CHAPTER FIVE: COMBINING ENVIRONMENTAL IMPACTS WITH ENGINEERING COSTS

> "...the strongest argument of the detractors [of mining] is that the fields are devastated by mining operations...further, when the ores are washed, the water which has been used poisons the brooks and streams, and either destroys the fish or drives them away...thus it is said, it is clear to all that there is greater detriment from mining than the value of the metals which the mining produces."
>
> Agricola (1556)

> "According to the doctrine of objectivity, which is integral with traditional scientific method, what we like or do not like about *what we observe* [own words] has nothing to do with the correct thinking. We should not evaluate what we see. We should keep our mind a blank tablet which nature fills for us, and then reason disinterestedly from the facts we observe."
>
> Pirsig (1999:281)

5.1 Introduction

Chapter 4 presents the predictive modelling results for the various tailings impoundment configurations modelled in this study. It was observed that a change in impoundment slope and cover has a quantifiable effect on the visual and air environmental aspect influence zones as well as the sulphate mass flux. The following section combines the environmental impacts with engineering costs using an innovative technique. The three environmental aspects are described, the changes modelled and quantified, and the quantified results combined with engineering costs.

5.2 Engineering costs

Although the engineering costing system is relatively straightforward its development required considerable care to ensure that sufficient input data was obtained to provide a reliable result without overburdening the data acquisition process or the system itself with unnecessarily detailed information. In practice there is a strong tendency to over measure. The final results, however, for either a single cost item or a development stage give a clear indication of the major cost items. The initial input sheets show the sensitivity of these items to their input parameters hence indicates the required accuracy of measurement or estimation for these parameters.

The benefits of the engineering costing system have been found to be even more valuable than had been anticipated. Clearly the primary benefit is that decision makers tasked with the configuration of tailings impoundments can now reliably estimate engineering costs for proposed impoundments in good time so that stakeholders can readily assess the financial risks and liabilities associated with tailings impoundment construction.

The system is simple to operate, as most computer users are familiar with the spreadsheet programme, Microsoft EXCEL, used in this study to capture data and model outcomes. Additional items can be inserted or existing items can be deleted. Quantities and rates can easily be modified and escalating costs can be accommodated. The sensitivity of total costs to changes in individual rates or measurements can be tested, so that, for example a feasibility cost estimate can be updated as more reliable information becomes available.

Another benefit of the system is that it is transparent and can be used not only as an internal management tool but can also be reviewed by an independent assessor to determine the validity of say the costs provided for the rehabilitation and closure of an impoundment. These provisions can be updated on an annual basis with little effort to assess the liabilities and adjust the provision for these as required by legislation.

A further significant benefit of the system is that it is a practical tool for use by mining groups, managers, environmental practitioners, and others who are responsible for mine closure. It makes closure costs more readily available and tangible. It allows mine management to assess potential future costs which places them in a position to plan works to remedy environmental liabilities and reduce costs wherever possible.

Without modelling the engineering costs and environmental liabilities before tailings deposition commences a commitment may be made to rehabilitate to a higher standard than might be necessary. The amount of materials, such as soil and rock, required to undertake rehabilitation to a pre-determined post-closure land use can be easily and reliably calculated with the system. The system also informs reactive closure of abandoned tailings impoundments where shortfall of materials may exist and certain strategic decisions need to be made as to feasible rehabilitation alternatives and cost implications of each of these. It is, perhaps unrealistic to rehabilitate to a pre-mining land use for example, crop cultivation, if grazing is acceptable and in some cases may even be preferable. It would not be economical to rehabilitate by placing for example a 450 mm subsoil covered by 300 mm topsoil (typically required for reinstating to arable land use) compared with subsoil and topsoil depths of 150 mm and 100 mm respectively which are required as a minimum requirement for grazing land use. The difference in cost could easily be hundred millions for a mining group with no real benefit being achieved.

5.2.1 Flattening embankment slopes

The comparative column charts (Figure 158 and Figure 159) compare the engineering costs for deposited and mechanically flattened tailings impoundment embankment side slopes. The scenario codes for ES1 to ES29 were defined in Table 20 (p. 162) of which the engineering life-cycle costs are given in Figure 156 and Figure 157 on p. 260.

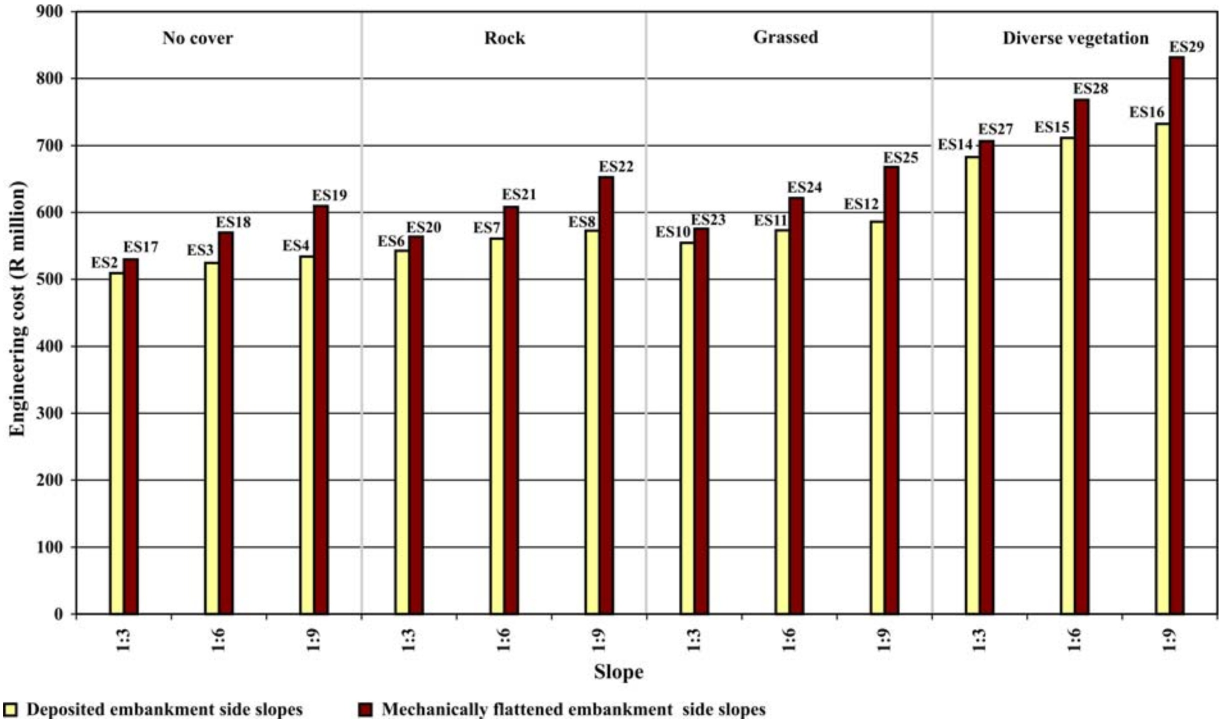

Figure 158: Comparing total cumulative costs for deposited and mechanically flattened slopes.

