld grassland broad vegetation type. The regional terrain morphology varies between slightly irregular to moderately undulating plains, that is to say a rolling topography (Figure 87). The surrounding land is mainly used for agriculture such as grazing, and the cultivation of sunflowers, maize and beans (Figure 88). The Endicott and Viskuil agricultural holdings are located about 5 km to the East of the site. The biological productivity, i.e. primary productivity expressed as the harvestable yield in tonnes per hectare for a complete growing season, is estimated at 6,25 t/ha (van Riet et al., 1997:28).

Figure 87: The ERGO Daggafontein tailings impoundment lies within an area with a rural character and rolling topography.

The Blesbokspruit wetland is located to the West of the impoundment. A tributary lies South of the impoundment and joins the Blesbokspruit at the northern boundary of the Maryvale Bird Sanctuary. The site slopes gently in a westerly direction towards the Blesbokspruit.

Figure 88: The land surrounding the ERGO Daggafontein tailings impoundment is extensively used for grazing and the cultivation of cash crops such as maize, sunflowers and soya beans.

3.3.1 Climate

The South African Weather Services maintains two automatic weather stations within the Ekurhuleni Metropolitan Municipality, one situated at the O.R. Tambo International Airport (erstwhile Johannesburg International Airport) and a second at Springs. Data, unless otherwise indicated, were used from the weather station at O.R. Tambo International Airport (26° 8' S and 28° 14' E) for the period 1961 to 1990.

Rainfall

Rainfall is highly seasonal over most parts of South Africa and precipitation over the interior, including Eastern Gauteng, follows an annual cycle. The impoundment falls within a summer rainfall area with an average annual precipitation of 713 mm (Figure 89). However, during the period monitored the annual rainfall has been as high as 1019 mm (1987) and as low as 443 mm (1984).

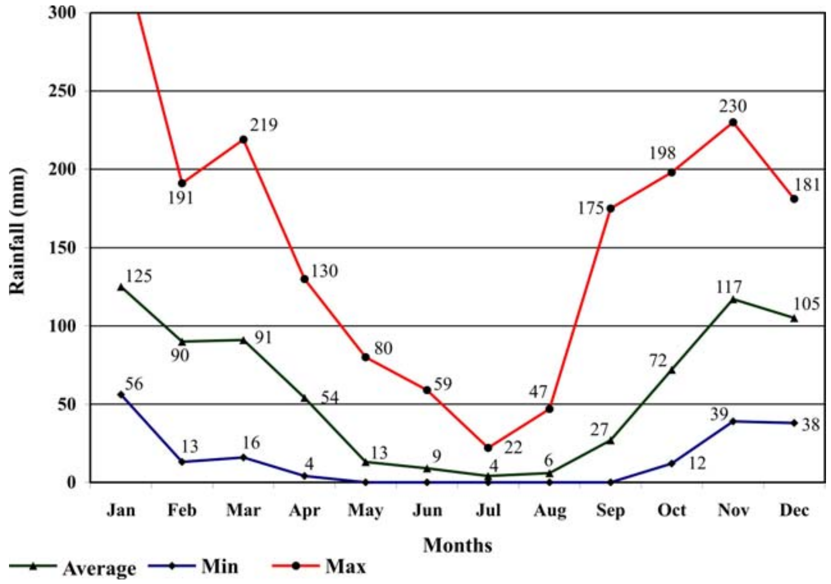


Figure 89: Graph indicating annual average, minimum and maximum rainfall figures.

Rainfall figures for the O.R. Tambo International Airport monitoring station is given in Table 24. Rainfall in the region is almost exclusively due to showers and thunderstorms that fall mainly during summer in the period between October and March. Summer months receive about 70 % of the rainfall and winter months are normally dry. The maximum rainfall occurs during December and January. The average monthly rainfall for the months April to September ranges between 3 mm and 34 mm. An average number of 90 to 95 rain days are experienced per year.

Table 24: Long-term average monthly rainfall for O.R. Tambo International Airport (Schulze, 1986).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Ave rainfall (mm)	188	55	92	49	70	31	30	25	42	89	65	102	838
Average number of rain days	14,4	11,0	11,0	8,5	3,6	2,0	1,2	2,0	3,5	9,6	14,3	14,0	95,5

Temperature

The temperature for Eastern Gauteng varies greatly from summer to winter (Figure 90). The average daily maximum temperature is 25,6^{o}C in January and 16,0^{o}C in June, while the average daily minimum temperature ranges from 14,7^{o}C in January to 4,1^{o}C in June.

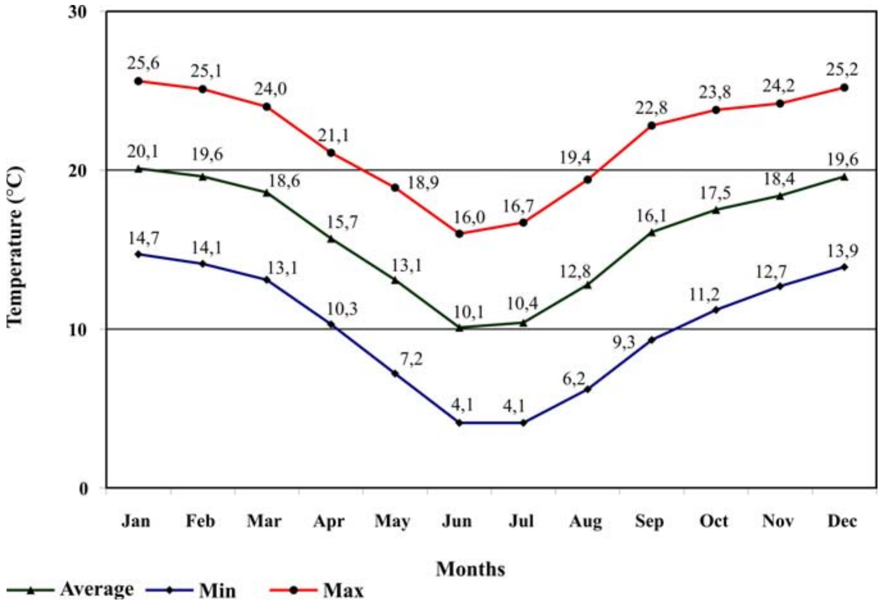


Figure 90: Graph indicating average, minimum and maximum temperature figures.

Long-term average maximum, mean and minimum temperatures for O.R. Tambo International Airport (1951-1984) are given in Figure 90 (Schulze, 1986). Annual mean temperatures for are given as 15,9°C. The average daily maximum temperatures range from 25,3°C in January to 16,0°C in June, with daily minimum ranging from 14,3°C in January to 4,0°C in June and July.

Table 25: Minimum, maximum and mean temperature (°C) for O.R. Tambo International Airport for the period 1951-1984 (Schulze, 1986).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Maximum	25,3	24,9	23,9	21,2	18,6	16,0	16,5	19,2	22,7	23,9	24,1	25,0
Minimum	14,3	14,1	12,9	10,2	7,0	4,0	4,2	6,0	9,2	11,3	12,7	13,8
Mean	19,8	19,5	18,4	15,7	12,8	10,0	10,4	12,6	15,9	17,6	18,4	19,4

At Springs the average daily maximum temperature is about 27 °C in midsummer and 17 °C in midwinter. Temperature extremes of 38 °C and 26°C may occur during summer and winter, respectively. Sunshine duration in summer is about 60%, whereas insolation duration of 80% is typical of winter months.

Mixing depth and atmospheric stability

The atmospheric boundary layer constitutes the first few hundred metres of the atmosphere. This layer is directly affected by the earth's surface, either through the retardation of flow due to the frictional drag of the earth's surface, or as result of the heat and moisture exchanges that take place at the surface. During the daytime, the atmospheric boundary layer is characterised by thermal turbulence due to the heating of the earth's surface and the extension of the mixing layer to the lowest elevated inversion. Radiative flux divergence during the night usually results in the establishment of ground based inversions and the erosion of the mixing layer.

Atmospheric stability is frequently categorised into one of six stability classes. These are briefly described in Table 26. Hourly standard deviation of wind direction, wind speed and predicted solar radiation are used to determine hourly-average stability classes.

Table 26: Atmospheric stability classes.

Designation	Stability Class	Atmospheric condition
A	Very unstable	Calm wind, clear skies, hot daytime conditions
B	Moderately unstable	Clear skies, daytime conditions
C	Unstable	Moderate wind, slightly overcast daytime conditions
D	Neutral	High winds or cloudy days and nights
E	Stable	Moderate wind, slightly overcast night-time conditions
F	Very stable	Low winds, clear skies, cold night-time conditions

The atmospheric boundary layer is normally unstable during the day as a result of the turbulence due to the sun's heating effect on the earth's surface. The thickness of this mixing layer depends predominantly on the extent of solar radiation, growing gradually from sunrise to reach a maximum at about 5-6 hours after sunrise. This situation is more pronounced during the winter months due to strong night-time inversions and slower developing mixing layer. During the night a stable layer, with limited vertical mixing, exists. During windy and/or cloudy conditions, the atmosphere is normally neutral.

For elevated releases, the highest ground level concentrations would occur during unstable, daytime conditions. The wind speed resulting in the highest ground level concentration depends on the plume buoyancy. If the plume is considerably buoyant (high exit gas velocity and temperature) together with a low wind, the plume will reach the ground relatively far downwind. With stronger wind speeds, on the other hand, the plume may reach the ground closer, but due to increased ventilation, it would be more diluted. A wind speed between these extremes would therefore be responsible for the highest ground level concentrations. In contrast, the highest concentrations for ground level, or near-ground level releases would occur during weak wind speeds and stable (night-time) atmospheric conditions.

Wind speed and direction

One of the main interests in wind data is to determine the potential for wind blown dust from the impoundment. The wind erosion potential is a function of the wind velocity. The vertical dispersion of pollutants is largely a function of the wind field. The wind speed determines both the distance of downwind transport and the rate of dilution of pollutants. The generation of mechanical turbulence is a function wind speed and surface roughness.

Wind roses comprise 16 spokes which represent the directions from which winds blow during the period. The colours reflect the different categories of wind speeds. The grey area, for example, represents winds of 1 m/s to 3 m/s. The dotted circles provide information regarding the frequency of occurrence of wind speed and direction categories. Each dotted circle within the wind roses in Figure 91 represents 5 % frequency of occurrence whereas the figure given in the centre of the circle describes the frequency with which calms occur, i.e. periods during which the wind speed is below 1 m/s.

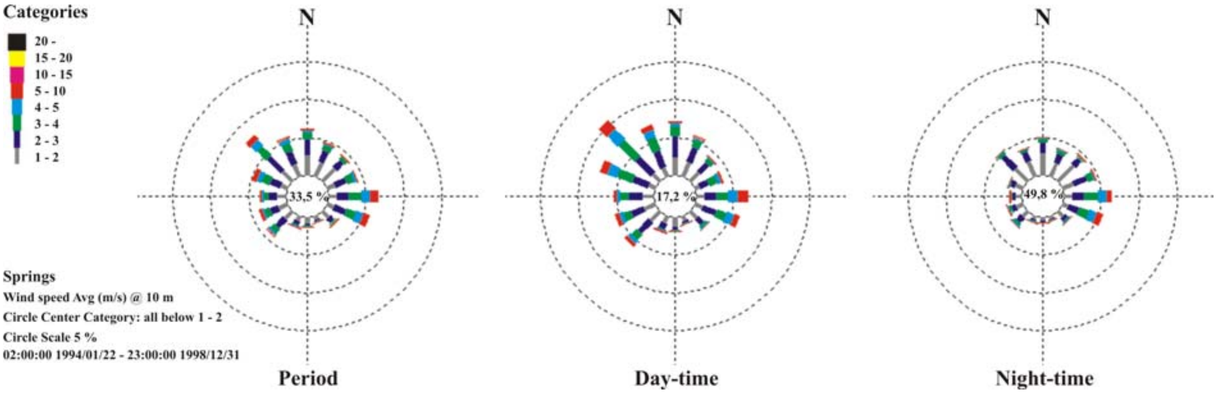


Figure 91: Period-average, day-time and night-time wind roses depicting the wind profile in Springs for the period January 1998 to December 2002.

The wind regime largely reflects the synoptic scale circulation. The flow field is dominated by north-westerly and easterly winds, with northerly winds prevailing due to the anticyclones that dominate the region throughout much of the year. Infrequent winds are noted to occur from the southern sector. Thermo-topographical impacts on the flow regime give rise to distinct diurnal trends in the wind field. During the day-time, the predominant wind flow is from the northwest with frequent wind also from the southwest and East. Strong winds (> 5 m/s) occur from the northwest and East and east-southeast. During the night-time the decrease in winds from the westerly sector are evident with the prevailing winds from the East and east-southeast. A decrease in the wind velocity is also apparent with wind mainly between 1 m/s to 3 m/s for most of the night. This is typical of night-time airflow when calm periods and low wind speeds are generally more prevalent.

Evaporation

In Eastern Gauteng evaporation is greater than precipitation, which gives a net loss throughout the year. Even in the wet season (November to April) when rainfall is higher, evaporation still exceeds precipitation. The evaporation figure 1165 mm is the average evaporation for the months November to April obtained from 1959 –1987.

3.3.2 Geology

Regional geology

The oldest rocks which outcrop within the region are sediments of the Witwatersrand Supergroup which form pronounced ridges in the Germiston region. Gold-bearing reefs within the Witwatersrand sediments have been mined over a significant portion of the East Rand (Figure 13, p. 19). Some of the reclaimed mine residue of these deposits have been disposed of at the ERGO Daggafontein tailings impoundment.

The Witwatersrand sediments are overlain by andesitic lava of the Ventersdorp Supergroup, which outcrops over the western portion of the study area. This formation is unconformably overlain by the Transvaal Sequence which is represented by the Black Reef Quartzite and Malmani Dolomite which outcrop along the southern and eastern margins of the study area.

Surface outcrops across the project area consist predominantly of Karoo age sediments of the Dwyka and Vryheid Formations which have been unconformably deposited on the older strata. This sedimentary sequence contains several coal seams which have been mined in the Springs area.

Strata generally dip at a variable angle in a South or south-westerly direction towards the centre of the East Rand basin.

The regional geology has been modified by the intrusion of both Karoo and Pilanesberg-age dykes. Extensive dolerite sills are also encountered during mining in the Springs area.

Site geology

The following provides a brief description of the geological sub-strata underlying the ERGO Daggafontein tailings impoundment site. The nature of the geology (Figure 92, p. 172) is considered important for the following reasons:

- the proximity to aquifers determine the susceptibility of groundwater to contamination; and
- the lithology and structure of formations influence the direction and rate at which contaminants migrate from the source.

The geology of the ERGO Daggafontein tailings impoundment site is varied with most of the site underlain by Karoo sediments consisting mainly of sandstone. These sediments are underlain by chert-rich tillite of the Dwyka Formation which weathers to wad and outcrops over the south-west corner of the site.

Karoo sediments are underlain by recrystallised Monte Christo dolomite of the Transvaal Supergroup which outcrops over the South and south-west of the site. The sediments in this area have been modified by the intrusion of Karoo age dolerite and Pilanesberg age syenite dykes cross-cutting the Transvaal strata.

Rocks of the Proterozoic Witwatersrand Super Group sub-crop at a depth of more than 400 m at the site, with the western edge of the Main Reef workings occurring at a depth of approximately 600 m. The oldest rocks mapped at the site are the Proterozoic-aged Monte Christo Formation (Transvaal Super Group), characterized by minor dolomite and interbedded chert.

Surface outcrops of the Jurassic-aged Vryheid Formation (Karoo Super Group), which overlie the Monte Christo Formation across part of the site, consist of gently dipping to horizontal mudstone, shale, siltstone, poor quality coal (occasional), and sandstone interbeds, the mudstone weathering to clay of low plasiticity. The underlying and Carboniferous-aged tillite of the Dwyka Formation (Karoo Super Group) comprises hard, sub-angular to angular chert fragments within a mudstone matrix.

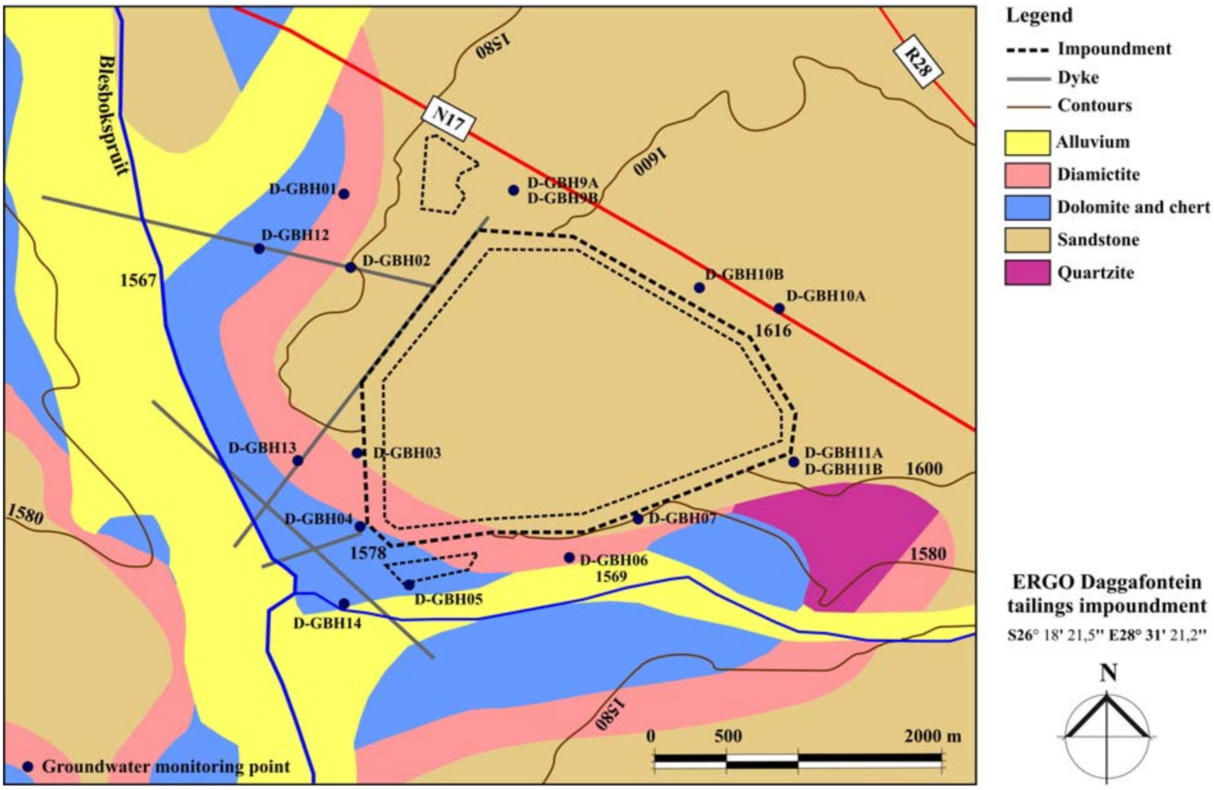


Figure 92: ERGO Daggafontein tailings impoundment site geology and structures.

3.3.3 Soil, land and landform

The regional topography is flat to gently sloping with isolated higher areas. The nature of the topography causes man-made landforms to be prominent features in the natural landscape and therefore quite visible. The ERGO Daggafontein tailings impoundment site slopes in a westerly direction towards the Blesbokspruit. An un-named tributary of the Blesbokspruit lies South of the impoundment and flows from East to West. The slope changes toward the south-west, over the western half of the site and toward the South of the eastern side of the site. A small valley runs from North to South to the West of the impoundment.

The toe of the tailings impoundment at the south-western corner is also at the lowest point with an elevation of about 1578 m.a.s.l. The highest point of the tailings impoundment toe is at about 1616 m.a.s.l. This local high dictates the site drainage. Stormwater and seepage from the tailings impoundment site either drains in a southerly direction or in a north-easterly direction away from this high. Drainage of seepage from the toe drain gravitates to either the collector dam at the south-western corner of the tailings impoundment or to the return water dam at the north-western corner of the tailings impoundment.

The soils covering the site can be described as predominantly pedogenic and colluvial soils with variable thickness. Pedogenic ferricrete deposits consist of well-cemented fine to coarse ferricrete gravels set in a sandy clay matrix, varying in thickness between 0,3 and 6,1 m. The colluvial soils consist of brown clayey sands and silts, which are occasionally ferruginised. These soils are highly variable in thickness, but cover most of the site to depths of between 0,2 to 0,4 m. Falling head permeability tests conducted on the soils in even 100 mm trial pits around the perimeter of the tailings impoundment during January 1984 displayed low permeabilities of between 6 – 10 m/s, which can be attributed to their elevated clay content.

Soil classification

For the purpose of conducting an initial soil-land evaluation and assessment of the site, it is necessary to study the key issues relating to the soil-landform. The main objectives of this study are to identify and classify the soil-landform resources at an appropriate level. From a soil classification perspective the soils found on the ERGO Daggafontein site can be classified into five main categories namely:

- <u>Undisturbed natural soils</u>. These soils are classified according to the standard South African soil classification system and can be mapped to give an indication of agricultural or crop production potential.
- <u>Disturbed natural soils</u>. The classification of disturbed soils in the South African soil classification system is restricted to one soil form namely the Witbank soil form. Although adequate for the physically disturbed soils on the site this form is not adequate for the chemically impacted soils. New categories incorporating the nature characteristics of the chemical degradation will have to be established. As such there is currently an effort underway by members of a working group to establish such categories.
- <u>Tailings material that will undergo some alteration due to mixing with soil or the establishment of vegetation</u>. The classification of tailings material suffers the same shortcomings as the chemically disturbed soils mentioned above. Dedicated categories are foreseen for the classification of such material. At present the body of information on suitability of tailings material to support new uses is very restricted and this aspect requires significant future research as well as structured compilation of existing knowledge.
- <u>Tailings impoundment armouring</u> (rock and soil mix used as cover) can currently be accommodated under the Witbank form but will be incorporated in an expanded classification of anthropogenic soils in the envisaged future classification system.
- <u>Tailings material that will undergo some form of alteration excluding further dedicated human activity</u>. This category presents the material that will not be exposed and as such does not require classification from a soils perspective.

In terms of chemical characteristics the closest soils to the tailings material is Fluvisols with sulphuric soil horizons. These soils are very restricted in their global distribution and are formed from the drainage of previously water-saturated soils and subsequent oxidation of high levels of sulphide minerals is the soil matrix.