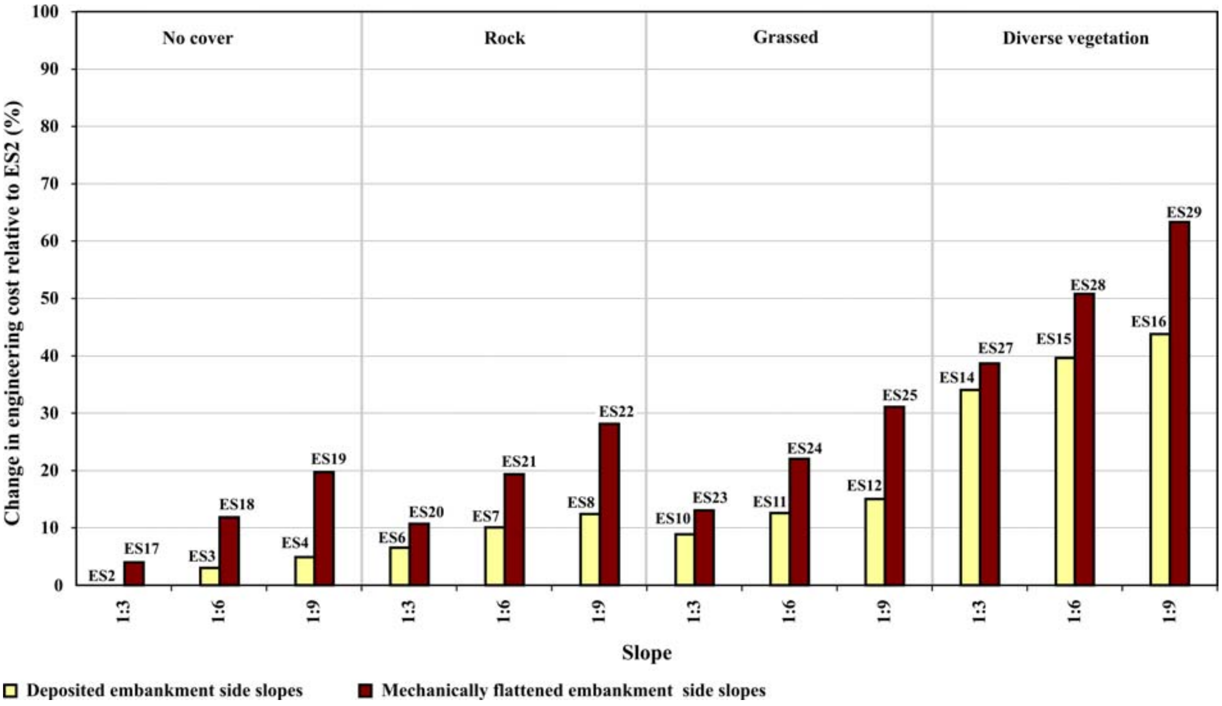

Figure 159: Comparing the costs of flattening embankment slopes for various covers to scenario ES2.

Many tailings impoundments were and in some instances are still constructed with steep embankment side slopes and when closure is sought, slopes are mechanically flattened to an embankment configuration acceptable to stakeholders. Impoundments can be designed and constructed with a final side slope configuration that does not require additional mechanical cut and fill of material during the closure stage in order to achieve an envisaged end embankment configuration. This can be accomplished by depositing the tailings at a predetermined flatter embankment configuration during the operation stage.

Cover systems significantly contribute to the overall costs of an impoundment and even more so than what may initially have been anticipated. The modelled results indicate that the cheapest option is not to cover the impoundment at all, followed by the rock cladding, grassed armoured cover and lastly and most costly the diverse vegetated cover. Constructing a vegetative cover with diversity in vegetation species costs the most. This is attributed to the 450 mm soil cover allowed for to sustain plant growth. It can be argued that even this is not sufficient and that even deeper soils may be required for sustainable root development and plant growth. The diverse vegetation covered impoundment scenario, whilst probably the best for all the adverse environmental aspects, is clearly the most expensive because it requires the most topsoil importation. The total cost depends on the presumption that 450 mm of topsoil is sufficient to sustain a diverse vegetation cover. The cost model can readily accommodate an increase or reduction in soil cover thickness if required.

It has been found that the addition of 300 mm of growth medium significantly affects the revegetation of non-acid tailings. Primary root growth occurs in the growth medium (Figure 95, p. 176), but roots can extend into the tailings to extract moisture during droughty conditions (Milczarek and Yao, 2004). At a gold tailings impoundment in Nevada a final cover thickness of 900 mm was selected to optimize evapotranspiration and minimize infiltration (Gorman, 2004). A natural soil deeper than 600 mm can be regarded as an arable soil on condition that the slope is not steeper than 1:14, whereas at least 250 mm of soil is needed to establish pastures (CM, 1981). If vegetation can be established in situ the cost of having to import soil to provide a suitable and sustainable growing medium will not be necessary and the cost therefore avoided.

Figure 159 compares various scenarios to configuration ES2. Configuration ES2 may be considered as the standard practice option in that it includes depositing tailings at an overall 1:3 embankment side slope, an allows for the planting of grass during operation to control erosion (rising green wall). However costs are not included for the construction of a final engineered cover.

This approach is standard practice in that it is at present the most common approach implemented by industry and approved by authorities. The figure compares the costs of flattening embankment slopes for various cover options to that of the scenario with an embankment slope of 1:3 and no cover (tailings in-situ). Scenario ES2 is estimated to cost R509,3 million. The most expensive option (ES29) is to construct the impoundment with an initial 1:1,5 embankment slope and then during the closure stage flatten the embankment to a 1:9 slope and cover the entire impoundment with diverse vegetation planted in 450 mm soil. This is estimated to cost R831,8 and is 63 % more than ES2.

Figure 160 uses scenario ES1 as the baseline configuration to compare scenarios ES4 and ES19 with. ES1 has a rate of rise of 2,5 m a year with an overall final embankment side slope of 1:1,5 with no cover. ES4 and ES19 both end with an overall embankment side slope of 1:9. The only difference between the these two configurations is that ES4's final embankment configuration is deposited during operation whereas ES19 is constructed at a steep slope (1:1,5) and then mechanically flattened during closure.