Land capability and agricultural potential

The criteria, regarding soil depth and slope, are summarised from the Chamber of Mines Rehabilitation Guidelines (CM, 1981) and for the purposes of this study, the following land capability classes apply:

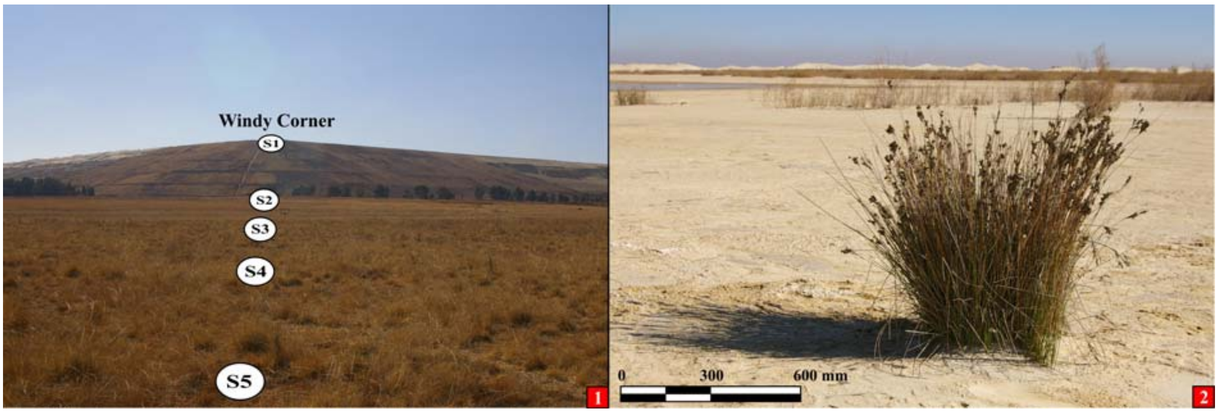
- Arable land: soil depth will not be less than 0,6 m and the slope will not exceed 7 % (1:14).
- Grazing land: soil depth will be at least 0,25 m an the slope will not exceed 30 % (1:3).
- Wilderness land: soil depth is less than 0,25 m but more than 0,15 m.
- Wetland: no criteria given.

The area covered by the tailings impoundment footprint can for all practical purposed be considered to be permanently lost. The land capability of the ERGO Daggafontein impoundment prior to deposition was mainly used for grazing with about 30 % cultivated. The arable section was used for growing cash crops such as maize, sunflowers and beans.

The agricultural potential of the ERGO Daggafontein tailings impoundment site is directly related to the quality of the soils in terms of physical and chemical characteristics. The undisturbed soils will have the highest potential (depending on depth and chemistry) and the disturbed soils will decrease in potential which is proportional to the extent to which they have been disturbed. The in situ tailings material is considered to be of zero agricultural potential mainly due to its characteristics as well as a general lack of information on possible crop types and yields.

Soil sampling and analysis

Seven surface soil samples were collected from the tailings impoundment as well as the surrounding area (Table 27 and Figure 94) and were analysed for a number of parameters (Table 28 and Table 29).



[1] Looking in a north-eastern direction towards Windy Corner of the ERGO Daggafontein tailings impoundment indicating the surface soil sampling points.

[2] Close-up photograph of a sedge (*Juncus* sp) growing on the ERGO Daggafontein tailings impoundment basin.

Figure 93: Surface soil sampling points.

The tailings samples exhibit typical mine tailings character in that it has a high salt content (low resistance) in the form of sulphates and low levels of the plant nutrients Ca, Mg, and K (T1). T2 sample has high levels of these plant nutrients and in sufficient quantities to support the growing of *Juncus sp*. at this point (Figure 93, photo 2).

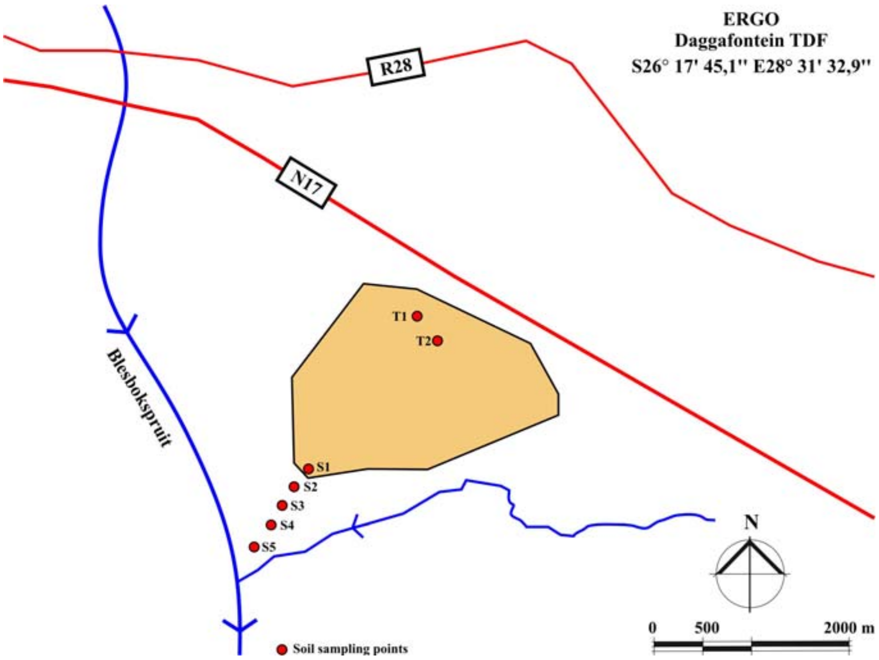


Figure 94: ERGO Daggafontein soil sampling points.

Table 27: Surface soil sampling point co-ordinates.

	Grid	Lat. and Long. (hddd°mm'ss,s'')
	Datum	**WGS 84**
Ref	**Description**	**Position**
S1	**Soil 1 Windy Corner**	S26 18 21,5 E28 31 21,2
S2	**Soil 2**	S26 18 36,1 E28 31 11,2
S3	**Soil 3**	S26 18 39,5 E28 31 10,9
S4	**Soil 4**	S26 18 42,3 E28 31 05,9
S5	**Soil 5**	S26 18 44,0 E28 31 04,6
T1	**Tailings 1 Beach**	S26 17 35,6 E28 32 07,6
T2	**Tailings 2 Pond *Juncus sp.***	S26 17 36,0 E28 32 07,6

Table 28: Surface sample soil analysis results from the ERGO Daggafontein tailings impoundment site.

	NH$_4$OAc Extr. Cations (mg/kg)				NH$_4$OAc Extr. Cations (cmol(+)/kg)					% of S-value			
Sample	**Ca**	**Mg**	**K**	**Na**	**Ca**	**Mg**	**K**	**Na**	**S-value**	**Ca**	**Mg**	**K**	**Na**
T1	12	180	217	571	0,06	1,48	0,55	2,48	4,58	1,3	32,4	12,1	54,2
T2	9454	340	151	871	47,27	2,8	0,39	3,79	54,24	87,2	5,2	0,7	7,0
S1	3304	150	7	28	16,5	1,2	0,02	0,12	18,89	92,3	6,9	0,1	0,7
S2	689	161	259	7	3,45	1,33	0,66	0,03	5,46	63,1	24,3	12,1	0,6
S3	858	239	347	14	4,29	1,97	0,89	0,06	7,21	59,5	27,3	12,3	0,84
S4	1414	723	269	73	7,07	5,95	0,69	0,32	14,03	50,4	42,4	4,9	2,3
S5	3384	1439	405	521	16,92	11,84	1,04	2,27	32,06	52,8	36,9	3,2	7,1

S1 sample, taken at Windy Corner, seems more like tailings material in its chemical composition than the Tailings 1 (T1) sample. This sample has very high Ca and sulphate levels and very low levels of Mg and K and therefore has a restriction in terms of its crop production potential. Samples S2 to S5 exhibit characteristics expected for natural soils with sulphate levels higher than what is expected from natural background levels. All the soil samples have high levels of micronutrients (especially Zn) and it is not clear what the source of these is.

Table 29: Analysis results of surface soil samples collected from the ERGO Daggafontein tailings impoundment site indicating micronutrients.

			NH_4EDTA (mg/kg)				**Texture**			
Sample	**pH water**	**Resistance (ohm)**	**Cu**	**Fe**	**Mn**	**Zn**	**Sand**	**Silt**	**Clay**	**SO_4 (mg/kg)**
T1	4,7	80	7,5	602	46	20	36,5	50,5	13,0	2023
T2	3,8	60	4,3	224	56	30	48,8	38,0	13,2	5089
S1	3,0	100	8,1	887	72	26	78,1	12,2	9,7	7584
S2	5,1	1200	7,2	135	72	54	66,5	13,1	20,4	251
S3	5,3	500	5,0	97	132	60	64,7	16,8	18,5	62
S4	5,5	900	6,6	281	318	162	48,5	22,3	29,3	34
S5	4,4	150	17,7	524	105	54	26,5	25,5	48,0	715

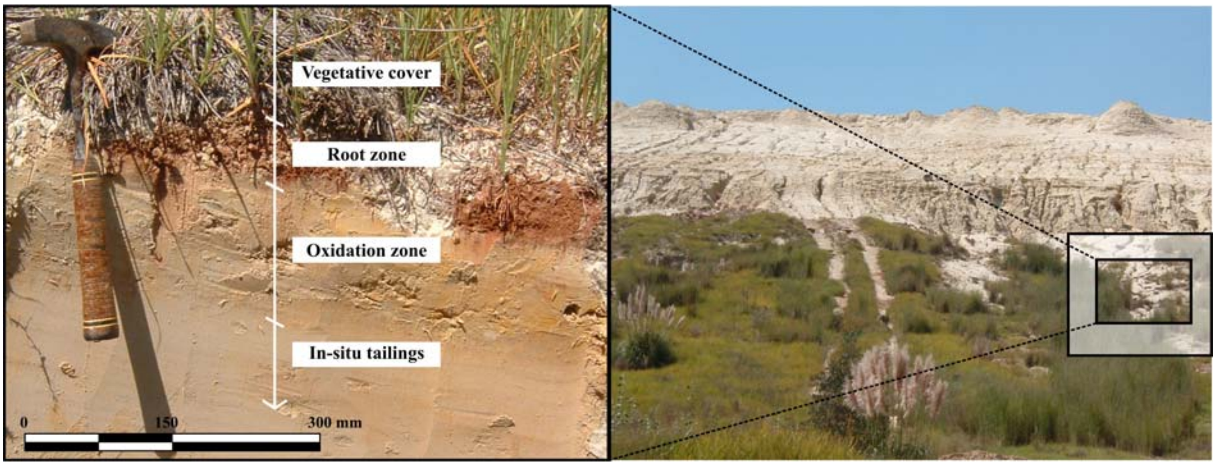


Figure 95: Shallow root zone of a typical profile of the ERGO Daggafontein tailings impoundment surface previously vegetated.

3.3.4 Hydrology

Groundwater quality

Data gathered from monitoring boreholes (Figure 96) at the ERGO Daggafontein tailings impoundment site indicates that conditions within the dolomite aquifer is confined with borehole D-GBH06 being artesian and other dolomite rest water levels lying within 10 m of the surface. Conditions in the overlying Karoo aquifer are unconfined with rest water levels lying within 5 m of the surface. Rest water levels within some areas may have been artificially depressed by the planting of blue gums to control near surface seepage (Blecher and Bush, 1993).

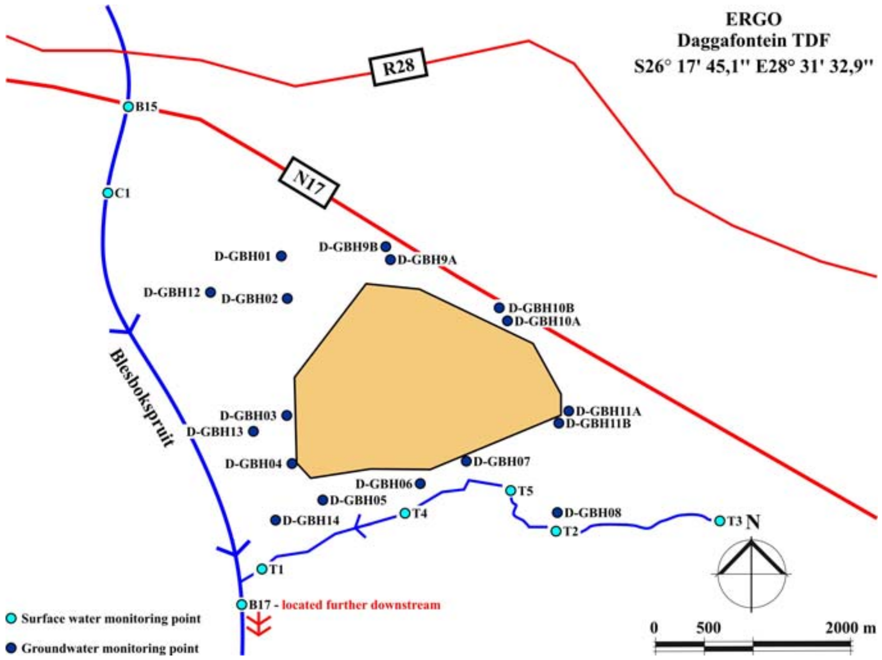


Figure 96: Water monitoring points.

Prior to the onset of cycloning at the ERGO Daggafontein tailings impoundment in 1987, rest water level data recorded in exploration boreholes indicated that groundwater flow took place towards the Blesbokspruit to the West and a tributary of this river to the South (Blecher and Bush, 1993). However, rest water levels determined during December 1995 indicate that groundwater flow in the phreatic Karoo aquifer now takes place towards the north-east and south-east over much of the site, and has a South to south-westerly component in the vicinity of borehole D-GBH07.

Drainage in the underlying dolomite aquifer presently takes place towards the north-east and south-east, and it is significant that rest water levels have dropped by up to 7 m along the eastern margin of the tailings impoundment between 1993 and 1995, whilst water levels determined in monitoring boreholes along the western boundary of the impoundment remained virtually static over the same period (Demmer and Hearne, 1996).

Groundwater quality in the two aquifers which underlie the Daggafontein tailings impoundment has been monitored on an irregular basis over the last ten years in a series of multiple piezometers which are located around the western and southern margins of the site, as indicated by Figure 92 (p. 172).

Surface water quality

Discontinuous surface water quality data is available for many sampling points along the two watercourses in the vicinity of the ERGO Daggafontein tailings impoundment. The following five surface monitoring points are discussed (Figure 96, p. 177):

- Sampling point T1, on the un-named watercourse located to the South of the impoundment, lies just upstream from the confluence with the Blesbokspruit.
- Sampling point T2, on the un-named watercourse located to the South of the impoundment, lies upstream from T1.
- Sampling point C1, on the causeway crossing the Blesbokspruit, is located to the West of the impoundment. The monitoring at C1 was discontinued in 2001.
- Upstream sampling point B15 is at the Blesbokspruit and N17 road crossing.
- Downstream sampling point B17 lies within the Marievale Bird Sanctuary. Other pollution sources exist on the western side of the Blesbokspruit between the impoundment and point B17. These sources are mainly mine residue deposits and are likely to impact on the Blesbokspruit.

The water samples taken from the monitoring points were tested for a broad spectrum of parameters. As high levels of sulphates, chlorides or conductivities in water samples are considered indicative of possible pollution from typical gold mine residue deposits, these parameters were considered in more detail. Levels of these key determinants become elevated due to the oxidation of sulphate-bearing pyrite residues present in the ore body, resulting in sulphuric acid formation and subsequent seepage from the dumps which impacts on both the surface and groundwater systems. The acid water generated may also mobilise other contaminants such as metals, leading to an increase in the total dissolved solids content of the water as reflected by elevated conductivity levels.

An analysis of conductivity, sulphates and pH data indicates that sulphate:

- concentrations have the greatest spatial and temporal variations throughout this area; and
- would be a reliable indicator of pollution from the tailings impoundment.

As samples are taken fortnightly and depending on the weather conditions and accessibility to the sites, it is unlikely that instantaneous pollution events, such as a paddock wall being breached, would be picked up by the monitoring system. Unless the water samples are taken shortly after an incident, pollutants released into the nearby water courses would not be picked up. The other obvious source of surface stream contamination is the visible occurrence of seepage zones along the southern tributary stream and associated areas of salt crystallisation. Salts precipitate along the stream where the perched aquifer daylights. The crystallised salts are flushed into the stream after heavy rains.

Some indication of the tailings impoundment's contribution to surface water salt loads can be obtained by comparing the concentrations of T1 and T2. While upstream areas occasionally contribute to the salt load in the stream, T1 concentrations are significantly higher than those observed at T2 indicating that:

- pollution is entering the system between these monitoring sites T1 and T2; and
- the most likely source is the ERGO Daggafontein tailings impoundment given its size and proximity.

Recurring association between high stream sulphate concentrations and rainfall events are of significance, which suggests that pollution is being flushed into the watercourse as part of the surface runoff. Patches of tailings material were also observed in the southern tributary (spruit) during field investigations.

If the impoundment is the pollution source, it implies that:

- the capacity of existing infrastructure has been exceeded during operation – it must be noted that site surface runoff conditions improved after November 2001 when decommissioning started; or
- pollutants contained in shallow aquifers are mobilized into site runoff during high rainfall events.

The ERGO Daggafontein tailings impoundment has been decommissioned with the following implications:

- no more water and tailings material are pumped or disposed onto the facility; and
- the return water dam, containment structures and canals are maintained to manage seepage water.

Blesbokspruit wetland

The Blesbokspruit wetland area comprises approximately 2000 ha privately and state owned land and is located to the East of Springs. This area covers approximately a 20 km section of the Blesbokspruit, which stretches from Grootvlei in the North to Marievale in the South. The wetland site was given Ramsar status in 1986.

The Blesbokspruit wetland system is currently influenced by:

- man-made structures such as bridges, causeways and embankments crossing the Blesbokspruit and restricting flow; and
- effluent released from mines, industry and waste water treatment works.

Effluent causes water eutrophication favouring vast reedbeds such as those established in the spruit. Reed such as *Phragmites australis* and *Typha capensis*, and sedges such as *Juncus* spp. and *Cyperus* spp. dominate the wetland. *Paspalum dilatatum* fringes the permanently waterlogged sections of the spruit while grasslands dominate drier areas.

Water quality data for the Blesbokspruit was sourced from the 2001 and 2003 Rand Water annual reports and contains a substantial body of data predating the impoundment. The information is useful to determine baseline surface water quality. The Rand Water monitoring sites are positioned both upstream and downstream of the ERGO Daggafontein tailings impoundment site. Sampling point C1 is immediately upstream of the impoundment. Prior to ending the sampling at C1 in October 2001, the total dissolved salts (TDS) concentrations at C1 were all above the unacceptable limit of > 500 mg/ℓ for the Blesbokspruit catchment in-stream target water quality requirements. The Grootvlei mine has permission from DWAF to discharge groundwater at a maximum rate of 96 Mℓ/day into the Blesbokspruit which contributes to the elevated salt concentrations measured at C1.

Levels of sulphates at points B17 are similar or better to those found further upstream at point B16. Sampling point T1 along the un-named watercourse located to the South of the impoundment and immediately upstream from the Blesbokspruit confluence have recorded high and elevated levels of sulphate mainly due to spillages and mismanagement at the impoundment.

Although the water quality in the Blesbokspruit's mini sub-catchment is improving, as measured at the catchment outflow (B17), it cannot be determined what influence the ERGO Daggafontein tailings impoundment has had, or is having on the water quality without sampling at additional points along this section of the Blesbokspruit.

Surface runoff

The ERGO Daggafontein tailings impoundment is situated within the catchment of the Vaal Barrage in the East Rand, and is contained within the boundaries of Rainfall Zone C2A, Catchment Zone C21E and Evaporation Zone 11A with a mean annual S-Pan evaporation depth of 1650 mm (Midgley, Pitman and Middleton, 1994). The closest registered rainfall measuring station to the site is that at Springs RWB (Midgley et al., 1994; Station No. 0476 736). The next closest rainfall measuring station is that at Nigel (Midgley et al., 1994; Station No. 0476 835). The statistics are given in Table 30 below.

Conceptual water control

Section 4 of Regulation No. 704, promulgated in terms of the National Water Act No. 36 of 1998 (NWA), requires that a mine residue deposit, i.e. tailings impoundment, must be located outside the 1:100 year flood line or 100 m from the centre of a watercourse. The ERGO Daggafontein tailings impoundment complies with this requirement. Section 5 of Regulation 704 also requires that the capacity of a dirty water system be designed to accommodate the 1:50 year recurrence interval event, and that any dam or holding facility shall have an additional 0,8 m freeboard above full supply level.

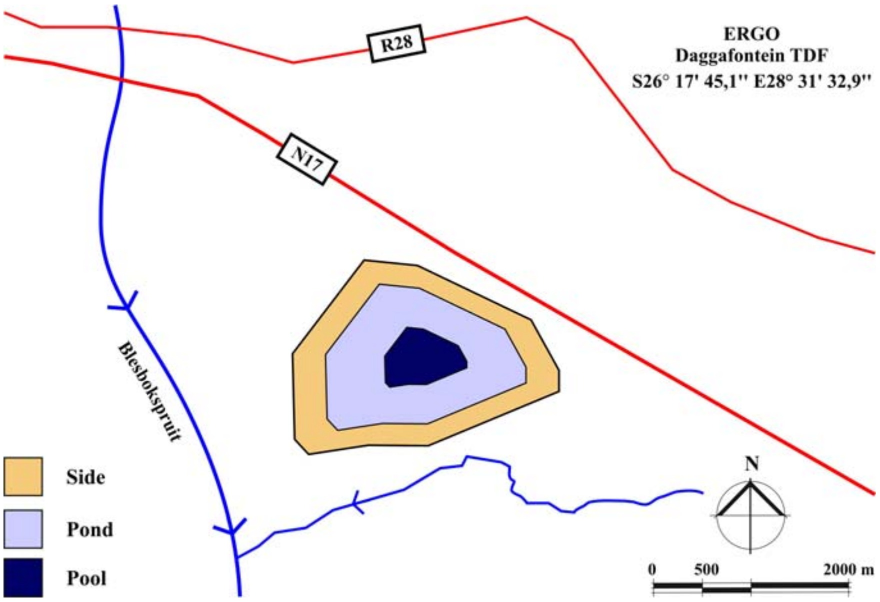


Figure 97: Delineation of the impoundment catchments for quantifying runoff.

Considering the site itself, if a configuration with an approximate physical footprint of 300 ha is chosen portions will be covered by the side slopes, pond and pool. The areas are indicated on Figure 97 and it can be assumed that the entire area contribute to runoff.

Table 30: Springs RWB and Nigel - 1 measuring station localities (Midgley et al., 1994).

Station	Lat.	Long.	MAP (mm)	Years of record
Springs RWB	26°16'	28°25'	658,7	60
Nigel - 1	26°25'	28°28'	705,7	73

Table 31: Preliminary estimate of surface runoff over pond surface, basin and embankment.

	Rain	**Rainfall MAP**	**Evaporation**	**S-Pan evaporation rates**	**Pan factor free surface**	**Runoff pool surface**	**Rainfall over basin**	**Runoff over sides**
Date	**%**	**mm**	**%**	**mm**		**m^3**	**m^3**	**m^3**
Jan	17,62	116,1	12,23	183,6	0,84	55124	183748	12543
Feb	13,15	86,6	9,86	148,0	0,88	41140	137133	9361
Mar	11,67	76,9	8,96	134,5	0,88	36510	121699	8307
Apr	6,42	42,3	6,55	98,3	0,88	20085	66950	4570
May	2,79	18,4	4,94	74,1	0,87	8729	29095	1986
Jun	1,13	7,4	3,78	56,7	0,85	3535	11784	804
Jul	1,11	7,3	4,22	63,3	0,83	3473	11575	790
Aug	1,05	6,9	6,12	91,9	0,81	3285	10950	747
Sep	3,62	23,8	8,61	129,2	0,81	11325	37751	2577
Oct	10,09	66,5	10,97	164,7	0,81	31567	105222	7183
Nov	15,71	103,5	11,39	171,0	0,82	49149	163829	11183
Dec	15,64	103,0	12,37	185,7	0,83	48930	163099	11133
Total	100,00	658,7	100,00	1501,0	-	312851	1042835	71185

A preliminary water balance was prepared based on regional average monthly rainfall and evaporation statistics obtained from Midgley et al. (1994) (Table 31, Figure 98). It is estimated that approximately 71 000 m^3 will fall on the side slopes, 310 000 m^3 run from the pool to the pond and 1 043 000 m^3 will fall directly on the entire basin.