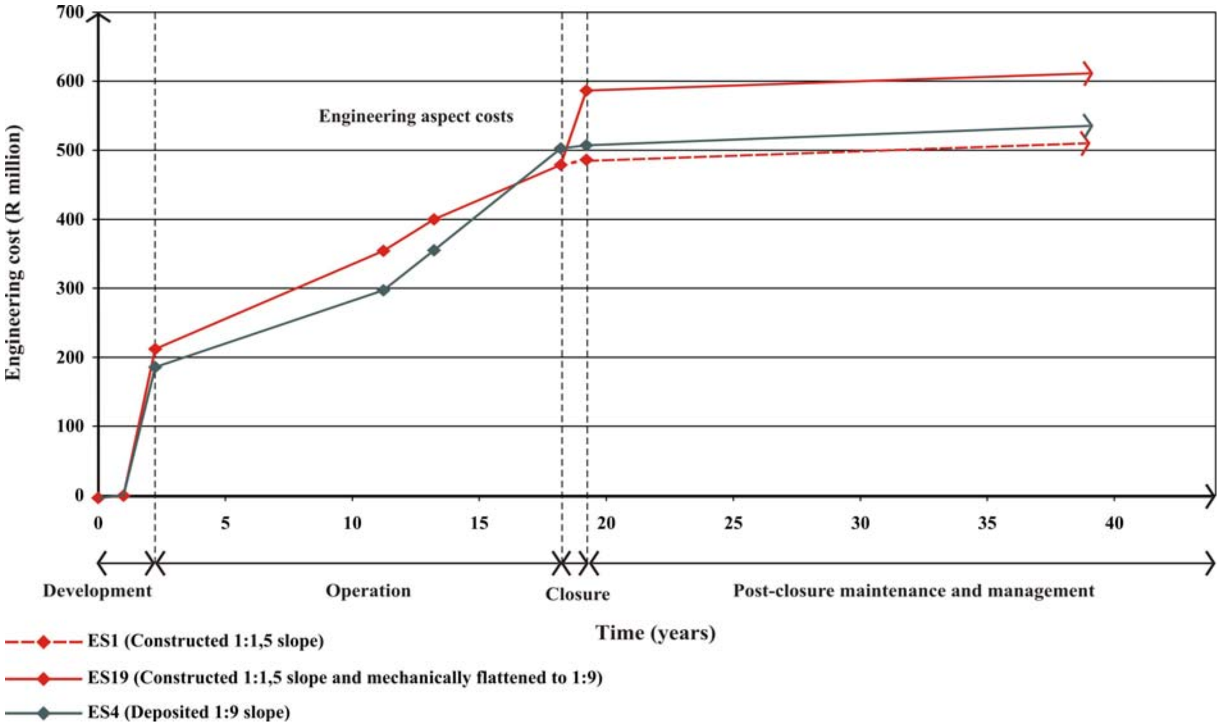

Figure 160: Comparing the engineering life cycle costs for an impoundment with no cover and a 1:9 deposited slope (ES4) and a 1:9 mechanically flattened slope (ES19). ES1 represents an impoundment with an overall side slope ratio of 1:1,5 with no cover.

Although configuration ES19's total life cycle cost is only 14% more than that of ES4, the closure cost of mechanical flattening the side slopes is almost twenty six times more than the closure cost for ES4. Minor routine activities are undertaken to close scenario ES4 whereas more than a R100 million will be spent to flatten scenario ES19's steep embankment side slopes mechanically to the same in situ deposited configuration as that of ES4. This example is used to illustrate the significant costs involved to mechanically flatten the embankment side slope for a tailings impoundment.

It is therefore cheaper to construct the final tailings embankment using deposited tailings as part of the operation stage compared to constructing an impoundment with a steep embankment and having to flatten such mechanically during the closure stage.

The initial total construction cost is higher for the steep (1:1,5) embankment slopes scenarios (ES1 and ES19) than that of the deposited flat (1:9) embankment slope scenario (ES4). Cost items which significantly influence the higher initial costs for the scenarios with steeper slopes during the construction state are:

- greater starter wall construction costs; and
- higher elevated chimney drain construction costs.

One would expect that the initial construction cost of impoundments with flatter embankment slopes must be more expensive than that of impoundments with steeper slopes because of:

- higher initial land acquisition costs to accommodate larger footprints; and
- additional initial construction costs resulting from the larger impoundment footprint.

These cost items are however far less than that of the starter wall and chimney drain costs which are more for impoundments constructed with steeper embankment side slopes.

5.2.2 Conclusion

This section demonstrates the use the engineering cost system by means of modelling different impoundment scenarios to test the effect on engineering costs when flattening tailings impoundment embankment side slopes.

The engineering costs for deposited and mechanically flattened slopes are also compared. The comparative cost analysis illustrates that the total costs for tailings impoundments are significantly influenced by the cost to mechanically flatten embankments during closure.

The choice in cover is one of the most important engineering cost items to consider for the impoundment life cycle. The variance in costs for the design, construction and operation stages are trivial especially when compared to the total tailings impoundment engineering costs and the potential costs that can be incurred during the closure stage. The final impoundment cover cost is also sensitive to the importing of materials required to construct such. For example, there is a significant difference between using a diverse vegetation cover (450 mm imported soil) and leaving it as is (no cover).

There is thus the opportunity to substantially reduce the engineering life-cycle costs by determining prior to deposition what the final impoundment embankment configuration must be and then use the tailings to deposit such during the operation stage.

The two main cost items during the closure stage are:

- the mechanical flattening of the slopes requiring the handling of large volumes of material; and
- the construction of a suitable cover that could require the importing of also large volumes of suitable material.

5.3 Combining environmental impacts with engineering costs

The combining of environmental impacts with engineering costs is demonstrated by using the practical examples of applying the results from the previous section in conjunction with the environmental data from the ERGO Daggafontein site for the purpose of illustrating these examples.

The two examples will elaborate on the typical standard practice approach where the overall impoundment embankment is constructed at a 1:3 side slope. The first example comprises using a constant 1:3 embankment slope with four different cover types which were previously defined, discussed and modelled, namely:

- not applying any cover (tailings in situ),
- rock cladding,
- grassed armouring, and
- diverse vegetative cover.

The second example focuses on using the same cover and flattening the overall tailings impoundment embankment side slope. The grassed armouring cover will be used for this application and the overall embankment side slopes will vary between what is considered to be steep (1:1,5) and flat (1:9), that is:

- 1:1,5;
- 1:3;
- 1:6; and
- 1:9.

5.3.1 Change in cover

Table 61 provides the codes for the scenarios modelled to calculate the engineering costs and quantify the environmental effects which result from the change in impoundment cover with an overall embankment slope of 1:3.