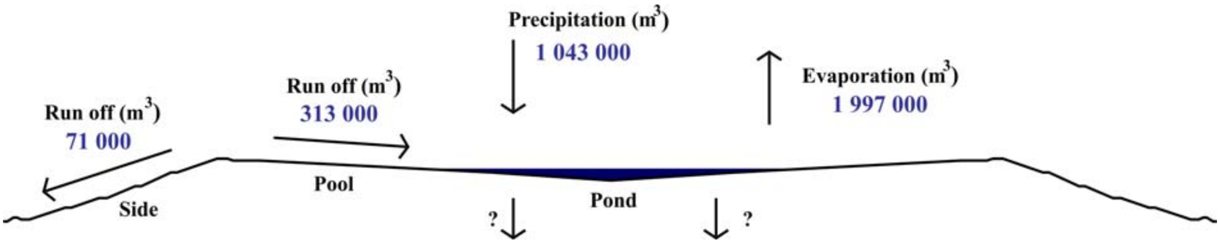


Figure 98: Conceptual water balance diagram.

The foregoing is only a preliminary theoretical appraisal and does not take local site conditions into account. In addition, the calculation does not allow for extremes. Nevertheless it does give an indication of the apportionment and magnitude of surface runoff which needs to be contained and managed.

3.3.5 Air

Suspended particles

The ERGO Daggafontein impoundment is situated within a region used for agriculture, industry, and mining and includes several primary metal smelters. An emission inventory of scheduled processes in the area is maintained by the Chief Air Pollution Control Officer from the Department of Environment Agriculture and Tourism (DEAT). A major section of the population relies on bituminous coal for domestic energy requirements. Traffic also contributes to emissions. Townships such as Springs and Nigel were established as a result of the underground gold mine operations in the region and are now extensively surrounded with mine residues deposits. Although some of these tailings dumps were vegetated as a pollution prevention measure, many impoundments remain that are not adequately covered. In some cases, the vegetative protective cover has deteriorated to expose bare tailings.

Reclaiming old mine residue deposits exposes sand and tailings to wind which contribute to wind-blown dust. Traffic-generated dust from unpaved roads is a minor secondary source, especially in urban areas and informal settlements. Frontal weather passing over surrounding maize farming areas contributes to intermittent dust storms. Moreover, the area is under the influence of elevated gaseous sulphurous concentrations attributable to emissions from power plants and from industrial and domestic use of coal.

The above sources of contamination have caused the levels of suspended particulates to exceed the annual guideline values for more than 25 % of the time. Domestic coal burning was found to account for about 50 % of the annual average concentration of suspended particulates; road dust for 16 % and industrial emissions for the remaining 34 %. The ambient air quality in the region is generally poor, specifically with regard to fine particulates.

Dustfall

Dustfalls, both near exposed gold mine tailings and at urban control sites, show distinct seasonal variations governed by wind and rainfall. The highest dustfalls occur in spring, caused by increasing wind speeds before the onset of spring rains. Dustfalls in summer are reduced due to rainfall, despite continued high winds. The dry months, March through July, have the lowest dustfalls. Despite the dryness, low wind speeds associated with frequent subsidence inversions result in low dust emissions. Conversely, the inversions contribute to trapping of domestic, traffic and industrial emissions, resulting in highest suspended dust concentrations during winter.

The monthly average dust fallout rates were determined for the Daggafontein tailings facility during the operation stage. A heavy fall-out (501 to 1 200 mg/m^2/day) zone was confined to a strip of between 500 m and 1 000 m towards the north-east and south-east of the tailings impoundment. Recent settable dust monitoring (October 2002 to January 2003) indicated that fall-out dust is currently in the slight (less than 250 mg/m^2/day) to moderate (251 to 500 mg/m^2/day) range.

Sporadic high levels of settable dust can be experienced during the winter months which is attributed to the mechanical re-profiling (earthworks) of the embankment slopes of the tailings impoundment. This will continue until the rehabilitation of the embankments is complete.

PM_{10} ambient air quality

A measured annual average value for PM_{10} at the Springs Old Boys Club for 2006 is 41 $\mu g/m^3$ and the annual average estimated ambient concentration value, determined by means of modelling, for the ERGO Daggafontein area is 28 $\mu g/m^3$ (Liebengerg-Enslin, 2006)

Radioactivity

ERGO (2004:4) states that radiation-related studies considered the following main potential exposure pathways:

- inhalation of radon gas containing radon (Rn) and its short lived progeny originating from tailings impoundments;
- inhalation of radio active dusts containing long-lived alpha-emitting nuclides, also originating from tailings impoundments; and
- external exposure to gamma radiation, also originating from tailings impoundments.

Ingestion or consumption of water potentially contaminated with radioactive particulates as well as ingestion of foodstuffs contaminated with radioactive particulates were also investigated and found to be inconsequential.

The findings of the investigations indicated that water is the most likely contributor of radio activity to the public dose. The maximum dose an adult will be exposed to is about 245 µSv/annum, and that of a fifteen year old, is 416 µSv/annum. The dose is the maximum that can be encountered on the site and is well below the internationally accepted public dose limit of 1 000 µSv/annum.

Studies conducted on three mines with high uranium content in their ores, indicated the highest inhalation dose of dust at these mines was only 47 µSv/annum. The findings also indicated that the highest dose due to the ingestion of vegetables is 2 µSv/annum.

The gamma dose is negligible compared to the background dose expected on the tailings impoundments. These areas are forbidden to the public and the dose rate is therefore of no consequence.

3.3.6 Vegetation

Of the more than 1000 species of trees and shrubs found in South Africa, more than 50 occur naturally in this region. The study area is a transitional region between the following two vegetation types (Low and Rebelo, 1996):

- Moist cool highveld grassland; and
- Rock highveld grassland.

Moist cool highveld grassland

Vegetation within the site and surrounding area is classified by Acocks (1988:100) as *Cymbopogon-Themeda* veld and classified by Low and Rebelo (1996) as Moist Cool Highveld Grassland. Dominant species within this tufted grassland include *Themeda triandra, Heteropogon contortus, Eragrostis superba, Elionurus muticus, Cympopogon pospischillii, Setaria sphacelata,* and forbs include large stands of *Crinum bulbispermum* and *Erythrina zeyheri*, *Ipomoea obscura* and *Vernonia oligocephala.*

According to Bredenkamp and van Rooyen (1996), when in pristine condition, *Themeda triandra* dominates this vegetation type.

Tainton (1999) suggests that these grasslands are relatively unstable and readily break down due to mismanagement. Disturbed areas are usually invaded by species such as *Eragrostis curvula, Sporobolus pyramidalis and Cynodon dactylon*. *Hyperrhenia hirta* follows these species in the 'recovery phase' and seems to remain dominant for many years. This is in agreement with Bredenkamp and van Rooyen (1996), who state that Moist Cool Highveld Grassland or *Themeda-Cymbopogon* veld, when overgrazed, replaces *Themeda triandra* (Red Grass) with species such as *Eragrostis curvula*.

Rocky highveld grassland

Rocky Highveld Grassland (Bredenkamp and van Rooyen, 1996) is a transitional vegetation type between grasslands of the high inland plateau and the bushveld of the lower plateau and is therefore also known as the central variation of Bankenveld (Acocks, 1988) that is typical of altitudes between 1 500 and 1 600 m.a.s.l. The ridges of the Witwatersrand and the dolomite plains of Gauteng fall within this vegetation type.

Characteristic grass species include *Diheteropogon amplectens, Trachypogon spicatus, Schizachyrium sanguineum,* and *Panicum natalense.* This vegetation type supports a diverse herbaceous stratum that includes dominant species such as *Senecio venosus, Senecio coronatus, Acalypha angustata, Pearsonia cajanifolia* and *Vernonia oligicephala.* Afromontane affinities are also evident through the presence of species such as *Alloteropsis semialata.* Woody elements of Zambezian affinity occur as temperate mountain bushveld and include species such as *Rhus pyroides, Rhus magalismontana, Rhus rigida, Celtis africana, Vangueria infausta, Canthium gilfillanii, Englerophytum magalismontanum, Ancylobotrys capensis* and *Protea caffra* (Bredenkamp and van Rooyen, 1996).

Acocks (1988) maintaines that the climax of this vegetation type would have been characteristic of woodland or open savannahs dominated by *Acacia caffra* were it not for the regulatory role of fires. Unfortunately, this grassland type is under severe threat from urbanisation, industrialisation, mining and agriculture, especially in Gauteng. Very few reserves have been proclaimed or set aside to protect this vegetation type within the Gauteng province and only a mere 1,38 % is conserved, while approximately 65 % is already transformed (Bredenkamp and van Rooyen, 1996).

ERGO Daggafontein impoundment site

Prior to the establishment of the ERGO Daggafontein tailings impoundment, the vegetation on the site consisted mainly of short grassland and the cultivated areas were used to plant maize and beans. The typical plant species occurring presently on site are shown in Table 32.

Table 32: Plant species that occur on site.

Botanical name	**Common name**
Acacia karroo	Soetdoring
Acalypha angustata	
Asparagus suaveolens	
Berkheya radula	Boesmanrietjie
*Bidens pilosa**	Black jack
*Cortaderia jubata**	Pampas grass
*Cortaderia selloana**	Pampas grass
Crassula capitella	Plakkie
Cymbopogon pospischillii	Turpentine grass
Cynodon aethiopicus	Star grass
Cynodon dactylon	Couch grass or "kweek"
Cyperus spp.	Sedge
*Datura stramonium**	Common thorn apple
Digitaria eriantra	Smuts finger grass
Eragrostis curvula	Weeping love grass
*Eucalyptus sp.**	Blue gum
Hyperrhenia hirta	Common thatch grass
Hypoxis hemerocllidea	African potato
Juncus spp.	Sedge
Ledebouria spp.	Slime onions
Panicum maximum	Blue buffalo grass
*Pennisetum clandestinum**	Kikuyu
Pennisetum macrourum	Hippo grass
Phragmites australis	Common reed
*Tagetes minuta**	Tall khakiweed
*Tamarix ramosissima**	Pink tamarisk
Temeda triandra	Red grass or "rooi gras"
Typha capensis	Bullrush

* denotes exotic plant sepcie.

3.3.7 Wildlife

Birds

Some birds migrate seasonally to and from an area, while others are resident to the area. In dry and wet years birds may migrate to different areas, according to their foraging, breeding, resting and nesting needs. Rainfall therefore plays a major role in the distribution of birds in an area. At least 286 bird species have been recorded in the Blesbokspruit reserve. The Blesbokspruit supports significant numbers of waterfowl, including yellow-billed duck (*Anas undulata*), redbilled teal (*Anas erythrorhycha*) and spur-winged geese (*Plectropterus gambensis*) in the dry season, when water levels are maintained artificially at a high level. Water provides food for greater flamingo (*Phoenicopterus ruber),* lesser flamingo (*Phoenicopterus minor*) and goliath heron (*Ardea goliath*). Other notable birds include avocet (*Recurvirostra avosetta*), purple heron (*Ardea purpurea),* spoonbill (*Platalea alba*), gloss ibis (*Plegadis falcinellus*) and yellow-billed stork (*Mycteria ibis*). The African marsh harrier (*Circus ranivorus*), which has been displaced from veld areas, maintains a strong population here. Table 33 below lists the most common bird species likely to be found on site.

Table 33: Commonly occurring bird species.

Scientific name	**Common name**	**Scientific name**	**Common name**
Actitis hypoleucos	Common Sandpiper	*Lanius collaris*	Common Fiscal
Amadina erythrocephala	Red-headed Finch	*Larus cirrocephalus*	Grey-headed Gull
Anas capensis	Cape Teal	*Lybius torquatus*	Black-collared Barbet
Anas erythrorhyncha	Red-billed Teal	*Milvus [migrans] parasitus*	Yellow-billed Kite
Anas smithii	Cape Shoveller	*Motacilla capensis*	Cape Wagtail
Anas undulata	Yellow-billed Duck	*Netta erythrophthalma*	Southern Pochard
Anhinga rufa	African Darter	*Onychognathus morio*	Red-wing Starling
Apus caffer	White-rumped Swift	*Passer domesticus*	House Sparrow
Ardea cinerea	Grey Heron	*Passer melanurus*	Cape Sparrow
Asio capensis	Marsh Owl	*Phalacrocorax africanus*	Reed Cormorant
Batis molitor	Chinspot Batis	*Phalacrocorax lucidus*	White Breasted Cormorant
Bostrychia hagedash	Hadeda Ibis	*Phoenicopterus ruber*	Greater Flamingo
Bradypterus baboecala	Little Rush-Warbler	*Phoeniculus purpureus*	Green Wood-hoopoe
Bubulcus ibis	Catte Egret	*Plectropterus gambensis*	Spur-winged Goose
Burhinus capensis	Spotted Thick-knee	*Plegadis falcinellus*	Glossy Ibis
Centropus burchellii	Burchell's Coucal	*Ploceus capensis*	Cape Weaver
Ceryle rudis	Pied Kingfisher	*Ploceus xanthops*	Golden Weaver
Chlidonias hybrida	Whiskered Tern	*Porphyrio madagascariensis*	African Purple Swamphen
Chlidonias leucopterus	White-winged Tern	*Pycnonotus tricolor*	Dark-capped Bulbul
Cisticola fulvicapilla	Neddicky	*Recurvirostra avosetta*	Pied Avocet
Cisticola tinniens	Levaillant's Cisticola	*Saxicola torquatus*	African Stonechat
Colius striatus	Speckled Mousebird	*Scopus umbretta*	Hamerkop
Columba guinea	Speckled Pigeon	*Serinus atrogularis*	Black-throated Canary
Cypsiurus parvus	African Palm-Swift	*Spreo bicolor*	Pied Starling
Delichon urbicum	Common House-Martin	*Streptopelia capicola*	Cape Turtle-Dove
Dendrocygna bicolor	Fulvous Duck	*Streptopelia semitorquata*	Red-eyed Dove
Elanus caeruleus	Blacks-houldered Kite	*Tachybaptus ruficollis*	Little Grebe
Emberiza capensis	Cape Bunting	*Threskiornis aethiopicus*	African Sacred Ibis
Estrilda astrild	Common Waxbill	*Trachyphonus vaillantii*	Crested Barbet
Euplectes orix	Southern Red Bishop	*Tyto alba*	Barn Owl
Falco naumanni	Lesser Kestrel	*Tyto capensis*	African Grass-Owl
Fulica cristata	Red-knobbed Coot	*Upupa africana*	African Hoopoe
Gallinago nigripennis	African Snipe	*Urocolius indicus*	Red-faced Mousebird
Gallinula chloropus	Common Moorhen	*Vanellus coronatus*	Crowned Lapwing
Himantopus himantopus	Black-winged Stilt	*Vidua chalybeata*	Village Indigobird
Hirundo fuligula	Rock Martin	*Vidua macroura*	Pin-tailed Whydah
Hirundo semirufa	Red-breasted Swallow	*Zosterops capensis*	Cape White-eye

Mammals

Mammals are a group of fur-bearing animals that suckle their young and maintain constant body temperature by generating metabolic heat. Possibly the most outstanding feature of mammals is their extraordinary range of size, shape and habits. In this respect they are unique among all groups of animals. There are about five thousand species of mammals on earth, belonging to some 20 orders. Of these, only seven orders are still represented in the Eastern Gauteng area. They are:

- bats (small flying mammals);
- primates (highest order of mammals including man);
- hares (medium size mammals with short tails, long ears and hind legs longer than fore ones);
- rodents (small mammals such as mice and rats);
- carnivores (large flesh-eating mammals including cats and dogs);
- hyrax (small rabbit-like mammals); and
- insectivores (small long-snouted mammal feeding mostly on insects).

Table 34 lists some of the common mammal species that occur on site.

Table 34: Commonly occurring mammal species.

Specie name	**Common name**
Canis mesomelas	Black-backed Jackal
Cryptomys hottentotus	Common Mole-rat
Lepus saxatilis	Scrub Hare
Mastomys coucha	Multi-mammate Mouse
Raphicerus campestris	Steenbok
Rhabdomys pumilio	Striped Mouse
Sylvicapra grimmia	Common Duiker

Reptiles and amphibians

Over time, the reptile species have dwindled in both size and variety until, out of seventeen orders, only four are left:

- crocodilians;
- lizards;
- snakes;
- chelonians (tortoises and turtles); and
- amphibians.

Reptiles are characterized by their scaly integument. They are exothermic, which means their body remains at the same temperature as their surroundings. This distinguishes them from the higher classes of vertebrates, birds and mammals. Reptiles have come to occupy almost all available niches in their environment through some remarkable adaptations. Eastern Gauteng is no exception, and a variety of reptiles remain in this area. Some of the more commonly occurring species are listed below in Table 35.

Table 35: Commonly occurring herpetofauna.

Specie name	**Common name**
-	Worm Snake (various spp.)
Agama hispida	African Spiny Agama
Bufo gutturalis	Guttural Toad
Bufo rangeri	Raucous Toad
Cordylus vittifer	Transvaal Girdled Lizard
Dasypeltis scabra	Common Egg-eater
Duberria variegata	Southern Slug-eater
Geochelone pardalis	Leopard Tortoise
Gerrhosaurus flavigularis	Yellow-Throated Plated Lizard
Hemachatus haemachatus	Rinkhals
Lamprophis inornatus	Olive House Snake
Mabuya striata	Striped Skink
Pelomedusa subrufa	Marsh Terrapin
Psammophylax tritaeniatus	Striped Skaapsteeker
Pseudaspis cana	Mole Snake
Varanus niloticus	Water Monitor

Fish

Many species of fish live and breed in the rivers and its system of tributaries, in Eastern Gauteng. From time to time several of these species move up into the headwater streams which drain Eastern Gauteng. The different species described in this chapter are those which are commonly found here. More fish would probably occur here was it not for water pollution by humans, factories, mines and industries. Urban engineering in the form of concrete canals and sewers has also contributed to the paucity of both the numbers and variety of fish species. Table 36 below lists commonly occurring fish found in the rivers of Eastern Gauteng – confirmed by specialist input and Skelton (1993).

Table 36: Typical fish species that occur in the rivers of Eastern Gauteng.

Specie name	**Common name**
Anguilla bengalensis labiata	African Mottled Eel
Barbus spp.	Minnow (Various spp.)
Clarias gariepinus	Sharptooth Catfish
*Cyprinus carpio Linnaeus**	Carp
*Gambusia affinis**	Mosquitofish
Labeo capensis	Orange River Mudfish
Labeo umbratus	Moggel
Labeobarbus aeneus	Smallmouth Yellowfish
*Micropterus salmoides**	Largemouth Bass
Oreochromis mossambicus	Mozambique Tilapia
Pseudocrenilabrus philander	Southern Mouthbrooder

* denotes exotic fish specie

3.4 Visual

3.4.1 Introduction

This part of the research examines the visual impacts of tailings impoundments in order to express them in quantifiable terms rather than descriptive terms as it has not been done before and is required for inclusion in the overall costing system. The visual impact forms part of the overall environmental impact and engineering cost model for the rational evaluation of tailings impoundments with an emphasis on post-closure land use.

The overall environmental impact and engineering cost model provides a framework that:

- informs the planning and design process when considering tailings impoundment configuration alternatives;
- provides a platform for constructive discussion with relevant regulatory authorities; and
- provides a neutral basis on which to consult with stakeholders.

This study determines the level of visual perception over viewing distance within the zone of visual influence (ZVI) and utilizes the nominal group technique (NGT) study method. The technique is used to reach consensus on results within a field of study often considered to be subjective.

The research aims to determine the following three critical perception thresholds where:

- a viewer becomes aware of a deposit within the landscape;
- a deposit is detected as a man-made landform within the natural landscape; and
- a deposit is recognized as a tailings impoundment.

The thresholds are obtained through projecting computer simulated images with modified visual attributes such as shape, surface, size, and landscape type within a controlled environment. Analysis reveals average and specific thresholds of high reliability.

The NGT study method, a specific application of the Delphi technique, was applied using participants knowledgeable in this field to reach consensus on the thresholds. This NGT is one of many methods used for combining expert knowledge and is appropriate especially where intensive field sampling cannot be undertaken under prevailing time and cost constraints. All the participants were planning professionals and most were landscape architects with experience in environmental planning and visual impact assessment.

Viewing distance, context and landscape character are all factors that influence the visibility of a tailings impoundment. Intuitively the visibility of an impoundment will decrease with increasing viewing distance. An impoundment can either dominate an environmental setting (contrast significantly with the landscape character) or be dominated by elements within the landscape (be visually absorbed by the landscape).

3.4.2 Visual impact

Aesthetics is generally accepted to be a subjective matter. The Department of Minerals and Energy (DME) requires that a tailings impoundment should blend into the landscape and the visible portions of the impoundment suitably covered. The lack of specific regulation bears testimony to the difficulty in prescribing solutions, for what may be regarded as primarily, a subjective matter.

In part the research attempts to reduce this subjectivity and introduce a rational approach which can express the potential visual impacts in terms of cost and thus form a manageable component of the general engineering model.

Theoretically the problem is twofold:

- rational assessment of the potential visual impact of a proposed tailings impoundment (or that of an existing impoundment) eliminating the concepts of aesthetic value judgements; and
- conversion of the assessed or measured impact into a cost which can be compared with other environmental impact costs and accounted for in the total project costs.

The following section of the study concentrates on the former aspect of impact measurement. The cost aspect although only briefly discussed here is dealt with in more detail in Section 6.2 of the thesis.

3.4.3 Mitigation

Debate often arises when attempting to classify an impact as being significant or non-significant. Significant means "...an impact large enough to require consideration and possible mitigation...", while non-significant means "...too small to be worth consideration" (Stamps, 1997:250). This classification is important to the stakeholders responsible for implementing mitigation measures, as it could mean extensive financial commitments. Many environmental practitioners distort the purpose and implementation of mitigation. Any scheme should be seen as an extension of the existing landscape and should respect the local environmental context. Consequently, mitigation should be an iterative part of the design process in order to improve its success (Figure 99).