Table 61: Scenario codes used in the study for calculating the engineering costs and predicting the change in effect on key environmental aspects for an embankment slope of 1:3.

Covers	**Engineering cost**	**Visual perception**	**Air quality**	**Water quality**
Tailings in situ (no cover)	ES2	VS1	AS2	WS2
Rock cladding (300 mm)	ES6	VS3	AS6	WS6
Grassed soil-rock armouring	ES10	VS5	AS10	WS10
Diverse vegetation	ES14	VS7	AS14	WS14

The combination of the environmental impacts with the engineering costs requires the demonstration and discussion of the scenarios (Table 61) and will address:

- engineering costs;
- visual perception zone of influence;
- air quality zone of influence; and
- sulphate mass flux.

Engineering costs

The engineering costs for the modelled scenarios are summarised in Table 62, Figure 161 and Figure 162. Scenarios ES2, ES6, ES10 and ES14 share the same embankment slope configuration and differ only in the cover placed during rehabilitation as part of the closure stage which includes:

- doing nothing and leaving the impoundment uncovered;
- covering the impoundment surface with rock;
- covering the impoundment with a grassed armouring; and
- using a diverse vegetative cover.

The design and construction is scheduled to take a year each, operation is calculated over 16 years, closure is scheduled to take two years, and 20 years are allowed for the post-closure maintenance stage. The cumulative engineering life-cycle costs are indicated in Figure 161 for these stages over the tailings impoundment construction period.

Table 62: Engineering costs for covers ES2, ES6, ES10 and ES14.

	Engineering cost (R million)					
Engineering scenario	**Design**	**Construction**	**Operation**	**Closure**	**Maintenance**	**Total**
ES2 (No cover)	3,4	203,5	270,4	6,4	25,7	509,4
ES6 (Rock cladding)	3,4	203,5	270,4	39,8	25,7	542,8
ES10 (Grassed armouring)	3,4	203,5	270,4	51,7	25,7	554,7
ES14 (Diverse vegetation)	3,4	203,5	270,4	179,8	25,7	682,8

The closure cost for the four configurations are R6,4 million, R40 million, R52 million and R180 million respectively. There is more than a R170 million difference in the closure costs when comparing the no cover scenario, i.e. leaving the impoundment as is after deposition, and rehabilitating the impoundment with a diverse vegetation cover (the most expensive cover modelled). It will cost about R33 million more to cover the impoundment with a 300 mm rock cladding and approximately R45 million more to rehabilitate the impoundment with a grassed armouring than it is to do nothing. The armouring is 300 mm deep and is made up of 67% rock and 33% soil. It is astonishing to realise how much covers can cost. Although it is expensive to construct an engineered cover, the cost of this item is in most cases still less than the total initial construction cost or the total cost to operate the facility.

The closure costs represent the money to be spent at closure on rehabilitation and may be regarded by regulators as a liability during the life of the facility in terms of cost to be incurred in order to meet some sort of acceptable post-closure end state. Legislation requires proponents to provide financially for liabilities setting the said amount aside during the life of the facility and in the event that the rehabilitation is not undertaken by the responsible party, government has the financial means to undertake such rehabilitation instead.

Design, construction and operation costs are the same for the four scenarios. The amount of tailings disposed is the same and the geometry remains the same. Similarly the overall embankment side slope configuration is constant. However, the covers are varied and it is evident that the choice of final cover has a significant impact on the overall impoundment construction cost. Closure costs vary between R6,4 million and R180 million. This presents a significant variance in costs.

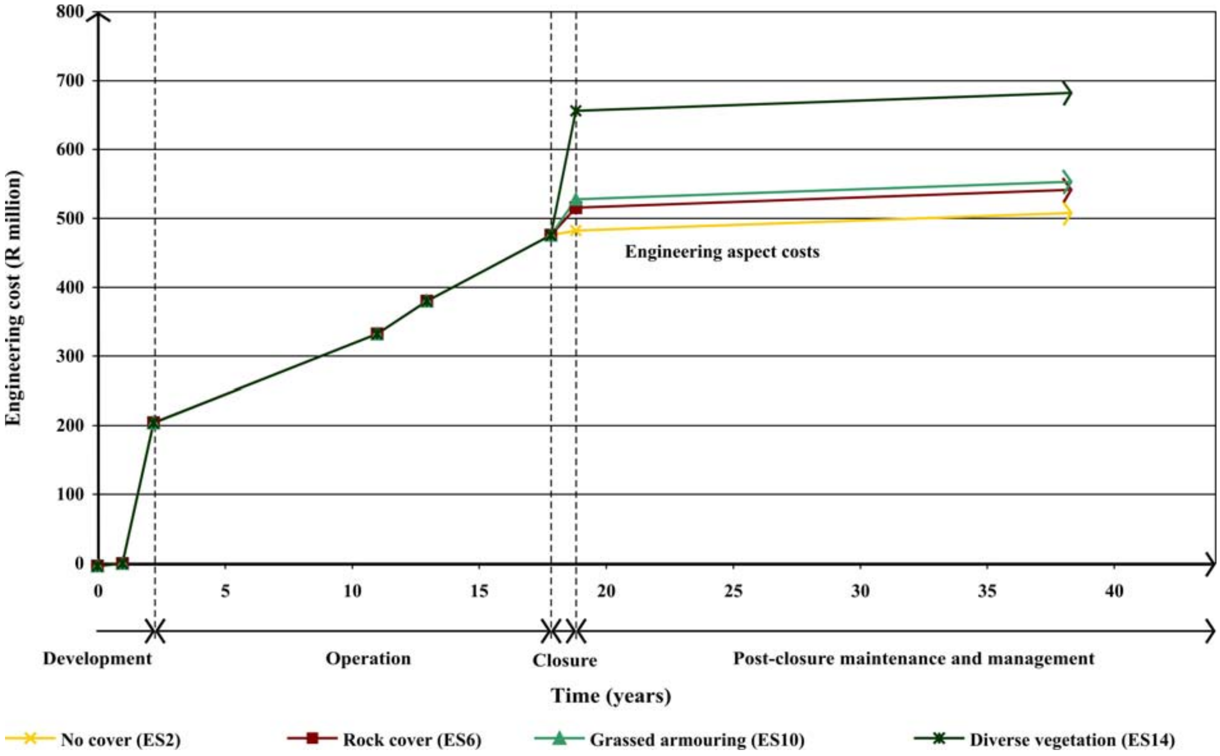

Figure 161: Cumulative engineering impoundment life-cycle costs indicated for ES2, ES6, ES10 and ES14.