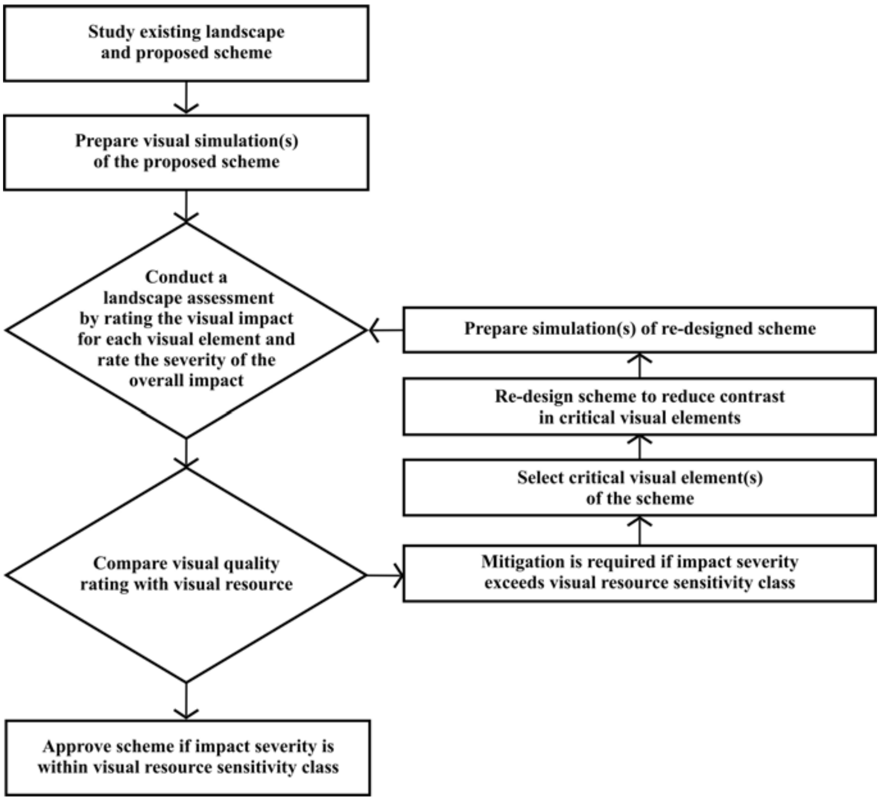


Figure 99: Mitigation procedure for a typical scheme (Smardon et al., 1986:216).

The purpose of mitigation is to avoid, reduce, and where possible, remedy or offset any significant adverse effects on the environment arising from a scheme. If integrated environmental planning and design principles are applied, together with a flexible approach to design, a high degree of mitigation can be proactively built into a scheme from the outset, thereby reducing the extent or scale of adverse effects (Landscape Institute, 2002:43).

Mitigation measures can be divided in two categories:

- Primary measures. An intrinsic part of the scheme design through an iterative process.
- Secondary measures. These specifically address the residual negative effects of the final scheme.

Mitigation is often relied on to reduce visual and also other impacts to acceptable levels. It is a common misconception that mitigation is remediative, attempting to resolve negative impacts once identified. The true value of mitigation can only be appreciated when it is part of an iterative integrated planning and design process.

Some of the more common mitigation measures include:

- the sensitive choice of site and location of an impoundment; and
- the choice of an appropriate configurations when designing a tailings impoundment.

Many tailings impoundments cannot be screened nor is it always desirable or practicable to do so. In such circumstances it is important to camouflage or disguise a scheme. Tailings impoundment design can incorporate visual attributes such as form (shape and size), line (silhouette), colour (shine, shadow and shade), and texture (surface) to reduce the visual influence and result in a landform that blends more readily into the landscape (Figure 100).

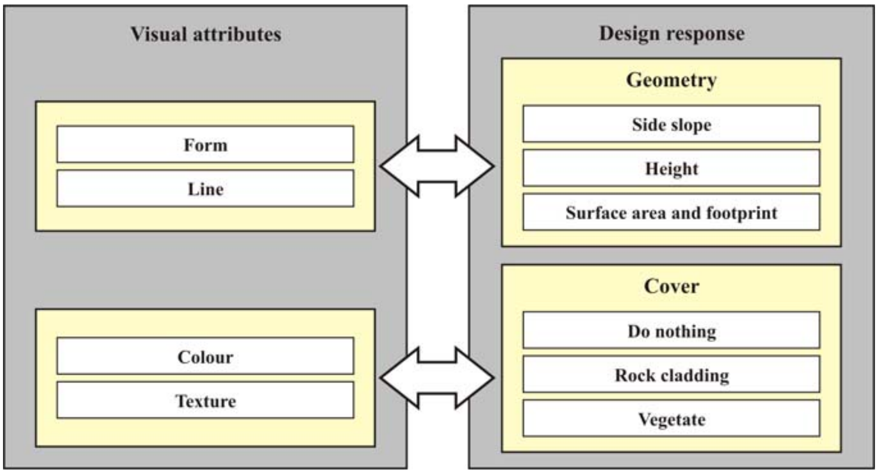


Figure 100: Visual configuration attributes and corresponding design responses for a tailings impoundment.

3.4.4 Study method

The visual zone of influence study method comprises the following steps and is covered in the section indicated in the subtitles:

Visualisation of various impoundment configurations (Section 3.4.5 to 3.4.8)

- Define the configurations to be visualised.
- Select a test impoundment.
- Photograph the test impoundment.
- Manipulate photographs to simulate different impoundment configurations.
- Present the visualisations to a panel of experts.

Analysis of data (Section 3.4.9)

- Analyse the results using the nominal group technique (NGT) and develop visual perception distance data for the various impoundment configurations.

Illustration of the results by example and confirmation of findings (Section 4.2.1)

- Apply the results in the field to test its efficacy.
- Confirm the results and findings by presenting such to a panel of experts.

3.4.5 Configurations

The final impoundment material layer can consist of the following:

- tailings in situ (no cover);
- topsoil (imported soil suitable to sustain plant growth);
- rock cladding (rip-rap); and
- armouring (cover consisting of a rock and soil mixture)

The vegetation cover on the tailings impoundment consists of:

- grass; and
- diverse vegetation (diversity of plant species).

An overall embankment slope of 1:3 (vertical to horizontal) is the current practice for most upstream deposited tailings impoundments. A 1:6 slope configuration was chosen as an alternative as it is considered to enhance vegetation establishment as well as to test the common opinion that flatter embankment side slopes reduces visual impact. The visual perception scenarios simulated for the study are summarised in Table 21 (p. 162).

3.4.6 Selection of test impoundment

In order for the study to deliver conservative results, a tailings impoundment representative of the typical impoundment height, shape, side slope configuration, and cover had to be located. It is also preferred that the test impoundment site should be within an environment with a low visual absorption capacity (low capacity to camouflage the visual impact of the impoundment). It was therefore important to find a landscape:

- with a relatively flat topography covered with typical grassland;
- which allowed direct lines of sight to the impoundment; and
- with little or no clutter caused by other visual elements.

The ERGO Daggafontein tailings impoundment complies with the criteria and was therefore chosen. The impoundment lies within a typical highveld grassland environment with a rural, relatively flat and rolling topography, minimal visual clutter as a result of man-made structures such as buildings, roads and transmission lines. Unobstructed photographs could be taken up to distances of 8 km. It is an exceptionally large tailings impoundment allowing the testing of worst-case scenarios and expecting conservative results. The impoundment is at different rehabilitation stages with a variety of surfaces.

This particular impoundment is one of the largest of its kind in the world and covers an approximate area of 450 ha extending for about 2,8 km along an east-west axis and 2,2 km along its north-south axis. It was designed as a free-standing upstream cycloned ring-dyke impoundment with the outer perimeter wall built from coarse cycloned underflow impounding the fine tailings overflow. The toe of the tailings impoundment at the south-western corner is also the lowest point with an elevation of about 1578 m.a.s.l. and a maximum height of about 68 m (Figure 86, p. 165).

The impoundment is in various stages of rehabilitation with the embankments slopes being mechanically flattened to an approximate step-in angle of 19° with 13 m vertical steps and 7 m wide benches. The flattened embankment slopes are covered with a mixture of topsoil and rock applied as armouring against wind and water erosion. It has been proposed to return the impoundment to a wilderness land use category once establishment with grass (Wates et al., 2001).

The impoundment is surrounded by agricultural land used for grazing and cultivation of maize, sunflowers and beans. The Blesbokspruit and associated wetlands are located to the West. A tributary to the South joins the Blesbokspruit at the northern boundary of the Maryvale bird sanctuary. The regional topography is fairly flat and rolling with the site sloping gently in a westerly direction towards the Blesbokspruit (Figure 101).

[1] Looking north-east over ERGO Daggafontein tailings impoundment.

[2] Looking South towards ERGO Daggafontein tailings impoundment. Photographs [1] and [2] with courtesy of AngloGold Ashanti.

Figure 101: Landscape setting of the ERGO Daggafontein tailings impoundment.

3.4.7 Photography of test impoundment

The ERGO Daggafontein tailings impoundment was photographed from distances ranging between 800 m and 8300 m. Global positioning system (GPS) points were taken around the base of the impoundment with a Garmin eTrex Personal Navigator GPS and photographs were then taken in a straight line from the GPS points to the impoundment (Figure 102) providing distance readings.

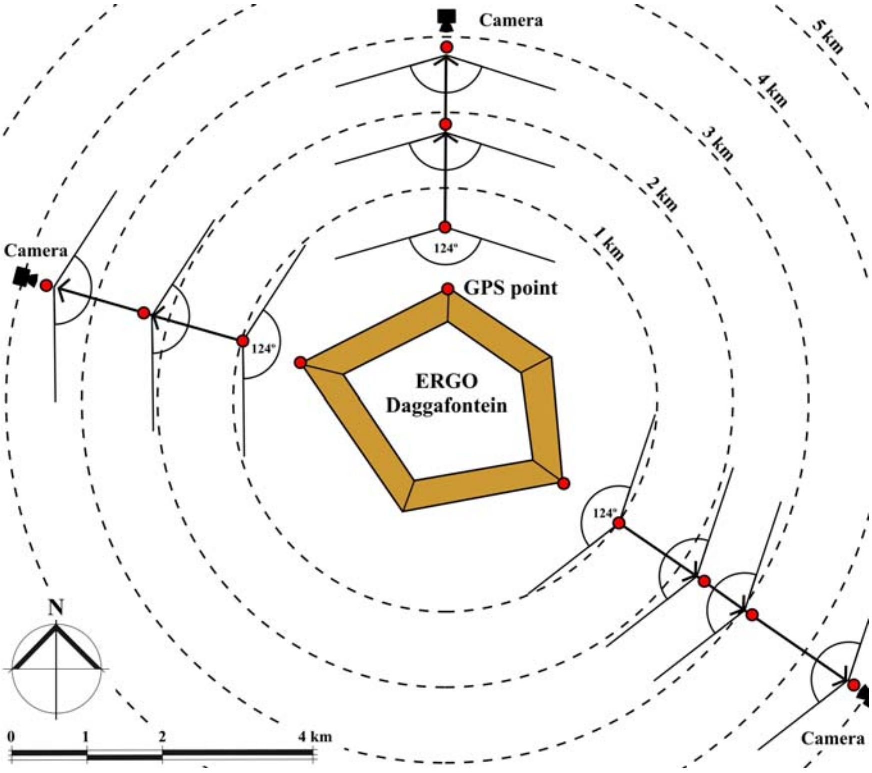


Figure 102: The test impoundment was photographed at various distances.

Effort was made to exclude major interfering man-made structures such as roads, masts and buildings in order to keep the photographs uncluttered. However, minor elements such as power lines, fences and farm buildings appear in some of the photographs. A Sony Cybershot P-92, 5 mega pixel high resolution digital camera was used in this study to give maximum clarity for computer manipulation and projection purposes.

Two sets of photographs were taken; one during late summer (13 May 2004) and the other during late winter (15 August 2004) since the surrounding landscape changes as a result of farming practices and seasonal changes.

Haze and smog experienced early in the day as a result of pollution and atmospheric conditions necessitated that photographs be taken late mornings on clear days. Photographs 1 and 2 in Figure 103 to Figure 105 indicate the same views during summer and winter respectively with the effect of smog clearly visible in the photographs taken during winter. Figure 103 (p. 195) compares two photographs of one of Grootvlei Proprietary Mine's impoundments taken from the same viewpoint and is a good example of the influence of seasonal change on visibility.

Figure 103: Looking South to a Grootvlei Proprietary Mine tailings impoundment.

Figure 104 and Figure 105 are both of the ERGO Daggafontein tailings impoundment and illustrate the influence of seasonal change on the visibility of an impoundment in the landscape. The dashed red lines are included to indicate the outline of the impoundment in the photographs.

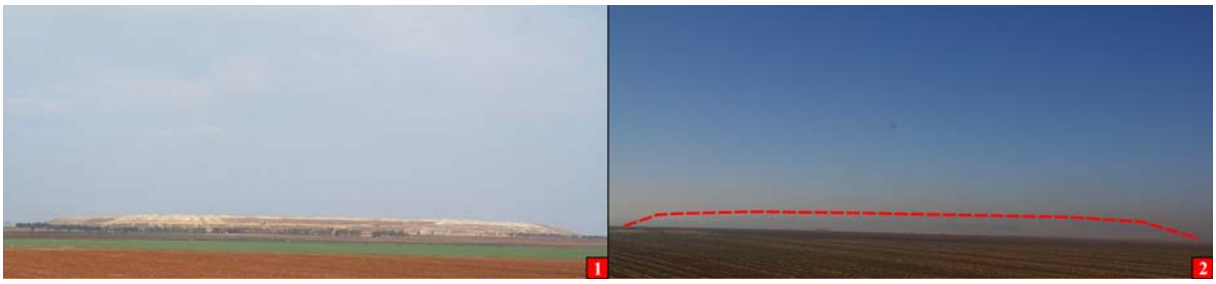


Figure 104: Looking south-east towards the ERGO Daggafontein tailings impoundment.

Figure 105: Looking north-west towards the ERGO Daggafontein tailings impoundment.

Photograph panoramas were composed by (Figure 106, p. 196):

- using a high resolution camera placed at eye level on a tripod to take the photographs;
- taking enough photographs to cover the 124º binocular human field of vision;
- expressing as much as possible of the vertical dimension of the scene within this field by taking photographs in portrait format;
- stitching the photographs together using PixMaker Pro (Developer Edition) Version 1,0; and
- cropping the stitched photographs into the final photograph panorama format for further electronic manipulation.

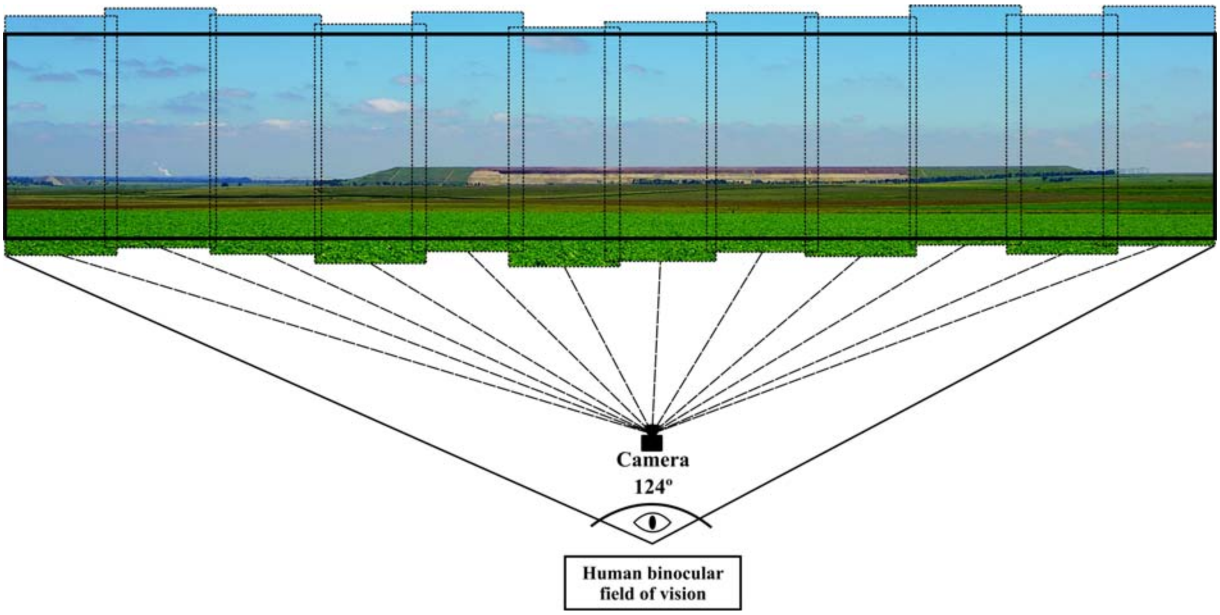


Figure 106: Photographs taken to form a 124° panorama scene.

3.4.8 Manipulation of site photographs

From the various visualisation techniques referenced, manipulating photographic panoramas is the most suitable approach within the context of this study. The methodology to evaluate different impoundment configurations has to be simple, time efficient, and reliable. Enough photographs of the ERGO Daggafontein tailings impoundment were taken making sure that a library of textures could be compiled and the appropriate ones isolated for later use. These textures were superimposed on to ERGO Daggafontein tailings impoundment photograph panoramas thus manipulating images directly and visualising different impoundment configurations (Figure 107 to Figure 109). This was done by retouching or painting the desired textures and colours utilising a photo editing software package such as Adobe Photoshop 7.0 onto the original photo image. Sixty-eight different tailings impoundment configurations were graphically produced and presented to a panel of experts who evaluated the different visualisations through the NGT study method.

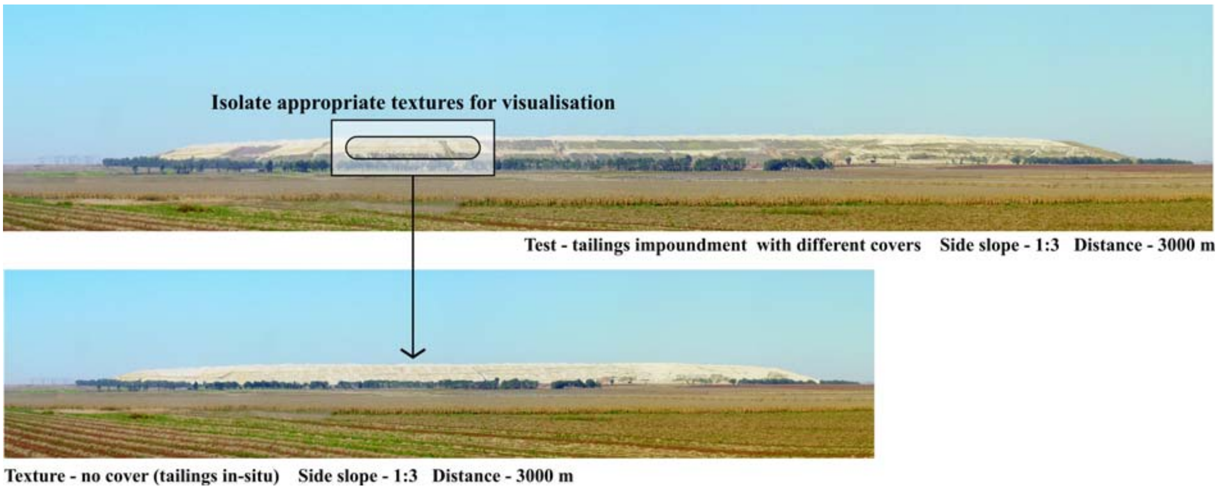


Figure 107: Visualisation of impoundment with no cover.

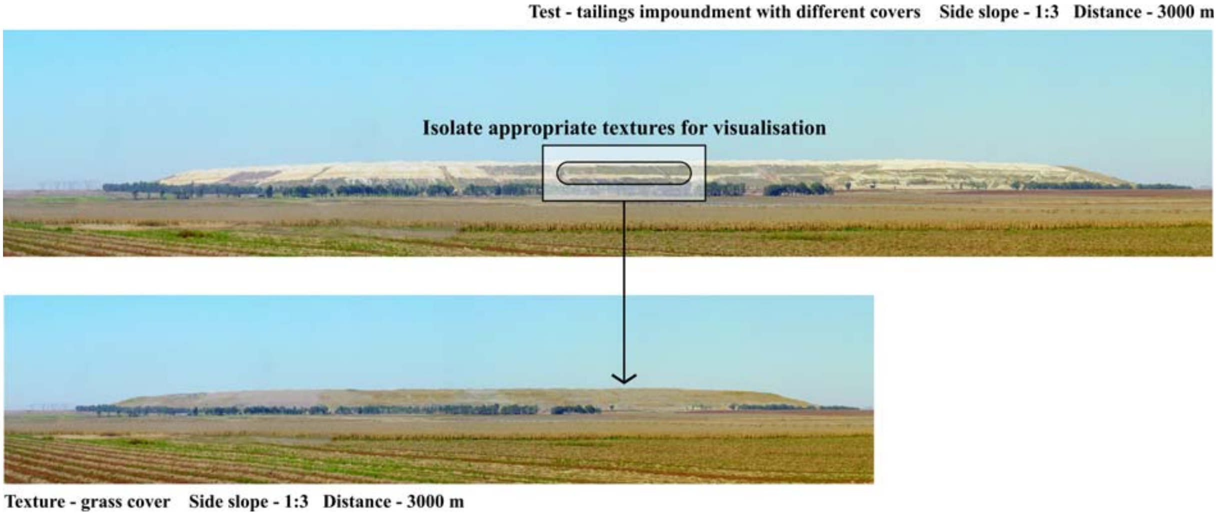


Figure 108: Visualisation of grass covered impoundment.

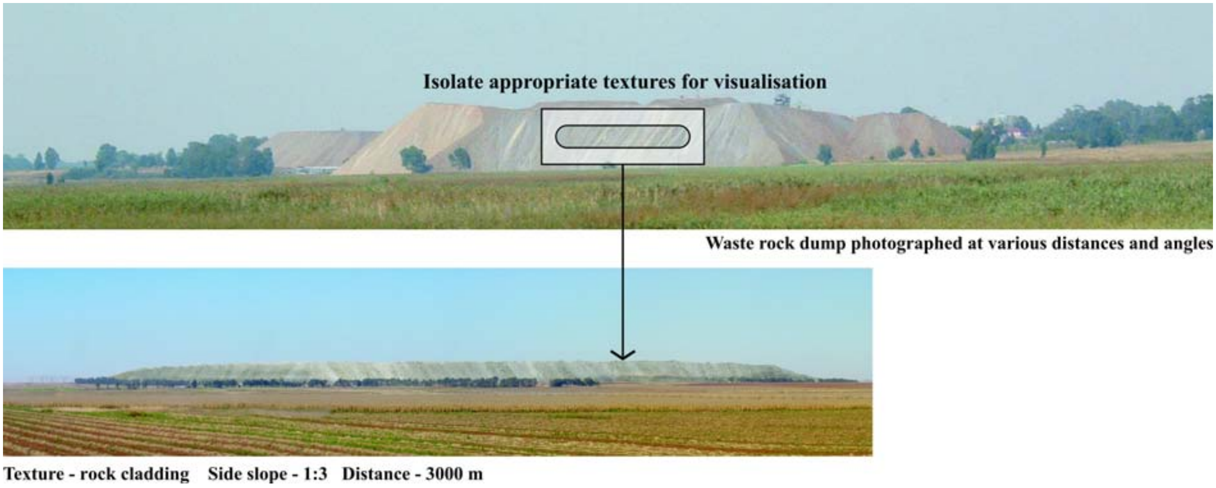


Figure 109: Rock-clad tailings impoundment visualisation.

Photo manipulation (the electronic visual photo simulations or also referred to as visualisations) could be done with high precision and in less time relative to the other techniques discussed in Section 2.10.2. Photographic manipulation of panoramas was also made possible because the impoundment was in various stages of rehabilitation allowing isolation of different covers at various distances. It was therefore possible to isolate textures from areas previously grassed, covered with rock armouring, and uncovered tailings impoundment and apply these photo realistically to the test impoundment at various distances. The greatest challenge was to portray the appropriate colours and textures of the various covers at the viewing distances reliably. The required haze factor could also be realistically applied.