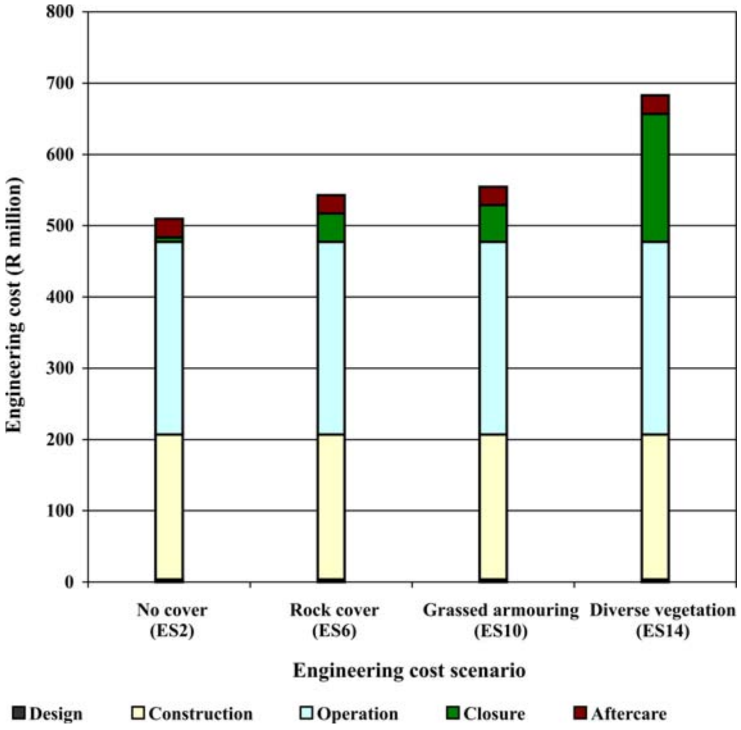

Figure 162: Influence of change in cover types on engineering stage costs.

When comparing the closure stage cost items to that of the construction stage it becomes apparent that the total closure stage cost are still less than the total initial construction stage costs. The perception is that it is expensive to close and rehabilitate a tailings impoundment. Indeed, it can be expensive to rehabilitate an impoundment, but relative to other impoundment stage costs it is not orders of magnitude more.

The slopes of the lines in Figure 161 for the post-closure maintenance and management stage are identical. In practice this will not be so as different cover types will result in varying maintenance requirements. Presently the engineering cost system allows for the following standard post-closure maintenance and management (aftercare) cost items:

- access road maintenance;
- external storm water controls maintenance;
- fence line maintenance;
- paddock maintenance; and
- third party (external) monitoring and inspections.

Visual

The visual perception influence zone results presented in Figure 148 (p. 252) are used in Figure 163 to compare the critical visual perception zones of influence for the visual scenarios VS1, VS3, VS5 and VS7. There is a marked change in the various perception zones of influence resulting from the change in cover.

Surface areas of the detection perception zones for the scenarios are VS1 (21 800 ha), VS3 (16 000 ha), VS5 (7 400 ha), and VS7 (1 200 ha). A remarkable change in the detection visual perception zone of influence is achieved by changing the impoundment cover. The detection visual perception zone of influence is reduced from more than 21 000 ha to 1 200 ha when comparing the best performing diverse vegetative cover with poorest alternative of doing nothing and leaving the impoundment uncovered.

Covering the impoundment with rock will cost R 33,4 million more than doing nothing. This is an increase of 7 % in cost (ES6 compared to ES2). However, by spending 7 % more a reduction of 26 % in the detection visual perception zone of influence is achieved. Furthermore, by spending an additional R 12 million to cover the impoundment with a grassed armouring cover, a 66 % reduction in area can be achieved. The most expensive cover (diverse vegetation) will cost R128 million more than leaving the impoundment without any cover. However, by spending this additional amount (34 % more than doing nothing) the detection visual perception zone of influence area is reduced by almost 95 % (Figure 164, p. 272).

The option to cover an impoundment with a grassed armouring at an additional cost of about R45 million has the highest cost to reduction in surface area factor. For every additional R1 million spent, compared to the do nothing option, a reduction in 320 ha is achieved whereas rock cladding and diverse vegetation have a 170 ha and a 120 ha reduction respectively. A similar trend in reduction of the recognition visual perception zone of influence is observed although not as dramatic as with the detection visual perception zone of influence. Selecting the appropriate cover can significantly reduce the detection visual perception zone of influence. This additional cost, especially when compared with the total impoundment construction cost, and the reduction in zone of influence may justify the additional expense.

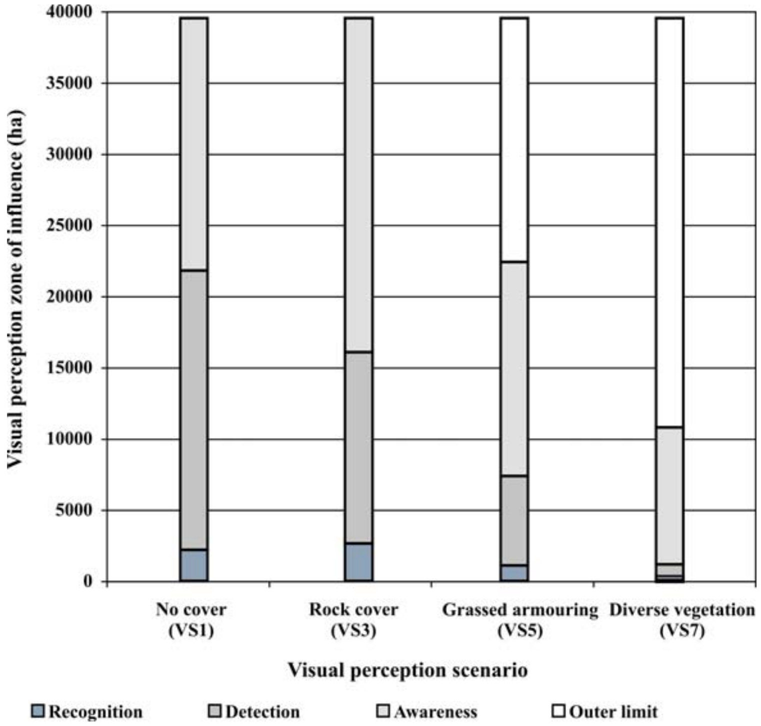

Figure 163: Comparing the various covers modelled shows a marked reduction in the critical visual perception zones of influence.