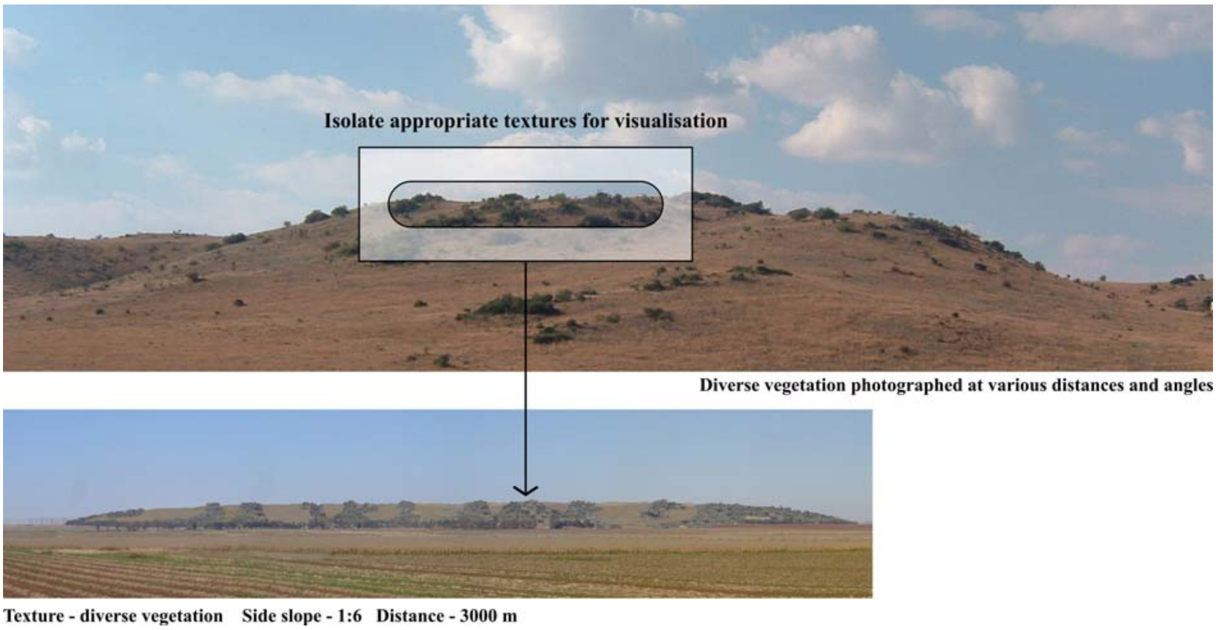


Figure 110: Visualisation of tailings impoundment covered with diverse vegetation.

The manipulated photo simulations could then be viewed using a 15" Proline Crystal View 7Klr computer monitor fitted with a NVIDIA GeForce 2MX/MX 400 graphics card. It is important that the size of the image on the screen must relate to the apparent size a viewer would see in the field at the particular view distance. Equation 31, 32 and 33 were applied assuming that the viewer's head would be approximately 0,45 m from the computer monitor.

$$Tan(\beta_1 / 2) = s_1 / 2d_1 \tag{31}$$

and

$$Tan(\beta_2 / 2) = s_2 / 2d_2 \tag{32}$$

where

$$\beta_1 = \beta_2$$

therefore

$$s_2 = s_1 . d_2 / d_1 \tag{33}$$

By keeping the visual angle the same the size of the impoundment on the screen could be calculated to represent the visual magnitude at that specified distance (Figure 111).

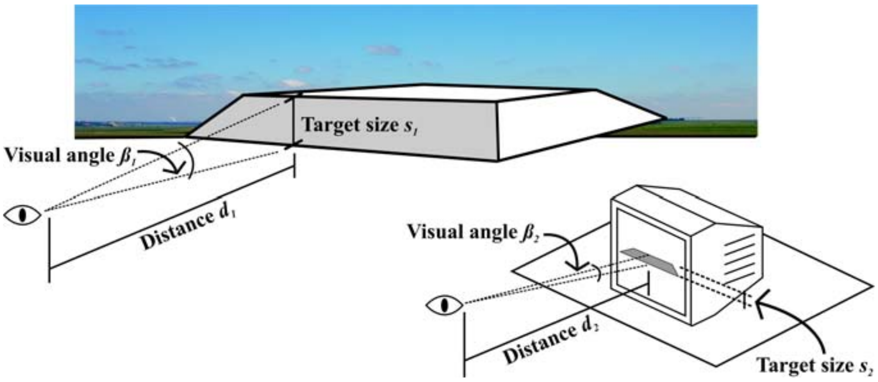


Figure 111: Determining the computer screen viewing target size.

3.4.9 Assessment of visualisations

The nominal group technique (NGT) study method is an application developed from the Delphi technique and was used to assess the visualisations and develop the visual perception distance curves. Delphi was the name of a site in ancient Greece where Oracles (people through whom a deity was believed to speak) met, held discussions and made wise and authoritative decisions. The United States Air Force first applied the modern day Delphi process to a strategic planning exercise in about 1953 (Dalkey and Helmer, 1963). More recently it has been applied to reach expert-opinion-based consensus on qualitative research aspects.

Crance (1987:1) states that a Delphi exercise is based on the premises that:
- opinions of experts are justified as inputs to decision making where absolute answers are unknown;
- consensus of a group of experts provide a more accurate response to a question than a single expert; and
- the process is repeatable and is used by researchers to produce defendable data.

If these assumptions are valid or acceptable to those that will receive and act on the product of the exercise, the conclusions reached should have value. Civil engineers have used this technique, albeit less formally, for the quality assessments of work for a long time such as road pavement surveys.

Both the Delphi technique and its derivative, NGT, are tools that assist researchers in generating a base for evaluation. They are methods designed to:
- increase the creative productivity of group action;
- facilitate group decision;
- help stimulate the generation of critical ideas; and
- give guidance in the aggregation of individual judgements.

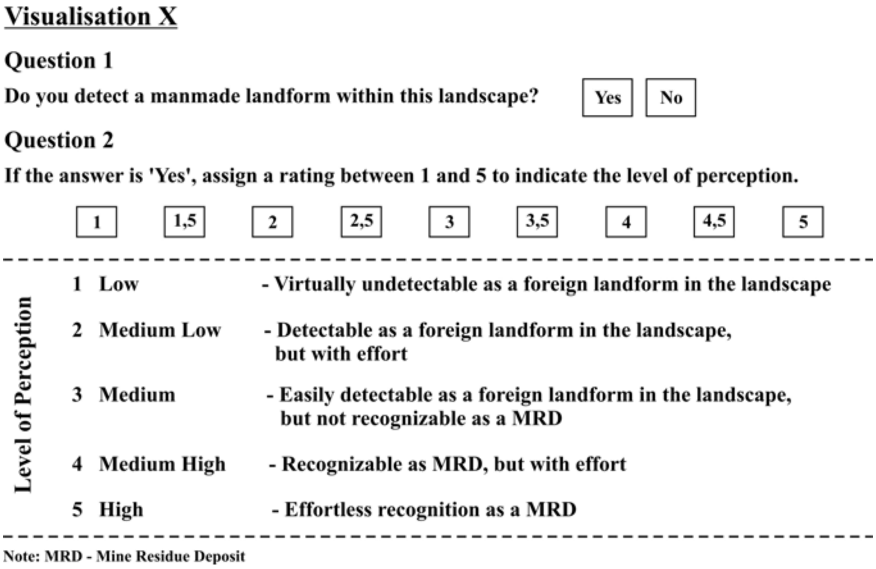
The NGT takes the form of a structured group meeting which follows a prescribed sequence of problem-solving steps. The process is described in detail by Delbecq, van den Ven and Gustafson (1975:43) and employs face-to-face meetings and discussions by knowledgeable participants to obtain and combine expert opinion in order to reach consensus. The advantage of using the NGT approach is that, if the participants have the time and are within reasonable travelling distance, the information can be collected rapidly. However, the Delphi technique is applied where experts are not readily available or not within close proximity and has to be polled through electronic or other means of correspondence.

Although the NGT can accommodate large numbers of participants, Delbecq et al. (1975:26) recommends a limit of approximately nine members. Crance (1987:2) states that a panel of ten experts is probably ideal but that more than ten may be used if desired.

For this project names were found through contacting and asking engineering consultancies whom they consider as experts within the field of aesthetics and visual analysis. Each of these potential panellists was asked to participate and recommend someone whom they considered to be highly knowledgeable; the process was repeated until no new names were suggested. Twelve experts participated in the study. Nine were landscape architects with specific expertise in the field of visual impact assessment and the other three were in the engineering or architectural planning professions. Appendix A.1 contains the particulars of each panellist whom participated in the NGT study.

The iterative decision-making process during the NGT study followed the steps recommended by Crance (1987:2):

- the experts were polled on the visualisations by capturing their independent ratings in writing and without discussion (Figure 112);
- the responses were keyed into an MS Office Excel spreadsheet and the results were presented back to the experts using graphs; and
- the group of experts re-evaluated their initial ratings in light of the information generated by the aggregate responses until consensus was reached among the respondents.



Visualisation X

Question 1

Do you detect a manmade landform within this landscape? ☐ Yes ☐ No

Question 2

If the answer is 'Yes', assign a rating between 1 and 5 to indicate the level of perception.

☐ 1 ☐ 1,5 ☐ 2 ☐ 2,5 ☐ 3 ☐ 3,5 ☐ 4 ☐ 4,5 ☐ 5

Level of Perception

1	Low	- Virtually undetectable as a foreign landform in the landscape
2	Medium Low	- Detectable as a foreign landform in the landscape, but with effort
3	Medium	- Easily detectable as a foreign landform in the landscape, but not recognizable as a MRD
4	Medium High	- Recognizable as MRD, but with effort
5	High	- Effortless recognition as a MRD

Note: MRD - Mine Residue Deposit

Figure 112: Example of questionnaire to assess each visualisation.

The initial rating of the 67 (Table 37) visualisations was undertaken individually. Each visualisation had a 15 second lapsed time indicator to remind the panellist to finalise the viewing of the particular slide as well as capture comments and ideas in writing and proceed to the next slide. The individual judgements were pooled, collated, summarised and presented to the group, ending the first iteration.

Table 37: Breakdown of visualisations by slope, season and cover.

Total Visualisations (67)

1:3 Side Slope (37)										1:6 Side Slope (30)									
Summer (11)					Winter (26)					Summer (10)					Winter (20)				
T	G	R	Tl	D	T	G	R	Tl	D	T	G	R	Tl	D	T	G	R	Tl	D
3	2	2	2	2	10	4	4	4	4	2	2	2	2	2	4	4	4	4	4

T – Test G – Grass R – Rock Tl – Tailings in situ (no cover) D – Diverse vegetative cover

During the second iteration panellists were given the opportunity to discuss the findings within a structured group discussion process. In light of the results generated by the collective responses to the first iteration the group then sequentially discussed, verbally clarified and eliminated misunderstandings, provided logic behind arguments and disagreements, recorded differences of opinion and lastly re-evaluated each slide in turn until consensus and an acceptable level of agreement was reached. The results and their interpretation are given in Section 4.2.

3.5 Air

3.5.1 Introduction

The aim of the fugitive impact modelling was to determine the area of impact due to wind blown dust from tailings impoundments in terms of nuisance and human health impacts. The air quality impact potential of dust from tailings impoundments depends on:

- the amount of material being entrained from the impoundment;
- the dispersion potential of the material in the atmosphere;
- its removal by deposition; and
- its proximity to sensitive receptors.

Fugitive dust emission rates, atmospheric dispersion potential and deposition rates are largely a function of:

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

In order to quantify the emissions and determine the potential impacts the following methodology was followed:

- Estimate emission rates from a gold tailings impoundment using the airborne dust dispersion from area sources (ADDAS) model.
- Determine the dispersion of wind entrained dust using the US EPA approved Industrial Source Complex Short Term (ISCST3) dispersion model.
- Plot the areas of impact as isopleths, i.e. contours, using Surfer. Surfer supports the import of data from a number of applications to generate contours. It generates contour maps of surface plots and was used in this study to calculate surface area of influence in hectares.

The following air quality modelling objectives have been set:

- to quantify the air quality influence zone for various tailings impoundment configurations;
- determine the environmental cost for resulting zones of influence; and
- compare the different configuration cost results and draw conclusions.

3.5.2 Calibrating the emission estimation software

During the initial runs to estimate the emissions for various impoundment scenarios using the Airborne Dust Dispersion from Area Sources (ADDAS) software package it became apparent that:

- the software requires the user to input physical characteristics of the tailings impoundment; and
- the roughness height input parameter required calibration.

ADDAS is a software programme developed by Airshed Planning Professionals for ESKOM, South Africa’s largest provider of electricity, to estimate the emissions from residue deposits. The equations used in the ADDAS model and described in Section 2.11.4 requires various source specific input. ADDAS quantifies an emission rate for every hour of the period for which meteorological data is provided. For the purpose of the roughness height calibration, a period of one year of meteorological data was used. This included hourly wind speed, wind direction and temperature data. Stability classes and mixing depths are then calculated for each hour. The hourly emissions file generated by ADDAS and the meteorological data are then used as input into the dispersion model.

It was realised that an impoundment with available and reliable dustfall monitoring data must be used to calibrate the surface roughness height input parameter in ADDAS. The DRD 2L24 impoundment of Durban Roodepoort Deep (DRD) was selected for the purpose as:

- dust fallout monitoring data from around the impoundment was available to assist with the calibration;
- the impoundment has a low percentage cover; and
- permission to access the site was granted by DRD in order to take samples of the cover material for characterisation.

1 Looking East over a section on the top surface of the DRD 2L24 tailings impoundment which had been ridge ploughed.

2 Dune formation downwind of one of the compartments of the DRD 2L24 tailings impoundment.

Figure 113: DRD 2L24 tailings impoundment top surface.

All source parameters could be obtained through physical measurements and sample analysis except for the surface roughness height. It was therefore decided to calibrate the surface roughness height by using different roughness heights while keeping the rest of the inputs the same and then comparing the predicted dust fallout levels to actual measured dust fallout data.

1 Looking north-west towards the southern slope of the south-western compartment of the DRD 2L24 tailings impoundment.

2 Looking East towards the western side of the DRD 2L24 tailings impoundment showing the remains of a vegetation trial area. The remainder of the slope is characterised by deep erosion gullies (photograph courtesy of SEF).

Figure 114: Views of the DRD 2L24 tailings impoundment embankment.

The DRD tailings impoundment offered the perfect site to assist with the calibration of the roughness height. DRD currently operates 23 dust fallout buckets located around the tailings impoundment. Seven of these dust fallout buckets have been operational since November 2002 with 7 new buckets installed during September 2005.

In order to calibrate the roughness height parameter samples were taken from the DRD 2L24 impoundment to determine the physical characteristics of the tailings. Once the physical material characterisation was complete a process of iterative re-estimation of fugitive dust emissions was undertaken until the modelled dispersion zone of influence correlated with the dust fall monitoring data collected from the single bucket fallout monitors.

DRD 2L24 environmental setting

The DRD 2L24 impoundment lies directly North of Soweto and South of Roodepoort on the western outskirts of Johannesburg, Gauteng (Figure 115, p. 203). The impoundment is located 1 500 m East of the R558 and 2 500 m South of the R41. The site falls within the jurisdiction of the City of Johannesburg Local Municipality and the approximate site co-ordinates are 26°11’57,2” S and 27°50’21,6” E. The impoundment was constructed on DRD mining land and is no longer operational. Sections that had previously been vegetated are either showing signs of stress or have died off completely resulting in an impoundment that is largely uncovered. It is estimated that the percentage cover on the side slopes are less than 30 %.

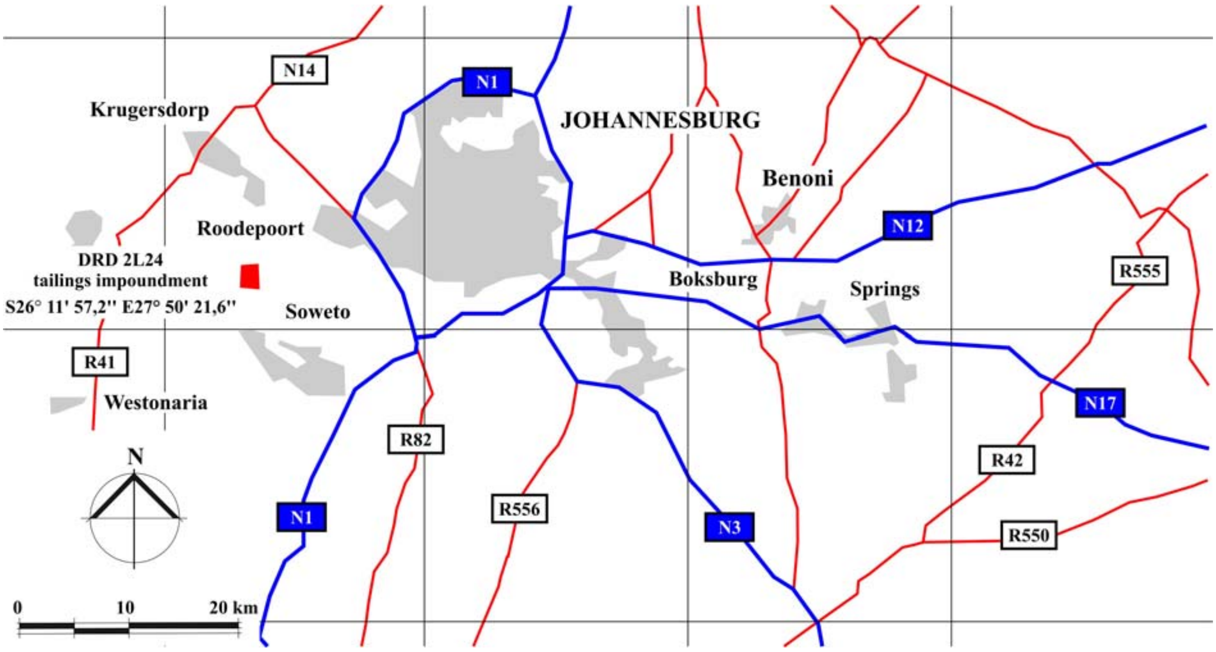


Figure 115: Regional locality of the DRD 2L24 tailings disposal facility.

The impoundment is situated along the mining belt that forms the transition between Soweto and Roodepoort. Bram Fischerville township extensions surround the impoundment (Figure 117, p. 204) and Meadowlands and Dobsonville, suburbs of Soweto, lie approximately 2,5 km to the south-east.

Surrounding environment

The location and land use of the impoundment is important as it can impact on both current and future surrounding land use. The area has a typical Highveld climate characterised by warm, wet summers and cool dry winters. The summer rainfall averages between 650 – 750 mm/annum and temperatures range from 12°C to 39°C with an average of 16°C (Bredenkamp and van Rooyen, 1996). The site is surrounded by township establishments and typical Highveld grassland most suitable for grazing with some areas suitable for arable agriculture. Acocks (1988) describes the vegetation as the northern variation of Cymbopogon-Themeda veld. Low and Rebello (1996) refer to this veld as Moist Cool Highveld Grassland.

The open veld surrounding the impoundment is degraded and has low species diversity. Species such as *Seriphium plumosum*, *Tagetes minuta*, *Bidens pilosa*, and *Stoebe vulgaris* occur and is indicative of overuse and disturbance. Alien invasive species such as *Cortaderia selloana* (pampass grass), *Acacia dealbata* (silver wattle) and *Eucalyptus sp*. (blue gum) occur within the impoundment site. Land surrounding the impoundment shows no evidence of sensitive habitats or species of conservation concern and since no ecologically significant landscape elements occur it is unlikely that any sensitive or protected species will be found. The site is thus considered to be of low ecological and conservation value.

[1] Looking East towards Bram Fischerville township extensions surrounding the DRD 2L24 tailings impoundment.

[2] A view towards the toe of the impoundment with the low cost houses, typical of Bram Fischerville, in the foreground (photograph courtesy of SEF).

Figure 116: DRD 2L24 tailings impoundment environmental setting.

There are no prominent geomorphological features in the study area and the landscape undulates slightly in the northern parts of the study area decreasing in height towards the South. The Klip river floodplain is situated to the West of the impoundment.

Figure 117: Current and proposed extensions of Bram Fischerville adjacent to the DRD 2L24 impoundment.

Rainfall

Rainfall data for the site was obtained from the Roodepoort weather station (Figure 118). The mean annual rainfall for the area is 721,4 mm and falls mainly in the summer between October and March in the form of thunderstorms. The wettest month of the year is January with an average rainfall of 128,4 mm. On average January also has the largest number of days with rain and the most rainfall recorded in a 24 hr period was 163,5 mm. The driest month is June with an average of 6,7 mm.

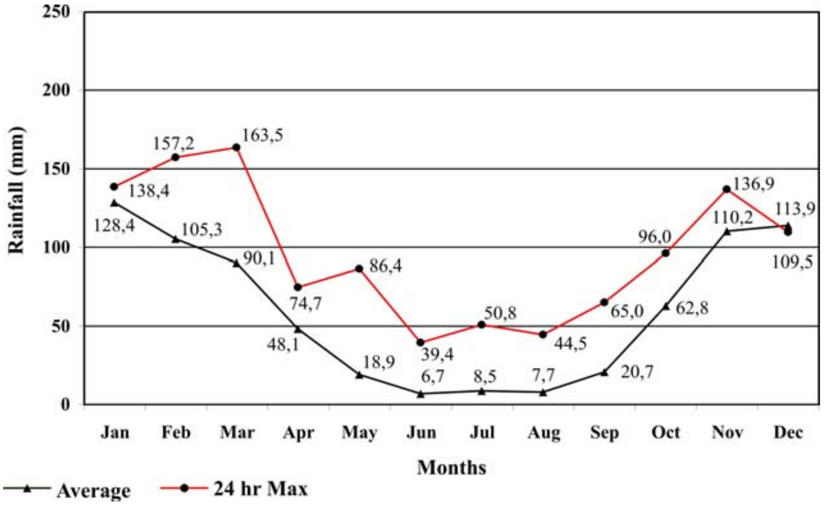


Figure 118: Monthly rainfall data for the Roodepoort weather station.

Temperature

The impoundment falls within a climatic region that experiences moderate fluctuations in seasonal temperature (Figure 119).

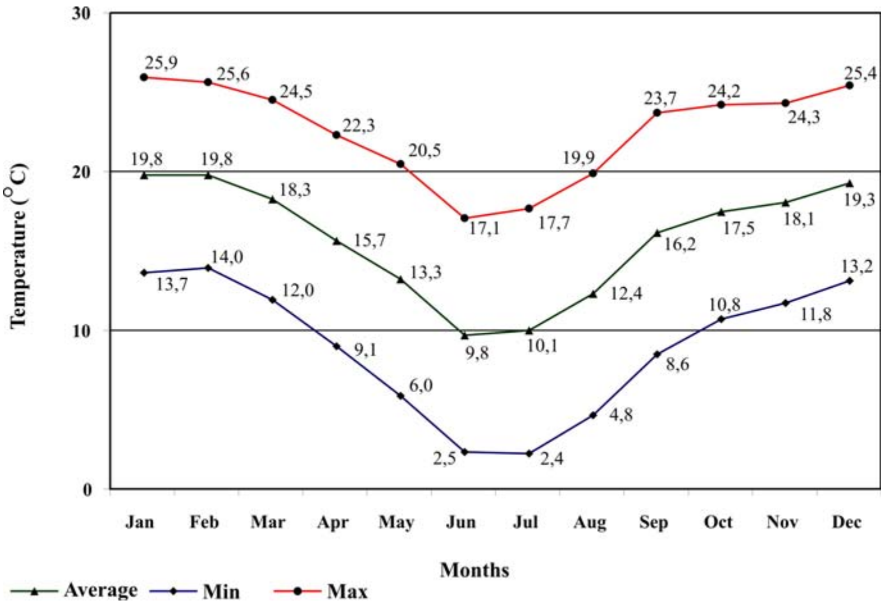


Figure 119: Temperature data for the Roodepoort weather station.