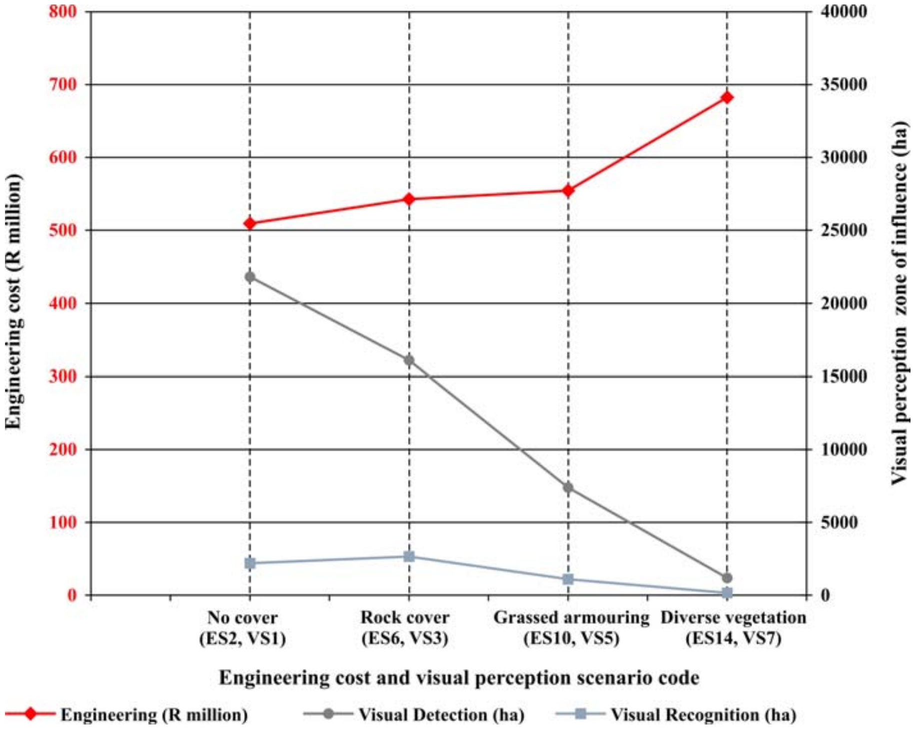

Figure 164: Combining visual perception zone of influence and engineering costs for different cover types.

Air

Figure 165 compares the 25 µg/m^3 PM$_{10}$ concentration and the dustfall (TDS) air quality zones of influence for scenarios AS2, AS6, AS10 and AS14.

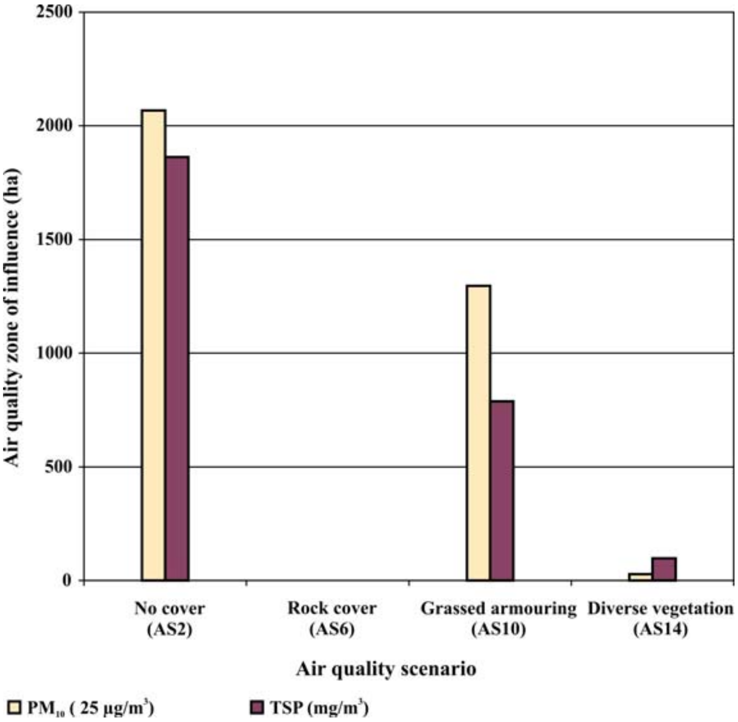

Figure 165: Influence of change of cover on air quality zone of influence.

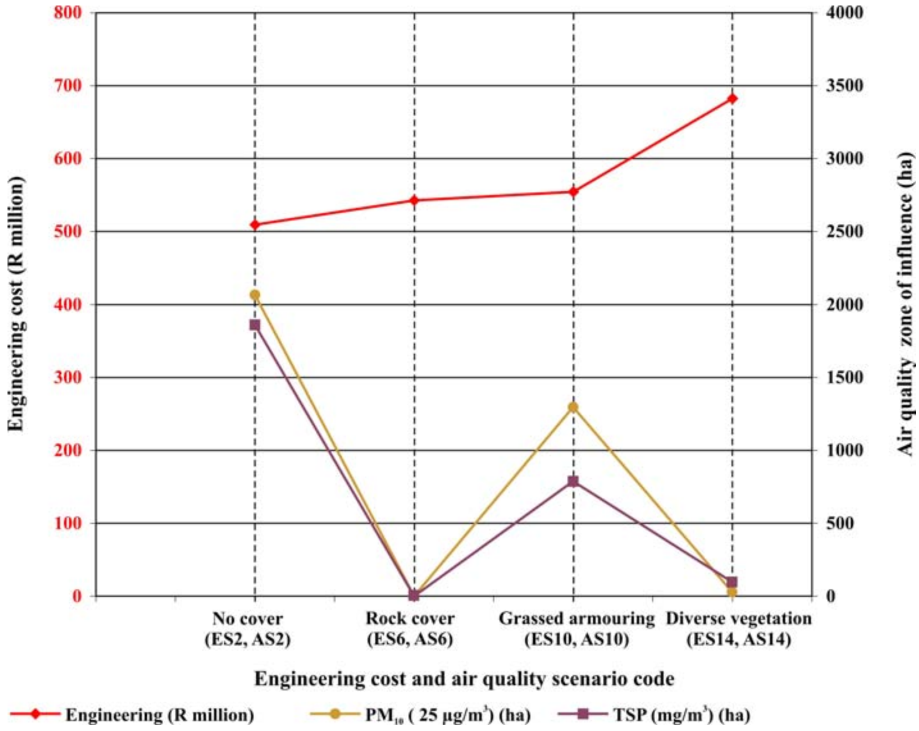

Figure 166: Combining air quality zone of influence and engineering costs for different cover types.

The covers (control efficiencies) are applied to the entire impoundment surface, which is the embankment slopes and top of impoundment. At the time of the modelling of the air quality impacts it was assumed that using a rock cover will reduce the emissions off the impoundment by 100 % which is maybe over conservative as an imported rock cover is likely to contain some fines. Also, a mitigation efficiency of 50 % is attributed to the grassed armouring cover and 80 % to the diverse vegetation cover. It is possible that both the afore-mentioned covers will be more effective in reducing the potential impact on air quality.

A pronounced change in the air quality zone of influence results from the change in cover. The approximate air quality influence zones are AS2 (2 070 ha), AS6 (0 ha), AS10 (1 300 ha), and AS14 (30 ha) for the 25 $\mu g/m^3$ PM_{10} concentration and AS2 (1 850 ha) AS6 (0 ha) AS10 (790 ha) and AS14 (100 ha) for dustfall. The air quality influence zone is reduced from 2 070 ha to 30 ha when comparing the doing nothing option with using a diverse vegetative cover.

By spending R34 million more in covering the impoundment with rock than the no cover option a reduction of 2 070 ha is achieved. At an additional cost of R45 million the grassed armouring reduces the 25 $\mu g/m^3$ PM_{10} concentration air quality influence zone by 770 ha to 1 300 ha. Using a grassed armouring reduces the emission influence zone by 37 %. Furthermore, the diverse vegetation cover achieves a 99 % reduction in influence area at an additional cost of R173 million (comparing VS14 to VS2).

The option to cover an impoundment with rock at an additional cost of about R34 million has the highest cost to reduction in influence area ratio. For every additional R1 million spent, compared to the no cover (tailings in situ) option, a reduction in 60 ha is achieved whereas the grassed armouring and diverse vegetation have a 17 ha and a 12 ha reduction for every additional R1 million spent respectively.

Water

Figure 167 compares the change in mass load for the water modelling scenarios WS2, WS6, WS10 and WS14 representing an impoundment with an overall embankment side slope of 1:3 and no, rock, grassed armouring and diverse vegetation covers respectively. A change in the mass load results from a change in cover. The mass load sulphates measured in tonnes for the various water modelling scenarios are WS1 (1 800 t), WS6 (2 200 t), WS10 (1 600 t), and WS14 (1 200 t). The mass load is reduced from 2 200 t to 1 200 t when comparing a rock covered impoundment and an impoundment covered with diverse vegetation.

WS6 indicates that the rock cover will result in less runoff, less evaporation, and more infiltration and discharge with the potential for slightly more sulphates to be released into the system. Scenario WS14 indicates the lowest mass load of 1 200 t when comparing the four covers. This can be achieved by spending an additional R 173 million than the no cover option. Similarly for an additional R 45 million the mass load sulphates released into the system can be reduced to 1 600 t. This is a 15 % reduction in sulphates compared to scenario WS2 (no cover). Although the diverse vegetation cover can reduce the mass load by 34 % the cost to reduction in mass load ratio is lower than that for the grassed armouring option. The cost to reduction in mass load ratio for the grassed armouring and diverse vegetation cover options are about 6 and 4 respectively. In other words, for every additional R1 million spent a reduction in 6 and 4 t sulphates can be accomplished.

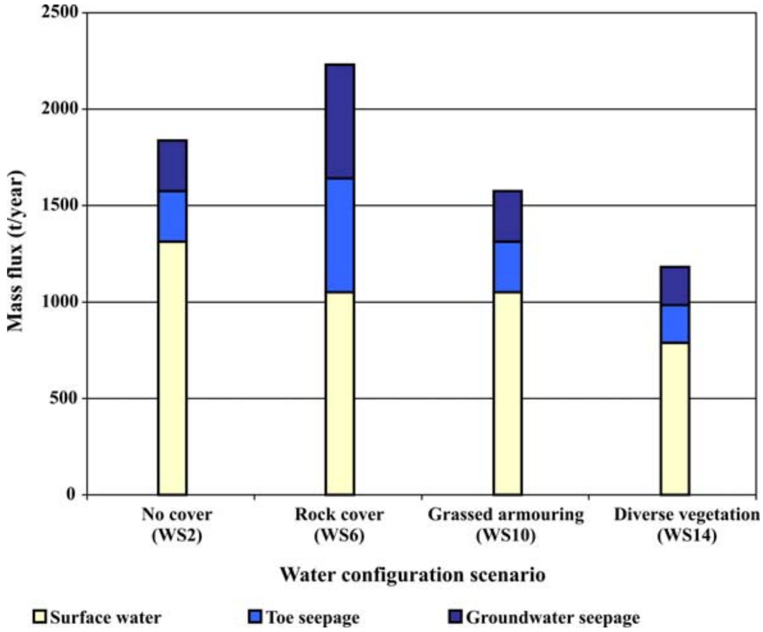

Figure 167: The comparative bar chart illustrates the influence of change in cover on mass flux.

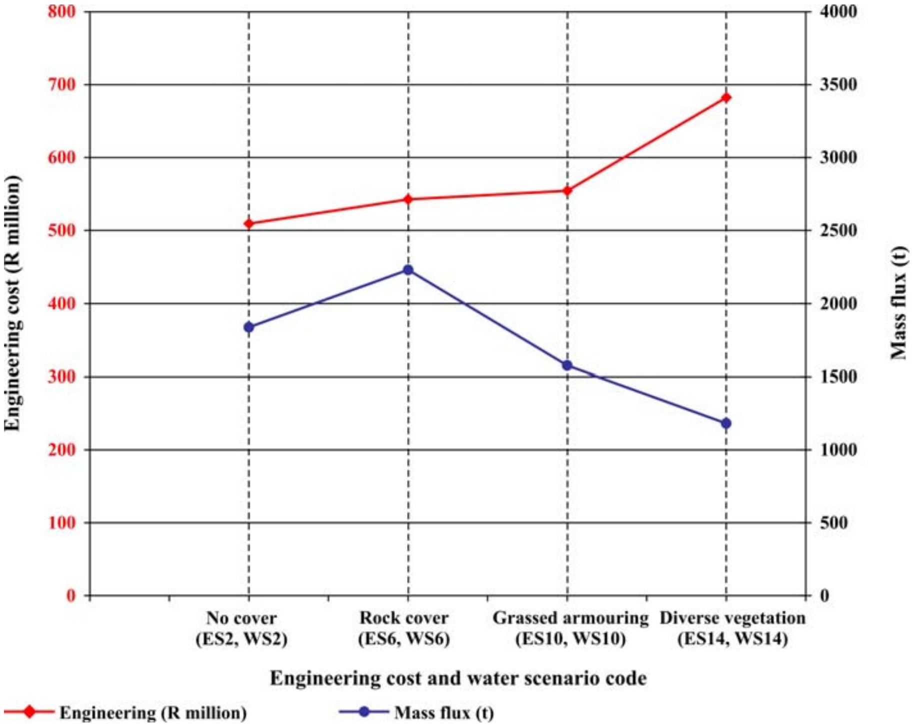

Figure 168: The combination of mass flux and engineering costs for changes in cover types.