October to March reflect a mean temperature range of between 17 °C and 20 °C with the warmest temperatures occurring during January and February. Temperatures range between 9 °C and 17 °C for the months April to September with June being the coldest month of the year. The site is affected by temperature inversions during winter nights (where cold air is trapped near to the surface) so that the temperature increases with height. Temperature inversions also trap pockets of pollution close to the surface.

Wind

The wind speed does not vary much throughout the year. The winds most frequently occurring blow from the North and north-west and winds blowing from the south-east are the least frequent. Frequency statistics indicate that August, September and October are the windiest months. For approximately 30% of the year, little or no wind is experienced. Generally winds are light except for short periods during thunderstorms.

Summary

The impoundment is a prominent man-made landform within the surrounding landscape showing signs of both wind and water erosion. Sheet, rill and gully erosion off the side slopes is visible and it can be expected that erosion will increase with the decrease in cover. This is not surprising as the impoundment:

- is not suitably shaped and covered to prevent erosion from taking place;
- lies within a region that experiences heavy rainfalls in summer resulting in increased runoff; and
- is located in an area where the dominant north-westerly wind has the potential to liberate dust from the impoundment impacting on land use to the East and south-east.

DRD 2L24 source characteristics

The purpose of determining the tailings impoundment's physical and chemical properties is to establish the material’s wind erosion and toxicity potential and hence the air quality zone of influence. Information regarding the characterisation guided the choice of parameters which needed further investigation. Nine grab samples were taken at different strategic points on the DRD 2L24 tailings impoundment and analysed using:

- laser diffraction to determine the physical characteristics; and
- X-Ray fluorescence to determine the chemical characteristics of the tailings.

Physical characteristics

Emissions from impoundments depend on various factors such as:

- the prevailing meteorological conditions; and
- the physical properties of the exposed surface material, i.e. the material covering the surface of the impoundment.

The latter is the topic of this section. The overall objective of the sampling and analysis program is to determine the:

- nature of the source;
- percentage of exposed surface area; and
- type of material on the DRD 2L24 impoundment.

This is done by:

- collecting representative grab samples of the material;
- analyzing the samples to determine the physical properties; and
- combining analytical results with material throughput and meteorological information in an emission factor model.

The nine samples collected were analysed for:

- particle size distribution;
- clay content; and
- moisture content.

Collecting grab samples

Effort was made to take representative samples from the following exposed surfaces of the impoundment:

- the top surface;
- the middle embankment side slope; and
- the bottom of the impoundment.

The sampling positions are indicated on Figure 121, and the coordinates included in Table 38. The following procedure was used to collect samples from the DRD 2L24 tailings impoundment (US EPA, 1995):

- A sketch plan and aerial photograph of the impoundment was studied to determine if any portion of the impoundment is not accessible. The plan was also used to identify possible sampling points. The US EPA recommends that a minimum of 6 samples must be taken.
- The material was collected with a small garden spade, and stored in a clean, labelled container of suitable size with a sealable lid (Figure 120, photograph 1). The container size was amenable to the SGS South Africa (Pty) Ltd. laboratory analysis requirements.
- The samples were collected by skimming the surface in an upwards direction. Sampling did not exceed a depth of 2,5 cm and did not avoid collecting larger pieces of aggregate present on the surface.
- The required information was recorded on a sample collection sheet.
- The sampling coordinates were captured using a geographical positioning system (GPS) and indicated on a map.

[1] A garden spade was used to skim tailings from the top surface in an upward direction and not exceeding a depth of 2,5 cm.

[2] Typical close-up view of the impoundment surface denude of vegetative cover.

Figure 120: Sampling of tailings for particle distribution analysis.

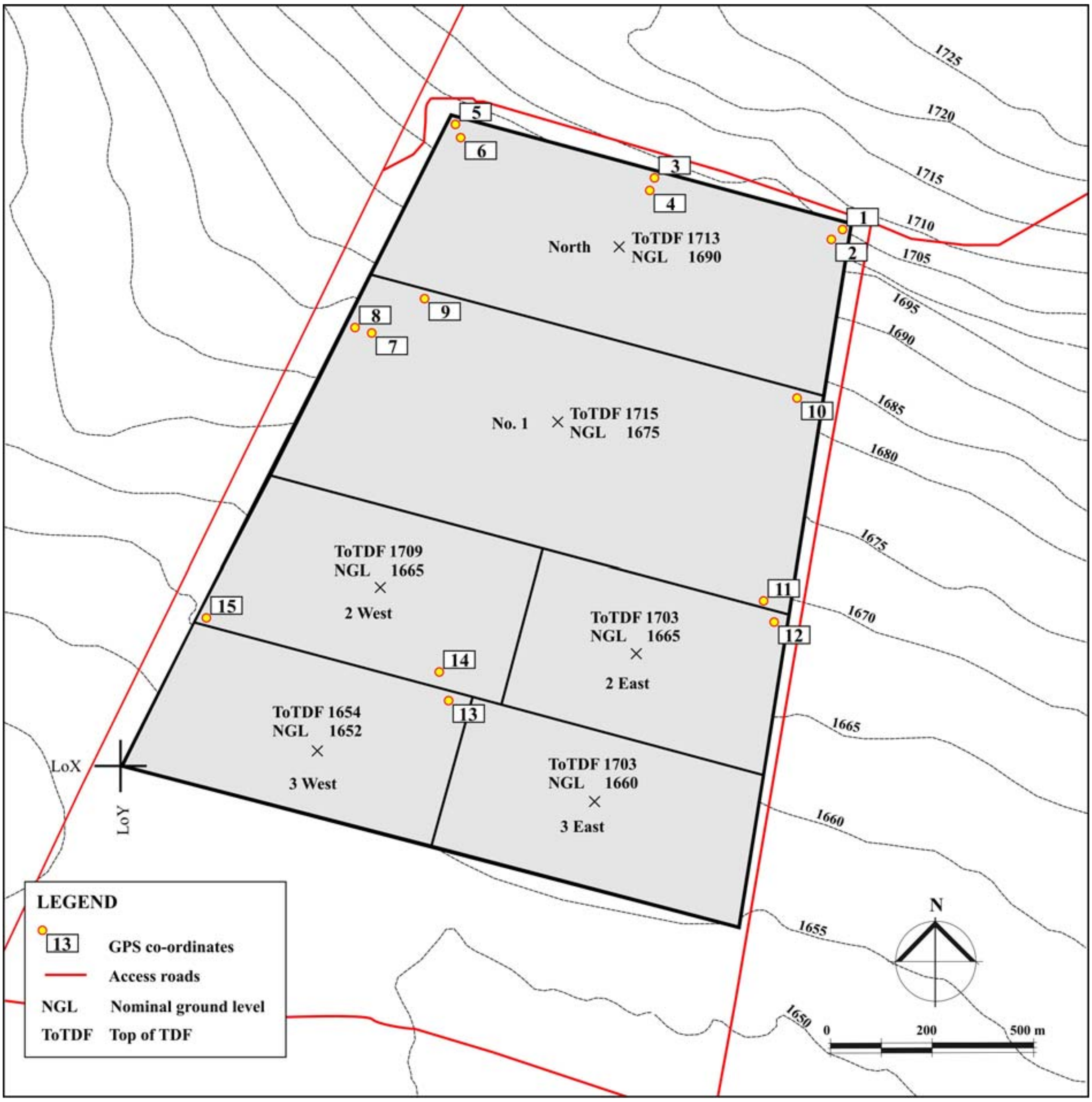


Figure 121: DRD 2L24 layout plan indicating the sampling points.

The sampling method can be summarised as follows:

- <u>Sampling device</u>: Collect increments by skimming the surface in an upwards direction using a garden spade.
- <u>Sampling depth</u>: Do not skim the surface deeper than 2,5 cm and do not avoid collecting larger pieces of aggregate present on the surface.
- <u>Sample container</u>: Use a clean plastic bottle with tight fitting lid to place the tailings in.
- <u>Gross sample specifications</u>: Sampling for wind erosion purposes requires at least 6 samples.

Table 38: GPS points and coordinates of the DRD 2L24 tailings samples.

		Latitude	**Longitude**
Sample number	**GPS Point**	**South**	**East**
	1	26° 11' 42,96"	27° 50' 41,16"
	2	26° 11' 43,26"	27° 50' 40,44"
1	**3**	26° 11' 38,76"	27° 50' 22,92"
2	**4**	26° 11' 40,26"	27° 50' 22,98"
	5	26° 11' 35,46"	27° 50' 7,56"
	6	26° 11' 36,12"	27° 50' 7,56"
3	**7**	26° 11' 55,74"	27° 50' 1,50"
4	**8**	26° 11' 54,24"	27° 49' 59,76"
5	**9**	26° 11' 49,50"	27° 50' 8,34"
6	**10**	26° 11' 57,00"	27° 50' 35,94"
7	**11**	26° 12' 11,88"	27° 50' 35,76"
	12	26° 12' 11,94"	27° 50' 35,76"
8	**13**	26° 12' 20,52"	27° 50' 10,26"
9	**14**	26° 12' 16,38"	27° 50' 8,10"
	15	26° 12' 14,70"	27° 49' 45,72"

Physical characterisation of the grab samples

The objective of the physical characterisation of the tailings material is to determine the following parameters:

- particle size distribution;
- bulk density;
- roughness height;
- particle density;
- fractions of impoundment surface area open;
- clay content; and
- moisture content.

Particle size distribution

When characterizing a material's particle size it is important to assess whether the chosen method of analysis is fit for the purpose. This requires the analyst to determine which parameters are critical to quality, i.e. why size analysis must be performed, and whether the chosen size analysis technique can be used to assess these. Within this the robustness of the technique must also be assessed, both as part of the process of determining if the technique can be reasonably applied, and for the purposes of specification setting. Laser diffraction, more correctly called Low Angle Laser Light Scattering (LALLS), is a widely used method used for analysing particles ranging from 0,05 µm to 3,5 mm. The basic principle is that the diffraction angle is inversely proportional to particle size and the instrument consist of:

- A laser of coherent intense light of fixed wavelength. He-Ne gas lasers are most common with a wavelength of 0,63 µm.
- A suitable detector. Usually this is a slice of photosensitive silicon with a number of discrete detectors.
- Some means of passing the sample through the laser beam.

Laser diffraction is one of the most widely used techniques for particle size analysis. Its flexibility, wide dynamic range, and speed of operation yield significant advantages compared to traditional techniques such as sieving. However, as the ease of use of the technique has progressed to the point at which systems require virtually single-button operation, it is easy to forget the requirements for accurate analysis in terms of sample preparation. If the processes of preparing a sample are not controlled, errors far beyond those associated with the laser diffraction technique itself will result. This can lead to results that are at best insensitive to changes in product quality and at worst are completely inaccurate.

Laser diffraction systems provide a rapid, accurate, and precise method for measuring particle size distributions. However, this relies on the following of standard operating procedures (SOPs) that take into account the way that samples are obtained and then dispersed within the instrument.

SGS South Africa (Pty) Ltd., an accredited laboratory, ensured that:

- the dispersion of the material with the laser diffraction system was controlled;
- the samples were measured in a stable, reproducible state of dispersion;
- wet dispersion was used as it represents the most robust method for measuring accurate particle size distributions.

Dispersion for wet analysis involves a two stage process. First, the particles must be fully wetted by the dispersant. This is aided by the choice of the most appropriate dispersant, by vigorous stirring, and by the application of ultrasound. Following this, the particles need to remain in a stable state. This will be dependent on the nature of the dispersant and the use of surfactants and other additives to prevent agglomeration.

The LALLS results indicate that on average more than 70 % of the material is smaller than 75µm and about 7 % is less than 10µm in diameter. An important conclusion from this is that the DRD 2L24 tailings impoundment can be considered as being an unlimited reservoir of fugitive particulate matter. Mizelle (1997) states that if more than 60 % of the material is less than 0,25 mm in size that it qualifies as having the potential to be a reservoir of unlimited fugitive particulate matter.

Table 39: Mean fraction of the particles smaller than 75 µm.

			Fraction of sample									
	Size (µm)	**Size (m)**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Mean fraction**
< 75µm	**76**	**0,0000760**	0,34	0,18	0,41	0,20	0,19	0,49	0,28	0,48	0,20	0,30
	56	**0,0000560**	0,35	0,23	0,29	0,31	0,23	0,25	0,29	0,32	0,24	0,28
	30,53	**0,0000305**	0,08	0,11	0,06	0,13	0,12	0,03	0,09	0,03	0,12	0,09
	19,31	**0,0000193**	0,05	0,12	0,05	0,11	0,14	0,04	0,08	0,03	0,13	0,08
	10,48	**0,0000105**	0,04	0,11	0,03	0,08	0,11	0,03	0,06	0,03	0,09	0,07
	5,69	**0,0000057**	0,04	0,10	0,04	0,06	0,08	0,03	0,05	0,02	0,08	0,06
	2,65	**0,0000027**	0,03	0,05	0,04	0,04	0,05	0,04	0,05	0,03	0,06	0,04
	1,06	**0,0000011**	0,07	0,10	0,09	0,07	0,08	0,09	0,09	0,06	0,09	0,08

Table 40: Mean fraction of the particles smaller than 10 µm.

			Fraction of sample									
	Size (µm)	**Size (m)**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Mean fraction**
< 10µm	**10,48**	**0,0000105**	0,24	0,31	0,17	0,32	0,34	0,15	0,24	0,19	0,30	0,25
	5,69	**0,0000057**	0,21	0,28	0,18	0,24	0,26	0,16	0,21	0,17	0,25	0,22
	2,65	**0,0000027**	0,19	0,15	0,21	0,16	0,15	0,22	0,20	0,23	0,18	0,19
	1,06	**0,0000011**	0,36	0,26	0,44	0,28	0,25	0,47	0,35	0,41	0,28	0,34

Bulk density

Measurements of settled dried densities range between 1250 and 1650 kg/m^3 as a function of depth. A value of 1450 kg/m^3 is generally used for design purposes. The settling dry density of tailings of an impoundment used in a study was reported to be 1500 kg/m^3 (Mizelle, 1997:34). In situ dry density quoted in Vermeulen (2002:2-67) and described by Blight, Rea, Daldwell and Davidson (1981) is given as 1835 kg/m^3. A bulk density of 1800 kg/m^3 was used for the purposes of this study.

Roughness height

In most earth sciences applications the logarithmic law takes a more general form that employs (Z_0), the aerodynamic roughness height, sometimes also referred to as roughness length, above the bed at which flow velocity tends to be zero (Lee and Zobeck, 2002). The drag coefficient and the roughness height (Z_0) are interchangeable descriptions of roughness. A classical approach consists in characterizing the roughness height of the erodible surface in relation to the size of the erodible particles (D_P)(Bagnold, 1941:50; Marticorena and Bergametti, 1995:16.425).

$$Z_0 = D_P / 30 \tag{33}$$

Table 41: The typical range of roughness heights.

Various surfaces	**Roughness height (Z_o) (m)**
Wheat field[1]	0,04
Plowed field[1]	0,01
Natural snow[1]	0,001
Overburden[2]	0,003
Ground coal[2]	0,0001
Fine coal dust on concrete pad[2]	0,002

[1] Cowherd, Muleski, Englehart and Gilette (1985)

[2] US EPA (1996)

Particle density

Ritcey (1989:222) provides a mean particle density value of 2,91 g/cm^3 with a range of 0,01 – 4,29 g/cm^3. It was decided that the value of 3,6 g/cm^3 will be used for the type of tailings material.

Impoundment surface area open fractions

Uniform percentages were used assuming that a particular cover technology can achieve a uniform reduction in exposed surface.

Clay content

The clay fraction is the fraction of the particles in the sample less than 2 µm in diameter. The arithmetic mean of the nine samples is 3,46 % (Table 42).

Table 42: Percentage (%) of particles smaller than 2 µm, i.e. clay particles.

Sample	Particle diameter (µm)	Percentage of sample (%) less than < 2µm
1	1,95	3,42
2	1,95	4,35
3	1,95	1,62
4	1,95	5,29
5	1,95	4,58
6	1,95	1,32
7	1,95	3,96
8	1,95	1,88
9	1,95	4,72
Arithmetic mean		3,46

Moisture content

The moisture content input parameter was taken as 0,18% which is the arithmetic mean of values from the nine samples measured by SGS. Mizelle (1997:66) reported moisture contents of between 0,83 % and 5,04% on the benches, outer or side sloped of the embankments and the top walls (dividing and crest walls). The moisture content varies considerably over the impoundment and depends on the characteristics of the tailings, position on impoundment, aspect of embankment and management practices.

DRD 2L24 chemical characteristics

Certain chemical elements and compounds have adverse effects on human health, wildlife and infrastructure. Information on the chemical composition of the tailings from impoundments helps to determine the risk associated with the release of particulates.

The objective of the chemical characterisation of the material was to determine and document the chemical make-up of the tailings at the DRD 2L24 tailings impoundment. The same grab samples used for the physical characterisation was analysed at the Geochemical Laboratory at the Department of Geology, University of Pretoria, using a standard ARL 9400XP+ Wavelength dispersive X-Ray fluorescence (XRF) spectrometer with Rh tube. The composition of five samples was determined for:

- chemical oxides; and
- single heavy elements.

XRF is an analytical technique to do qualitative and quantitative elemental analysis on inorganic samples. Elements between F and U on the periodic table can be analysed in concentration ranges from a few ppm to 100%. Organic material is X-Ray transparent, but due to the low mass absorption coefficient of such substances, inorganic impurities can be analysed to very low detection limits.

The source grab samples that were analysed had the advantage of already being crushed and ground through metallurgical processes. This avoids unnecessary contamination which can easily be incurred by crushing and grinding.

XRF analysis

Samples were taken on the impoundment and analysed using XRF analysis. The coordinates and sample numbers are indicated in Table 43.

Table 43: Coordinates of samples and GPS points for XRF analysis.

		Degrees Minutes Seconds	
		Latitude	**Longitude**
Sample Number	**GPS Point**	**South**	**East**
2	**4**	26° 11' 40,26"	27° 50' 22,98"
3	**7**	26° 11' 55,74"	27° 50' 1,50"
6	**10**	26° 11' 57,00"	27° 50' 35,94"
7	**11**	26° 12' 11,88"	27° 50' 35,76"
9	**14**	26° 12' 16,38"	27° 50' 8,10"

XRF analysis procedure

The XRF spectrometer was calibrated using certified reference materials. NBSGSC fundamental parameter program was used for matrix correction of major elements as well as Cl, Co, Cr, V, Sc and S. The Rh Compton peak ratio method was used for the other trace elements.

The samples were dried and roasted at 1000ºC to determine the percentage loss on ignition. Major element analyses were executed on fused beads, following the standard method used in the University of Pretoria XRF laboratory, as adapted from Bennett and Oliver (1992:67-93).

About 1 g of each sample was mixed with a 6 g lithium tetraborate flux in a 5% Au/Pt crucible and fused at 1000ºC using a muffle furnace swirling the sample occasionally. The sample dissolves rapidly after which the mixture was poured into a pre-heated Pt/Au mould to form the fusion disks. As soon as the fusion disks were ready, they were mounted in the spectrometer for surface analysis. Trace elements were analysed on pressed powder pellets, using an adaptation of the method described by Watson (1996: 173-174), using a saturated Mowiol 40-88 solution as binder.

XRF analysis results

The chemical characterisation indicates that the material contains mainly silica, enriched with chromium, zirconium and barium. This is similar as to what was measured by Mizelle (1997).

Table 44: XRF results of elements as oxides in DRD2L24 tailings samples.

%	GSNcert	GSN	Sample 2	Sample 3	Sample 6	Sample 7	Sample 9
SiO_2	65,80	65,31	93,16	94,37	93,25	93,73	90,33
TiO_2	0,68	0,65	0,21	0,20	0,25	0,21	0,19
Al_2O_3	14,67	14,57	2,68	2,58	2,74	2,55	5,05
Fe_2O_3	3,75	3,69	1,01	1,12	0,97	1,23	1,59
MnO	0,06	0,05	0,01	0,02	0,02	0,02	0,01
MgO	2,30	2,19	0,13	0,09	0,09	0,09	0,17
CaO	2,50	3,00	0,07	0,16	0,06	0,29	0,35
Na_2O	3,77	3,69	0,06	0,14	0,14	0,22	0,15
K_2O	4,63	4,70	0,19	0,16	0,14	0,11	0,12
P_2O_5	0,28	0,29	0,02	0,02	0,02	0,02	0,02
Cr_2O_3	0,008	0,008	0,02	0,03	0,01	0,03	0,02
NiO	0,0043	0,0034	0,01	0,01	0,02	0,01	0,01
V_2O_5	0,01	0,01	0,00	0,00	0,00	0,00	0,00
ZrO_2	0,03	0,03	0,03	0,03	0,03	0,03	0,04
LOI	1,32	1,29	1,02	1,12	0,79	1,57	2,17
Total	99,82	99,48	98,62	100,05	98,53	100,12	100,23

Table 45: XRF results of elements present in the DRD2L24 tailings samples.

ppm	GSNcert	GSN	Sample 2	Sample 3	Sample 6	Sample 7	Sample 9
As	1,6	3	10	19	14	16	84
Cu	20	21	12	12	11	24	19
Ga	22	18	3	3	3	5	5
Mo	1,2	1	1	1	1	1	1
Nb	21	23	4	4	3	5	5
Ni	34	33	18	14	11	26	26
Pb	53	55	31	11	8	57	23
Rb	185	184	5	5	3	4	7
Sr	570	578	12	15	11	12	16
Th	42	42	3	3	3	3	3
U	8	12	3	3	3	3	3
W*	450	452	1028	1395	944	1377	905
Y	19	13	9	8	8	14	9
Zn	48	52	17	14	14	27	37
Zr	235	237	158	148	138	238	169
Cl*	450	499	8	10	8	8	8
Co	65	57	436	291	234	1089	198
Cr	55	45	101	90	88	146	116
F*	1050	1177	877	923	828	808	609
S*	140	556	1737	610	491	4371	1792
Sc	7	6	2	3	2	4	3
V	65	63	17	17	17	17	17
Cs	5	6	9	9	9	9	9
Ba	1400	1417	34	36	32	30	38
La	75	60	33	31	29	34	30
Ce	135	138	29	29	31	38	31

DRD 2L24 calibration input parameters

The physical parameters determined and described in the previous section were used as input parameters in ADDAS and ISCST Breeze to estimate and disperse the emissions for the various impoundment configurations. The following input parameters were used in ADDAS to estimate emissions for the DRD 2L24 impoundment and calibrate the roughness height:

• Bulk density:	1800 kg/m^3
• Mean particle size distribution:	Table 39 and Table 40 provide a detailed breakdown of the mean particle size distributions and mass fractions.
• Average moisture content:	The arithmetic mean value of 0,18% was determined and used from the nine samples measured by SGS.
• Tailings impoundment dimensions:	The tailings impoundment input dimensions used for the DRD 2L24 calibration is provided in Table 46.
• Roughness height:	A value of 0,00012 m was used for the simulation of the various impoundment configurations provided in Section 3.2. The calibrations process is described in Section 3.5.2.
• Clay content:	The arithmetic mean value of 3,46 % was used (Table 42).
• Moisture content:	The moisture content input parameter was taken as 0,18% which is the arithmetic mean of values from the nine samples measured by SGS.

Table 46: DRD 2L24 tailings impoundment dimensions.

Horizontal clockwise angle	14°
North-South length (m)	1775
East-West length (m)	1294,5
Compartments surface area (ha)	
North	46
No. 1	67
2 West	29
2 East	26
3 East	29
3 West	29
Total	227

DRD 2L24 dispersion calibration results

No site-specific ambient air quality monitoring data is available for the DRD 2L24 impoundment and reference is therefore made to results from bucket dust fallout monitoring stations in the vicinity of the impoundment. It must however be noted that likely sources contributing to the total dust collected in the dust buckets include:

- tailings dust from the DRD 2L24 impoundment;
- domestic coal burning emissions from neighbouring townships;
- fugitive dust from more distant tailings impoundments and mining operations; and
- vehicle entrained dust from unpaved roads in the area.

The material in the dust fallout buckets were evidence of the different sources with the colour ranging from brown to yellowish-grey. Gold tailings from the DRD 2L24 impoundment is homogeneous in composition and yellowish-grey in colour.

Dust fallout monitoring data

A total of 23 dust fallout buckets are currently operated by the DRD in the vicinity of their operations. The dust fallout buckets of Modise, Louis Spaza Shop, Leon Biko, Yvonne Meno, Thandeka Twani and Anna contained mainly tailings material. The location of the dust fallout buckets are shown in Figure 122 with Table 47 indicating the coordinates of the buckets used for calibration. The monitoring stations indicated in yellow were used to calibrate the models.

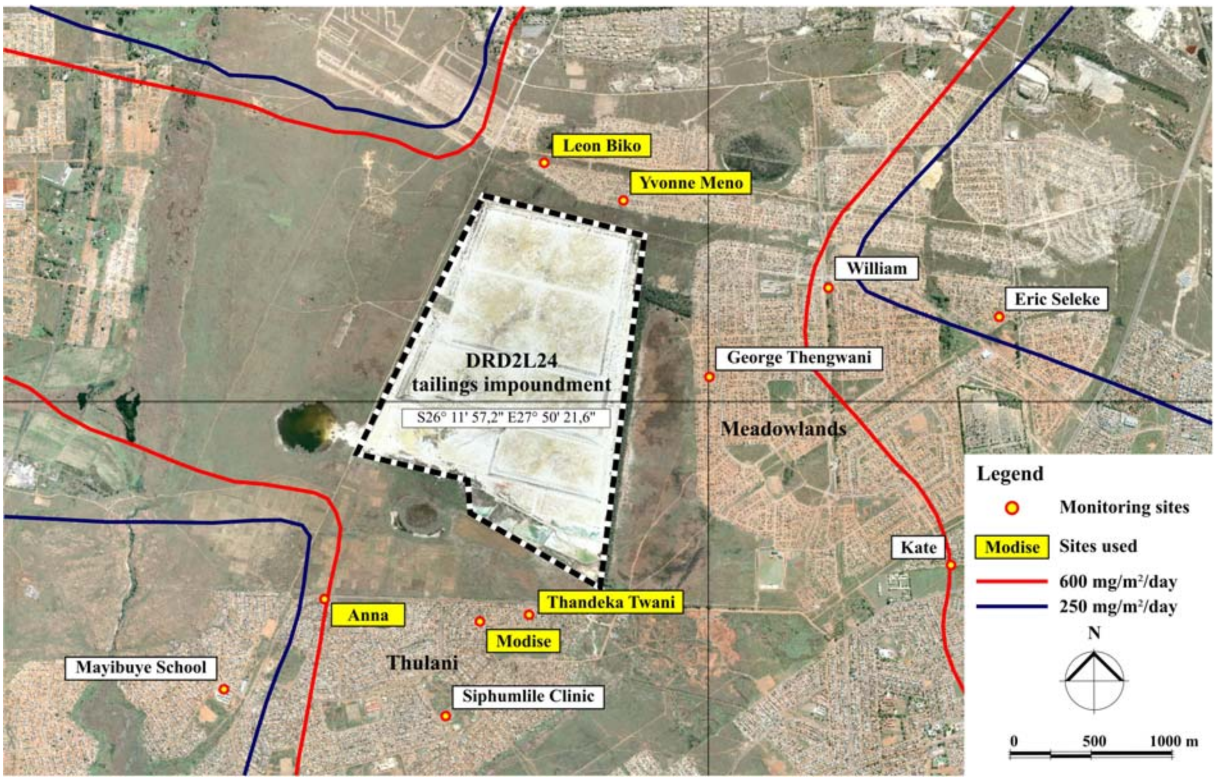


Figure 122: Dust fallout monitoring sites in the vicinity of the DRD tailings impoundment. Predicted total daily average dust fallout (mg/m^2/day) from the DRD tailings impoundment.

The highest dust fallout rates were recorded at Modise House and Mayibuye School which are located within Thulani on the southern side of the DRD tailings impoundment. Due to the high dust fallout recorded, the mine commissioned two additional dust fallout buckets in this area (Anna and Thandeka Twani). Additional buckets were also commissioned in other areas surrounding the tailings impoundment. The new buckets were commissioned during September 2005 with heavy dust fallout levels recorded within the first two months. Very heavy dust fall was recorded at Thandeka Twani during the month of October 2005. Only these two months of data for the newly commissioned stations was available for use during the calibration exercise.

Table 47: Dust fallout bucket coordinates.

		Latitude	Longitude
Site location	**Site No.**	**South**	**East**
Modise House	**3**	26° 12' 59,03"	27° 50' 4,88"
George Thangwani	**17**	26° 12' 9,73"	27° 50' 55,16"
Leon Biko	**20**	26° 11' 27,67"	27° 50' 19,03"
Yvonne Meno	**21**	26° 11' 35,27"	27° 50' 38,08"
Thandeka Twani	**22**	26° 12' 57,33"	27° 50' 15,89"
Anna	**23**	26° 12' 55,36"	27° 49' 29,84"

The dispersion simulations were done for dust fallout and depicted as total daily levels over a monthly average. This is for comparison to the dust fallout levels which is measured for a period of 28 to 31 days and then calculated as daily fallout levels. The predicted dust fallout levels are given for the main indicator buckets indicated (Figure 122, p. 216). Table 48 provides the predicted results for comparison to measured data.

Table 48: Modelled data compared to measured data from the DRD Tailings Impoundment. A surface roughness height of 0,0012 m provided the best correlation.

		Measured data		Modelled data	
		Maximum monthly (x)	**Annual average**	**Monthly (y)**	**Ratio**
Site location	**Site No.**	**($mg/m^2/day$)**	**($mg/m^2/day$)**	**($mg/m^2/day$)**	**(y:x)**
Modise House	**3**	812	575	362	0,45
George Thangwani	**17**	2060	746	3700	1,80
Leon Biko	**20**	703	531	3008	4,28
Yvonne Meno	**21**	4546	758	2109	0,46
Thandeka Twani	**22**	1633	1002	3220	1,97
Anna	**23**	5597	1817	6245	1,12

As discussed under Section 2.11.2, the range of uncertainty of the US EPA developed ISCST Breeze can range between -50% to 200%. The measured data compared favourably to the predicted results and are considered to be within the same range. Modise House, Thandeka Twani and Yvonne Meno were considered the most representative and fell within the range of -50% and 200% accuracy resulting for a surface roughness height of 0,0012 m (Figure 122, p. 216). Isopleth plots are used to spatially compare the highest daily and annual average PM_{10} concentrations and highest daily and annual average dustfall levels with the data from the bucket dust fallout monitoring stations.

3.5.3 Summary

ADDAS software was successfully calibrated using the DRD 2L24 impoundment site following a process whereby predicted results were compared to monitoring data. The calibration process provided a means to determine the surface roughness height for a typical uncovered gold tailings impoundment and is in the order of 0,0012 m. The calibrated ADDAS model can be used to predict the emissions for the different ERGO Daggafontein tailings impoundment scenarios.

3.6 Water

3.6.1 Introduction

The objective of this section of the study is to model the mass flux (sulphate flux) and contaminant (sulphate) concentration for different tailings impoundment configurations using a simple mass balance spreadsheet model. The literature review presents information on the modelling of groundwater flow, contaminant transport, and typical contaminants. Two dimensional groundwater models are discussed which assumes steady state, isotropic, and homogeneous conditions. Various approaches to groundwater modelling are also briefly discussed. The water model which was developed and used in this study calculates the mass-flux and does not consider the following:

- effects of hydrodynamic dispersion;
- chemical interactions between contaminants, the foundation and aquifer solid matrix;
- effects of multi-layered and confined aquifers;
- interactions between groundwater and surface water;
- consequences of anisotropic and non-homogeneous materials; and
- compressible fluids.

3.6.2 Predictive modelling of impacts

The scenarios defined and modelled are given in Table 23, p. 163. The configuration of a tailings impoundment could affect the off-site impact on the water resource. The geometry and cover which in turn affect the surface stability of the outer top surface and side slopes of tailings impoundments is central in assessing the impact of tailings impoundments on the environment. Two primary decision considerations comprise the possible impacts on the groundwater through seepage and the surface water as runoff (Figure 54, p. 109). The objective of this section is to predict the change in mass-flux using a simple mass balance spreadsheet model. It provides a reasonable estimate of seepage from an impoundment.

3.6.3 Water impact model

Objectives

The objective of the investigation was to develop a first order methodology to determine the water related impacts from a tailings impoundment, given various slope and cover closure configurations. An important requirement is that the method can be integrated with other environmental aspects such as visual and dust impacts. It should be used as a decision-making tool to inform the choice of tailings impoundment configurations.

Approach

To determine the potential water related impacts, an analytical mass balance model was developed for surface water and groundwater that could be used on a spreadsheet. This will allow integration and comparison with other environmental aspects such as the visual and dust impacts. The model is aimed at evaluating the post-operation impacts against different rehabilitation options. A steady-state approach was followed as it is able to emulate the long time scales that are associated with post-operation planning.

Model development

The analytical water flow and mass balance model has been developed for a tailings impoundment located in a surface water and groundwater catchment. The aim of the model is to:

- account for the water and mass balance components for the tailings impoundment, and
- evaluate the impact on the surface water and groundwater in terms of concentrations and mass load for the various configurations.

The model is based on the ERGO Daggafontein tailings impoundment which is located in the Blesbokspruit catchment was used for this purpose (Figure 81, p. 158).

Conceptual model

The first step in the development is the formulation of a conceptual model based on the field situation. The status quo is that the impoundment is operational and located 800 m up gradient from the Blesbokspruit. Rainfall on the basin and embankment slopes of an impoundment drives the contamination potential to surface water and groundwater. When rain falls on the impoundment, it infiltrates, runs off as surface water or evaporates. The component that infiltrates can seep out laterally as toe seepage or migrate downward towards the groundwater table. All three pathways would react with the tailings material and transport contaminants to the receiving surface water body. Surface water runoff would directly reach the stream while toe and groundwater seepage would have a lag which is controlled by the permeability and porosity of the tailings and subsurface lithologies.

Management options

The post-operation management of the facility should be aimed at minimizing the mass flux to the Blesbokspruit, which is the receiving water body (receptor). Due to net evaporation in the area, mass that reaches the stream, even if it is diluted could build up in downstream where it is dammed up. The mitigation options available during the post-operation stage should be aimed at controlling the contaminant source (tailings impoundment). A total of sixteen configurations were evaluated with the model. There are four different slope configurations with four different covering options for the tailings impoundments.

Analytical model

The conceptual model used to quantify the water flow and mass balances uses a simple analytical approach. Due to the fact that the evaluation is done for the post-closure stage of the scenarios and steady-state conditions are assumed.

Assumptions

The water balance assumptions for the four scenarios are listed below, numbers 13 – 18, 26, 28 and 30. The assumptions are important and were made based on the shape of the impoundment and the permeability of the capping material. The surface runoff, evapotranspiration losses and infiltration into the tailings impoundment must balance. A balance check is built into the model for verification. Some of the assumptions are qualified using the groundwater quality data from the monitoring boreholes and permeability values of the soil and tailings material (Figure 96, p. 177). The assumptions are considered conservative in that estimates produce higher mass fluxes to the environment.

Flow and mass balance calculations

The model is based on important input parameters. Reference is made by cross referencing assumptions and qualifications in Table 49 (p. 221) to the model input and calculated parameters by denoting the corresponding number e.g. (1) in Table 50 (p. 222). All the water and flow balances were calculated in annual terms but expressed in daily or annual volume and mass. The mass flux assessment was done by using sulphate as a tracer. The model development (

Table 50) is schematically presented below in Figure 123.

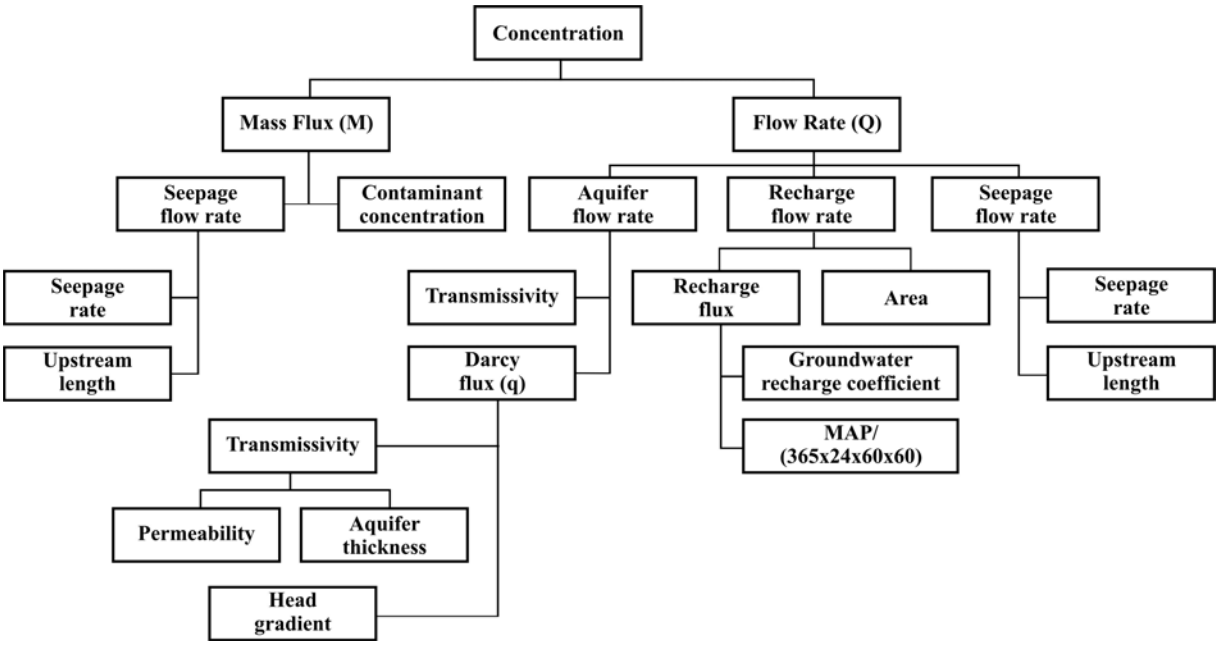


Figure 123: Schematic representation of the model.

The mass flux is calculated using the relationship:

$$M = Q.C \tag{34}$$

Where:
M = mass flux
Q = flow rate
C = concentration

All of the assumptions made and qualifications on each parameter are provided below. The idea is that this numerical list can be used together with the numerical model.

Table 49: Analytical water flow and mass balance assumptions and qualifications.

(1)	Input of mean annual precipitation (MAP) in mm/annum.
(2)	Input of mean annual evaporation (MAE) in mm/annum.
(3)	Calculation of actual annual evaporation (mm/annum) is based on the assumption in (15).
(4)	Input of the tailings impoundment surface area that varies as the slope changes (ha).
(5)	Input of the waste material permeability at surface (m/day).
(6)	Input of the upstream length of the facility (m). The upstream length influences the down gradient groundwater concentration.
(7)	Input of soil permeability below the impoundment (m/day).
(8)	Input of aquifer permeability below the impoundment (m/day).
(9)	Input of aquifer thickness below the impoundment (m).
(10)	Calculation of aquifer transmissivity (*T*). *T*=*k*.*D* measured in m^2/day. Where *k* is the permeability and *D* is the saturated aquifer thickness.
(11)	Input of measured groundwater head gradient (dh/dl).
(12)	Calculation of Darcy flux (*q*). $q = k.\frac{(h_1 - h_2)}{L}$ measured in m/day. Refer Equation (19) Section 2.12.10.
(13)	Assumption on site runoff coefficient as % of total water on site.
(14)	Assumption on site infiltration as % of total water on site.
(15)	Assumption on site evaporation losses as % of total water on site. Note that (13) + (14) + (15) must equal 100 %.
(16)	Assumption on site toe seepage component as % of infiltration (14).
(17)	Assumption on site groundwater seepage component that together with toe seepage (16) must equal 100 % of infiltration.
(18)	Assumption on off-site, down gradient groundwater recharge component as % of MAP.
(19)	Calculation of the total volume of surface water on site.
(20) - (24)	Calculation of the surface water runoff, infiltration and evaporation loss volumes.
(25)	The site groundwater unit seepage should not exceed the tailings, soil or aquifer permeability.
(26)	Assumption on runoff concentration in mg/ℓ. This value can be validated by measurements.
(27)	Calculation of site runoff mass flux [= (20) x (26)] in g/day.
(28)	Assumption on toe seepage concentration in mg/ℓ. This value can be validated by measurements.
(29)	Calculation of toe seepage mass flux [= (23) x (28)] in g/day.
(30)	Assumption on groundwater seepage concentration in mg/ℓ. This value should be comparable with the toe seepage concentration or can be measured.
(31)	Calculation groundwater seepage mass flux [= (27) x (34)] in g/day.
(32)	Calculation of groundwater unit seepage mass flux [= (31)/(4)] in g/m^2/day.
(33)	Input of groundwater background concentration in mg/ℓ.
(34)	Input of low flow volume in river in m^3/day. The low flow will provide the maximum impact on concentration, which is a conservative approach.
(35)	Input of average upstream or background surface stream concentration in mg/ℓ.
(36)	Calculation of low flow stream background mass flux in g/day.
(37) - (39)	Calculation of increase in stream concentration due to surface water, toe seepage and groundwater mass fluxes by mixing the respective mass flux with the flow volumes.
(40) - (42)	Calculate the impact as % increase in concentration.
(43)	Calculate the downstream concentration with mixing of total mass with total flow volume.
(44)	Calculate the cumulative impact of mass flux as % increase of background concentration.
(45) - (49)	Calculates and summarize the annual mass flux from the source to the receiving water body in t/annum.

Table 50: Daggafontein tailings impoundment water and mass balance model.

			Slope (1:1.5)			
	Type		No cover	Rock (300 mm)	Grassed armouring	Diverse vegetation
	Scenario reference		WS1	WS6	WS11	WS16
No	**Description**	**Unit**	**Quantity**			
1	Mean annual precipitation	mm/annum	680	680	680	680
2	Mean annual evaporation	mm/annum	1500	1500	1500	1500
3	Actual evapotranspiration rate	mm/annum	204	136	272	408
4	Surface area (status)	ha	303	303	303	303
5	Tailings permeability at surface	m/day	0,001	0,001	0,001	0,001
6	Upstream facility length	m	1739	1739	1739	1739
7	Soil permeability (below impoundment)	m/day	0,01	0,01	0,01	0,01
8	Aquifer permeability	m/day	0,45	0,45	0,45	0,45
9	Aquifer thickness	m	40	40	40	40
10	Aquifer transmissivity	m^2/day	18	18	18	18
11	Groundwater head gradient	*l*	0,018	0,018	0,018	0,018
12	Darcy flux	m/day	0,324	0,324	0,324	0,324
13	Site runoff coefficient	%	30	20	20	10
14	Site infiltration coefficient	%	40	60	40	30
15	Site evapotranspiration and losses	%	30	20	40	60
16	Site toe seepage component	%	20	30	20	15
17	Site groundwater seepage component	%	20	30	20	15
18	Groundwater natural recharge coefficient	%	5	5	5	5

Water balance						
No	**Description**	**Unit**	**Quantity**			
19	Surface water on site	m^3/day	5,637	5,637	5,637	5,637
20	Site runoff	m^3/day	1,691	1,127	1,127	564
21	Site evapotranspiration losses	m^3/day	1,691	1,127	2,255	3,382
22	Site infiltration	m^3/day	2,255	3,382	2,255	1,691
23	Site toe seepage	m^3/day	1127	1691	1127	846
24	Site groundwater seepage	m^3/day	1127	1691	1127	846
25	Site groundwater unit seepage	m/day	1,66E-04	2,49E-04	1,66E-04	1,24E-04

Mass balance (Sulphate)						
No	**Description**	**Unit**	**Quantity**			
26	Site runoff concentration	mg/ℓ	1200	1200	1200	1200
27	Site surface water runoff mass flux	g/day	2,0E+06	1,4E+06	1,4E+06	6,8E+05
28	Site toe seepage concentration	mg/ℓ	1200	1200	1200	1200
29	Site toe seepage mass flux	g/day	1,4E+06	2,0E+06	1,4E+06	1,0E+06
30	Site Groundwater seepage concentration	mg/ℓ	1200	1200	1200	1200
31	Site Groundwater seepage mass flux	g/day	1,4E+06	2,0E+06	1,4E+06	1,0E+06
32	Site Groundwater unit seepage mass flux	g/m^2/day	4,47E-01	6,71E-01	4,47E-01	3,35E-01
33	Groundwater background concentration	mg/ℓ	20	22	27	32

Stream Water Quality						
No	**Description**	**Unit**	**Quantity**			
34	Low flow in stream	m^3/day	7,00E+05	7,00E+05	7,00E+05	7,00E+05
35	Average upstream stream background concentration	mg/ℓ	200,00	202,00	207,00	212,00
36	Low flow stream mass flux	g/day	1,40E+08	1,41E+08	1,45E+08	1,48E+08
37	Concentration increase due to surface water mass flux	mg/ℓ	2,410	1,605	1,597	0,795
38	Concentration increase due to toe seepage mass flux	mg/ℓ	1,608	2,405	1,597	1,192
39	Concentration increase due to groundwater mass flux	mg/ℓ	1,608	2,405	1,597	1,192
40	Impact due to surface water runoff	%	1,205	0,794	0,771	0,375
41	Impact due to toe seepage	%	0,804	1,191	0,771	0,562
42	Impact due to groundwater seepage	%	0,804	1,191	0,771	0,562
43	Downstream stream concentration during low flow	mg/ℓ	205,61	208,39	211,77	215,17
44	Impact due to cumulative mass load increase in stream	%	2,80	3,16	2,31	1,50

Mass flux summary						
No	**Description**	**Unit**	**Quantity**			
45	Site surface water runoff mass flux	tonnes/annum	741	494	494	247
46	Site toe seepage mass flux	tonnes/annum	494	741	494	370
47	Site groundwater seepage mass flux	tonnes/annum	494	741	494	370
48	Total mass flux to stream	tonnes/annum	1728	1975	1481	988
49	% Mass relative to baseline		0	14	-14	-43

3.6.4 Summary

The previous sections describe the experimental work and modelling for the following environmental aspects:

- visual;
- air; and
- water.

The visual effect of an impoundment is quantified by determining its influence on visual perception. This innovative method of quantifying visual impacts for tailings impoundment is new and is in itself a substantial contribution this field of study.

The influence of tailings impoundments on air quality uses available software which was calibrated following an iterative process of comparing predicted results with monitoring data. The surface roughness height for a typical uncovered gold tailings impoundment has been determined and is in the order of 0,0012 m.

A first order analytical water impact model is described and can be used to calculate a mass balance and mass flux in sulphates. Steady-state conditions are assumed. The model can be used to model the various scenarios at the ERGO Daggafontein impoundment site. The results form the water impact modelling is provided in Section 4.5.

3.7 Engineering cost model

3.7.1 Introduction

This research describes an environmental impact and engineering cost decision-support system for assessing alternative upstream ring-dike tailings impoundment configurations and associated environmental liabilities. The following section of the study describes the engineering cost model which is the result of a collaborative effort with Caroline Holmes (Holmes, 2006). It comprises a hierarchy of spreadsheets using available software which follow the engineering steps of:

- specifications;
- quantities;
- rates; and
- costs (Figure 124).

Input data, quantities and rates can be readily modified so that the sensitivity of total costs to these changes can be examined and if necessary changes made to provide economies.

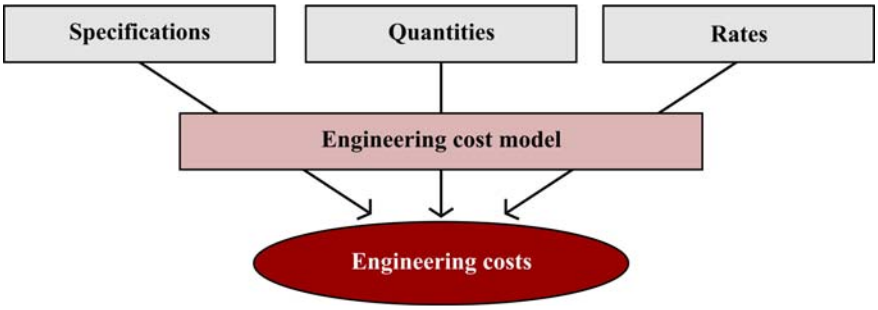


Figure 124: Typical components of the engineering cost model.

The design, construction, operation, closure, and post-closure stages can be considered separately for the purpose of developing a representative engineering cost model for the life cycle of tailings impoundments (Figure 125). The elements of each stage can be defined using conventional civil engineering methodology of estimating costs at standard rates for all the measurable quantities for design and construction (development), operation, closure, and post-closure maintenance and management. These unit costs were procured from recent and current construction contracts.

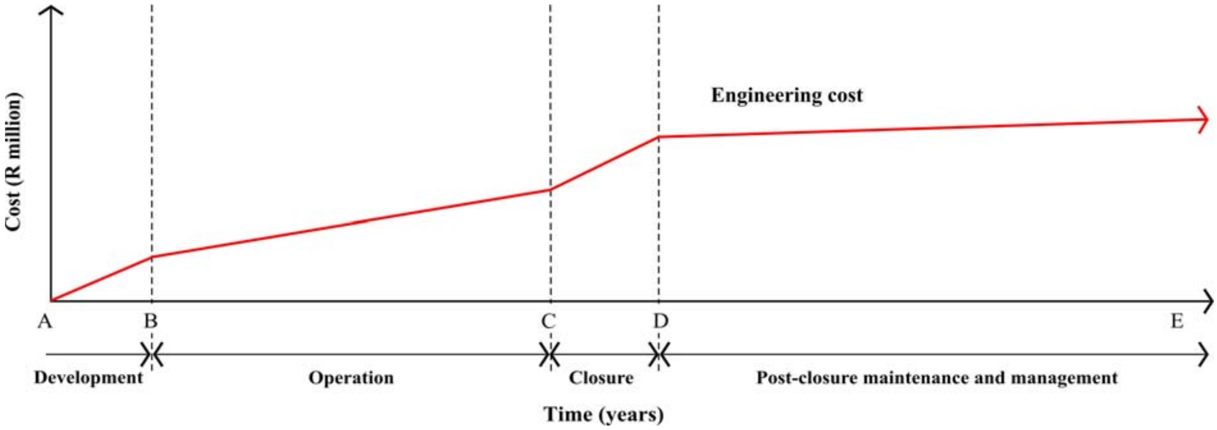


Figure 125: Cumulative engineering costs for the life cycle of tailings impoundments.

The post-closure stage costing represents many different options from return to pristine pre-deposition land use at one end of the spectrum to doing nothing at the other end. Since all closure options have not yet been developed cost estimates will necessarily be somewhat less reliable than those based on current practice and data. Nevertheless whatever option is selected the basic requirements comprise earthworks to reshape, drainage systems and a cover all of which can be costed provided the options are well described in terms of shape and function.

Throughout the life cycle of a tailings impoundment there are costs other than the direct construction costs. Initially there are the planning and design costs, some of which are professional fees for consultants and some are in-house costs primarily also for professional time. These continue throughout the total life cycle process and again may be both external, which are simple to estimate, and internal which may be rather more difficult to establish. In general, of course, the overall design and management costs are a small fraction of the total construction and operation costs hence the accuracy of the estimate of the former is not highly significant.

Tailings impoundment construction may be viewed either as an ongoing process through to completion of the impoundment or construction may be seen as part of the initial development stage with activities such as impoundment footprint preparation, starter walls, trenches, and drains followed by an operation stage when tailings is impounded. Since the initial and operational parts are very different they are divided into separate stages.

Similarly closure and post-closure are divided into separate stages. The former is viewed as simple closure to satisfy the minimum environmental legal requirements. At present this implies what has been called a semi-desirable or unacceptable state where an impoundment is sterile, safe, of original shape, and which most certainly requires some ongoing maintenance. Post-closure includes both the ongoing maintenance and if this happens, the conversion of the site to a desirable, acceptable and sustainable function in keeping with regulatory requirements. It is possible that this sustainable state could result in either a long term cost or a long term benefit.

The conceptual cost modelling methodology for the design, construction, operation, closure and post-closure stages is set out in Table 51 (p. 226).

The engineering cost model was developed to provide for all the necessary significant engineering cost items. Actual costs were obtained from recent tailings impoundment construction and operation projects so that unit costs for each item could be calculated and referred to a base year.

The result from this part of the overall research programme is that a comprehensive engineering cost model for upstream spigotted ring-dike tailings impoundments is available which is sufficiently reliable not only to estimate the overall life-cycle cost but also check costs of for example modifying the overall embankment side slope, cover, and environmental protection measures.

It must be noted that this comprehensive cost model enables trade offs to be determined when comparing various impoundment closure options which at present are necessary to inform the configuration of tailings impoundments.

The engineering cost model runs in conjunction with a parallel environmental impact model so that both costs and impacts are assessed and hence rational decisions made regarding minimising adverse environmental impacts and the preferred sustainable end use of a tailings impoundment.

Table 51: Conceptual engineering model costs the different tailings impoundment stages.

Stage	External Costs	Internal Costs
Planning and design	i) Planning a) Environmental – assess impacts and obtain approval b) Engineering – select site, decide shape, size, type based on assessment of impacts ii) Design a) Engineering – detail design, quantities, tender documents b) Determine and design post-closure land use c) Obtain approval	i) Planning – direct planning and approve, liaison with authorities ii) Design – oversee design and approve iii) Decide on initial post-closure land use
Construction	i) Procurement and construction (consulting fees) a) Call for tenders, adjudicate, award b) Contract documentation c) Supervise contract d) Arrange operating and monitoring system ii) Contract initial construction a) Items off schedule of quantities	i) Oversee construction – approve payments
Operation	i) Consulting fees a) Arrange operation contract b) Supervise contract ii) Operation contract a) Items off schedule of quantities (Separate out environmental control aspects)	i) Oversee operation – approve payments
Closure	i) Consulting fees a) Design closure measures b) Obtain closure permission c) Arrange closure contract d) Supervise closure ii) Closure contract a) Items off schedule of quantities (Separate out environmental control aspects)	i) Oversee closure – liaise with authorities and approve payments
Post-closure	i) Consulting fees a) Refine post-closure land use b) Obtain approval c) Arrange construction contract d) Arrange long term operation and maintenance ii) Post-closure contract a) Items off schedule of quantities	i) Check if post-closure land use will meet the necessary requirements ii) Liaise with authorities iii) Approve scheme – set up financial arrangements iv) Arrange operation and maintenance

The essential criteria for the engineering cost model are that is simple, reliable, flexible, and computer based. The approach begins with a listing of all the physical items which form part of the tailings disposal facility (Figure 20, p. 29) such as:

- access and perimeter roads;
- tailings delivery, ring main and distribution pipelines;
- starter wall;
- toe wall;
- solution trench;
- catwalk;
- penstock;
- catchment paddocks;
- drains;
- silt trap;
- cover; and
- return water dam.

Dealing with each of these to an acceptable standard is an engineering process which can be measured and costed provided that appropriate unit rates are established. Difficulties lie in the adequate definition of acceptable standards and specifications. These difficulties can, however, be readily overcome by providing a list of assumptions and implementing industry best practice.

3.7.2 Components

The basic building blocks (Figure 126) of the cost model are similar to those of a conventional engineering cost estimate and include:

- inputs;
  - user inputs;
  - default model inputs;
- specifications;
- schedule of quantities;
- schedule of rates; and
- cost estimate.

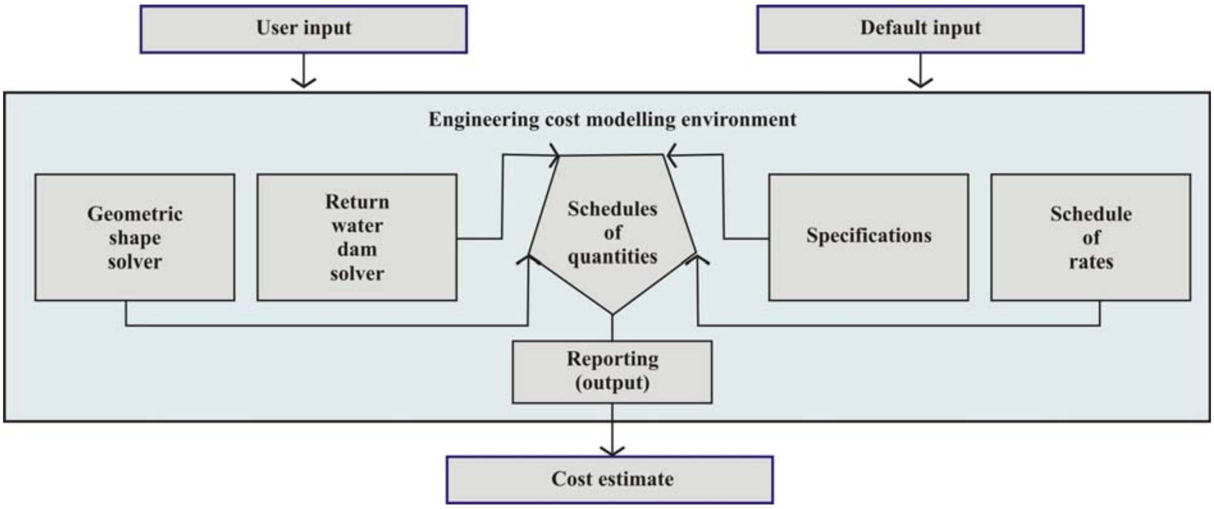


Figure 126: Basic elements of the engineering cost model.

The emphasis is however on the concept that a reliable cost estimate is required and not a detailed schedule for contract purposes. It is possible that the works may be required either next year or in twenty years time and standards and methods of construction may have changed and certainly unit rates for the items will have changed dramatically. Modifying specifications and updating unit rates will ensure the system continues to be reliable for current use and using standard financial methods will provide for future estimated costs based on current prices.

The following three key elements of the engineering cost model is described in the next section of the study:

- specifications;
- schedule of quantities; and
- schedule of rates;

for which the specification requirements are determined by engineering best practice.

Specifications

Arguably this is the most important element of the system since in it the various engineering works are described in sufficient detail to be meaningful for the purpose by inferring or defining the required quality or standards, but at the same time the detail should not be such as to overwhelm the system.

Clearly the criteria may at times be conflicting hence some compromises may be required. In practice this was not found to be the problem provided that the overall broad purpose of the system together with the sensitivity of the total cost to the particular item was considered.

The following list of specifications is included in Appendix C to illustrate the level of detail at which engineering items are specified. It is intended to provide information on the typical works required:

- access and perimeter roads;
- tailings delivery, ring main and distribution pipelines;
- starter wall;
- toe wall;
- solution trench;
- catwalk;
- penstock;
- catchment paddocks;
- drains;
- silt trap;
- cover; and
- return water dam.

This is not an exhaustive list of items included in the engineering cost model and it may well be that should the system be applied for other types of impoundments then further items will be required and some may be deleted. The complete engineering cost model comprises a total of 69 specifications. There are 37 construction stage, 16 operation stage, 8 closure stage and 8 maintenance and aftercare stage details.

All physical, chemical and biological processes for which maintenance has been specified must be monitored until they reach a steady state or as long as deemed necessary at the time of closure. Such processes include erosion of impoundment surfaces, surface water drainage, ground water recharge, air quality, surface water quality, ground water quality, performance of cover, invasion of weeds and colonization by animals. Measures must be implemented to manage, mitigate and monitor environmental impacts and a site that is unstable or hazardous must have a fence erected around the perimeter tocontrol access.

Schedule of quantities

This is a straightforward engineering schedule of quantities of all the items specified and it presupposes that all these items can be readily measured. It is again emphasized that the system is not intended to be equivalent to detailed design costing but is more akin to feasibility planning costing for which an accuracy of say ± 10% is required. Measurement of practically all the items can be made with sufficient accuracy from the quantifications made by the various solvers built into the engineering cost model. The most important factor is producing a reliable schedule of the required work although on the other hand where for example large volumes of earthworks are involved then care must be taken to ensure that the dimensions are accurate. This is particularly so for the vertical dimension of rehabilitation earthworks where what may appear to be relatively small changes have a very large influence on total volumes and hence on total costs, if the item itself constitutes a large proportion of the overall cost of rehabilitation. A typical schedule of quantities is shown in Table 52.

Table 52: Engineering schedule of quantities for selected closure cost items.

Item	Description	Unit	Quantity	Rate with CPI	Amount
Basin profiling (specification sheet R1)					
1	Basin profiling	m^3	0,00	11,00	0,00
2	Evaporation paddock wall construction	m^3	101 902,33	16,50	1 681 388,45
	Sub-total				1 681 388,45
Cladding of tailings dam basin (Specification sheet R7)					
1a	Topsoil to basin	m^3	0,00	22,00	0,00
1b	Vegetation of basin (diverse)	m^2	0,00	44,00	0,00
	or				
1	Rockfill cladding of basin	m^3	0,00	34,65	0,00
	or				
1	Rock armouring with topsoil and grassing	m^3	1 692 307,69	14,08	23 827 692,31
	Sub-total				23 827 692,31
Cladding of tailings dam outer slopes (Specification sheet R8)					
1a	Topsoil to outer slopes	m^3	0,00	22,00	0,00
1b	Vegetation of outer slopes (diverse)	m^2	0,00	44,00	0,00
	or				
1	Rockfill cladding of outer slopes	m^3	0,00	34,65	0,00
	or				
1	Rock armouring with topsoil and grassing	m^3	1 984 060,75	14,08	27 935 575,30
	Sub-total				27 935 575,30
Tailings dam outer slope flattening (Specification sheet R9)					
1	Tailings dam outer slope flattening (cut to fill)	m^3	0,00	11,00	0,00
	Sub-total				0,00

Schedule of rates

This again is a straightforward engineering schedule of rates. Similar comments apply as for the schedule of quantities; it is important to ensure that the whole of any item is included in a rate and that there are no significant extras. An aspect which requires particular attention is construction and rehabilitation materials availability where for example starter wall construction material or topsoil may be in short supply. In this case overhaul can become a major cost and poor planning can result in huge cost overruns. Conventional civil engineering rates were obtained from consulting engineers' and contractors' recent experience of tailings impoundment works. Generally works are carried out on a two cost basis i.e. an establishment item and a quantities related item. Depending on the nature and the extent of the work the former may be a large or small portion of the final cost. For the purpose of this model the rates used include any fixed cost items.

3.7.3 Modelling

The choice, for example, of engineering systems, methods and specifications and the extent they are interpreted for costing purposes depends on practical, economic and legal constraints. This engineering cost model allows the user to test various assumptions and different scenarios and also allows the user to change and test the variables. The engineering cost model (Figure 127) was constructed applying a system consisting of multiple sheets within a spreadsheet, as shown diagrammatically below.

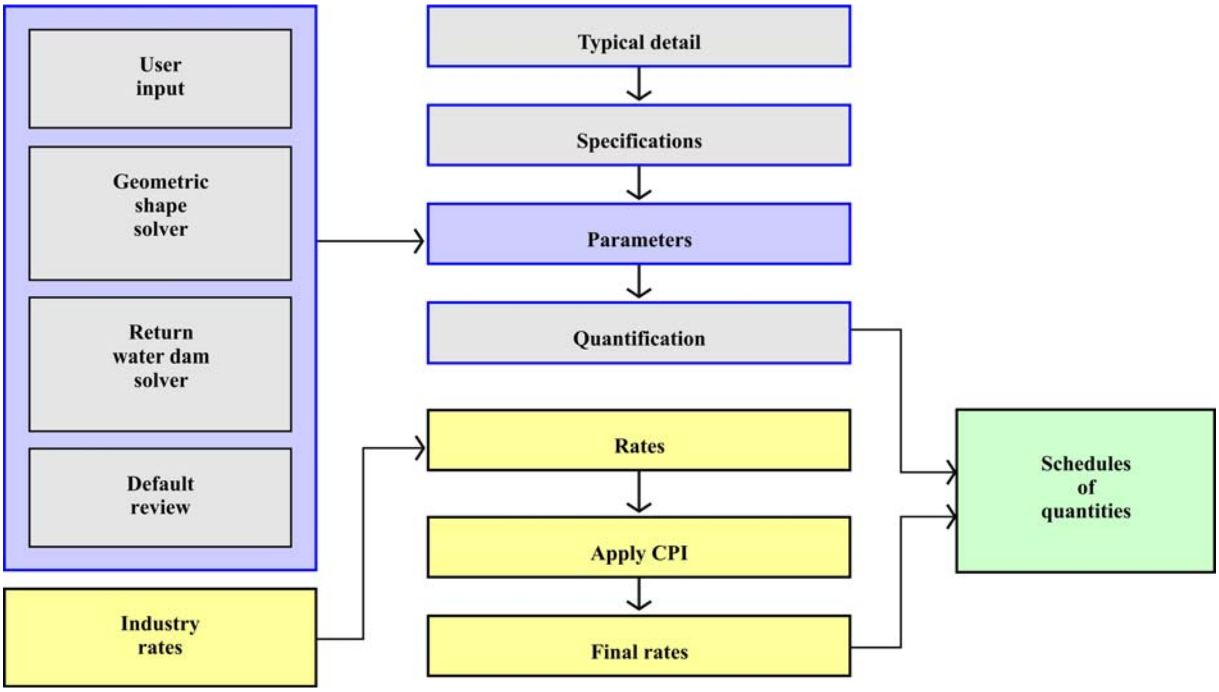


Figure 127: Schematic of the multi-sheet engineering cost model.

Each sheet reports an aspect of the modelled result – rehabilitation variables, general specifications and costs, costs for individual items, development stage summaries and so on. The input and edit sheet allows the users to change the model input variables and adjust any assumptions. The model itself comprises a number of datasheets depending on the amount of specifications within the afore mentioned. The sheets contain the model calculation and formulas.

Input and editing sheet

Each engineering specification input sheet can be adapted and communicates the specification graphically and describing the variables, assumptions, quantifications, rates and inputs that can be changed by the user by selecting a cell within any sheet and viewing the calculations. The model also allows for inflation adjustment by means of applying a consumer price index (CPI) factor. Values and numbers for the current year and all future years are in real or “constant currency” terms, referenced to the most recent complete year. This means that this year, 2007, and any future years are expressed in 2005 Rands until such time as new rates are procured and revised in the system. Input costs can be adjusted for changes in the relevant cost index, as shown in the detailed input and edit cost sheet. The input and edit sheet informs the specification or general costing sheet allowing for additional functionality through providing variables and making certain assumptions. Also, this sheet shows specific assumptions and information which are used at every step to construct the data input sheet.

General costing sheet

The main purpose of the general costing sheet is to automatically calculate the unit rate for each specification. The aspect of specifications has already been covered in the previous section describing each of the system elements.

Summary sheet

This is a summary of the costs captured for each stage and presented in a typical engineering schedule of quantities format. This sheet is in essence also based on an engineering schedule of quantities or bill of goods. The inputs used in this schedule are automatically linked to the general specification and costing as well as the input and edit sheets' outputs. Also, this type of system is based on direct estimates of each item within the specification.

The engineering cost model can be used to model the engineering costs for the various impoundment scenarios at the ERGO Daggafontein site.

3.8 Summary

This section describes the experimental work and the modelling undertaken as required by the overall system for the engineering costs and the visual, dust, and water aspects. ERGO Daggafontein is used to validate the preliminary models and devise rehabilitation options:

- As it is one of the largest free-standing upstream deposited ring-dyke impoundments in the world.
- As reliable information on the study area is available.
- For permission could be obtained to use the site in this research.
- Since it is not in close proximity to other tailings impoundments. This is beneficial when it is required to take unobstructed panorama photographs as part of the visual perception study.

The modelled impoundment final rehabilitation configurations include changing the geometry and changing the cover. The overall impoundment embankment side slopes vary between 1:1,5 and 1:9 and the cover material include tailings in situ (no cover), rock cladding, grassed armouring and diverse vegetation. Important criteria are defined early on in the experiment. The production of the modelled impoundment is 990 000 tpm over a 16 year period requiring a total storage volume of about 105,6 Mm^3. The modelled dry density of the placed tailings is 1,8 t/m^3 and the final height is kept constant at approximately 37 m.

The visual impact experimental work required the development of a method to quantify such impacts. This required the visualisation of the various impoundment configurations and included manipulating panorama photographs to simulate the different options. The Nominal Group Technique (NGT) study method was employed to analyse the results from this part of the research.

Before modelling the impacts on air quality the software used for this purpose needed to be calibrated. The process whereby the software was calibration is described and makes use of an iterative modelling process whereby the roughness height parameter is varied until the predicted results correlate to dust fallout monitoring data. The DRD 2L24 tailings impoundment was used for the necessary field work.

An analytical water flow and mass balance model was developed as part of this research and is used to illustrate the change in water related impacts changing the configuration of an impoundment.

Lastly, an engineering cost model is described which is used to calculate the costs of various engineering aspects during the design and construction (development), operation, closure, and post-closure maintenance and management stages.

The results of the experimental work and modelling are presented in the Section 4.