Combined results

Figure 169 is a plot of the total engineering life-cycle costs combined with the environmental aspects for the scenarios modelled in the previous section to illustrate the influence of cover type.

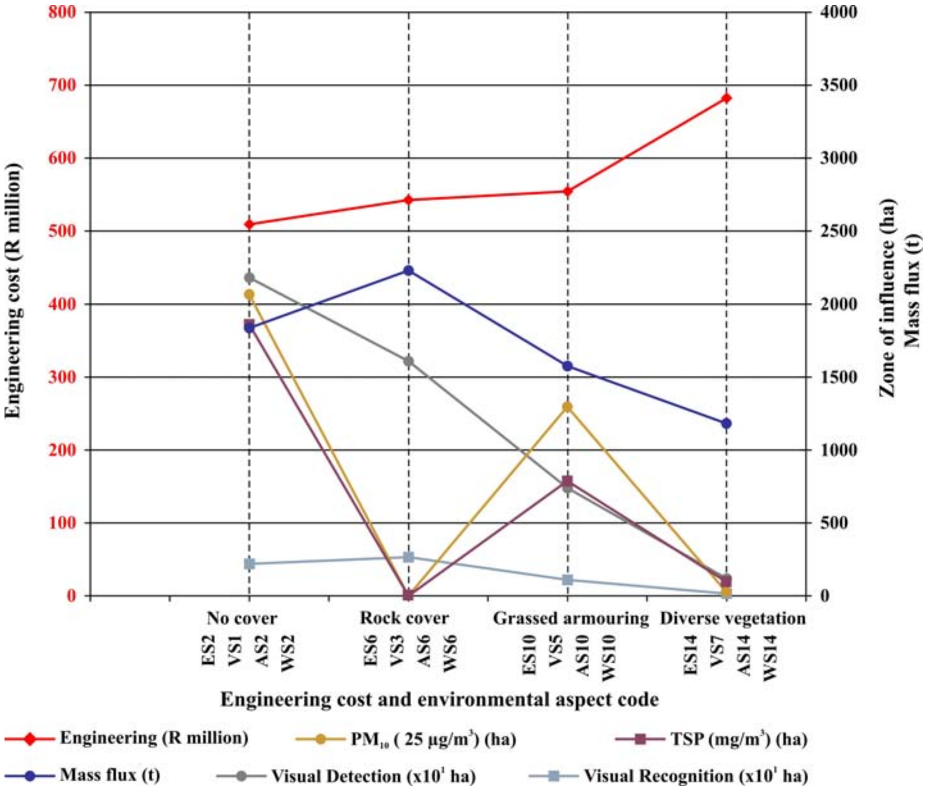

Figure 169: Combined environmental aspect influences and engineering costs for changes in tailings impoundment cover types.

This figure visually illustrates the combination of visual and air quality influence zones, sulphate flux mass flux, and engineering costs resulting from the change in cover type. Environmental lobbyists' may insist that the impact on the environment ought to be minimised at whatever expense and hence the engineering design with the diverse vegetation cover may be preferred. At an additional cost of R173 million (the option is 34 % more expensive than the total engineering cost of ES2) a decrease in 95 % visual detection perception influence zone, 99 % PM10 air quality influence zone, and 36 % sulphate mass load can be achieved. Using rock cover results in a 7 % increase in engineering costs and a 21 % increase in the sulphate mass load. However the visual detection perception influence zone is reduced by almost 26 % and decrease the PM10 air quality influence zone reduced significantly. On the other hand at an additional cost of R45 million to applying no cover, a grassed armouring cover (scenario ES10) results in a reduction of 66 %, 37 % and 14 % for the visual detection perception influence zone, PM10 air quality influence zone, and sulphate mass load respectively.

Engineering cover costs can be determined and compared to the expected change in both influence zones and water pollutant as mass loads. Graphs, such as Figure 169, can be used to communicate the relative change in environmental aspect influences for different engineering decisions made when considering the rehabilitation alternatives during closure.

5.3.2 Flattening embankment slopes

The previous section evaluated the influence of change in cover type on the environment and combined these aspects with engineering costs. The following section models and describes the effect of slope change on the environment and will combine these influences with engineering costs. Table 63 provides the codes for the scenarios modelled to demonstrate the effect that can be expected if the overall embankment side slope is changed while keeping the cover the same. A grassed armouring cover was used as this represents what is currently accepted as best practice. The overall embankment side slopes vary between what is considered to be steep (1:1,5) and flat (1:9):

- 1:1,5;
- 1:3;
- 1:6; and
- 1:9.

Table 63: Scenario codes used to illustrate the influence of change resulting from a change in slope. A grassed armouring cover is used in the scenarios.

	Grassed armouring cover			
Slope	**Engineering cost**	**Visual perception**	**Air quality**	**Water quality**
1:1,5	ES9	VS5	AS9	WS9
1:3	ES10	VS5	AS10	WS10
1:6	ES11	VS5	AS11	WS11
1:9	ES12	VS5	AS12	WS12

The following environmental aspects are modelled and combined with engineering costs:

- visual perception zone of influence;
- air quality zone of influence; and
- sulphates mass flux;

Engineering costs

It is more expensive to reactively flatten embankment slopes mechanically than it is to construct slopes during the operation stage using deposited tailings. For this reason, the following section investigates the influence for deposited slopes and not mechanically flattened slopes.

The engineering costs for scenarios ES9, ES10, ES11 and ES12 are presented in Table 64.

Table 64: Engineering life-cycle costs for scenarios ES9, ES10, ES11 and ES12 indicate the change in costs relative to the change in embankment slope.

	Cost (R million)					
Engineering scenario	**Design**	**Construction**	**Operation**	**Closure**	**Maintenance**	**Total**
ES9 (1:1,5)	3,2	210,7	264,1	50,9	25,0	553,9
ES10 (1:3)	3,4	203,4	270,4	51,7	25,7	554,6
ES11 (1:6)	3,7	191,9	296,9	53,8	27,0	573,3
ES12 (1:9)	4,1	183,7	314,0	55,9	28,2	586,0

The results indicate the overall engineering costs varying between R554 million for the 1:1,5 slope and R586 million for the 1:9 embankment slope configurations covered in grassed armouring. When comparing the total engineering costs of scenarios ES10 with an embankment slope of 1:3, ES11 with an embankment slope of 1:6 and ES12 with an embankment slope of 1:9 to the scenario with the steepest embankment slope of 1:1,5 (ES9), the increase in costs varies between R0,7 million (0,1 %) and R33 million (6 %).

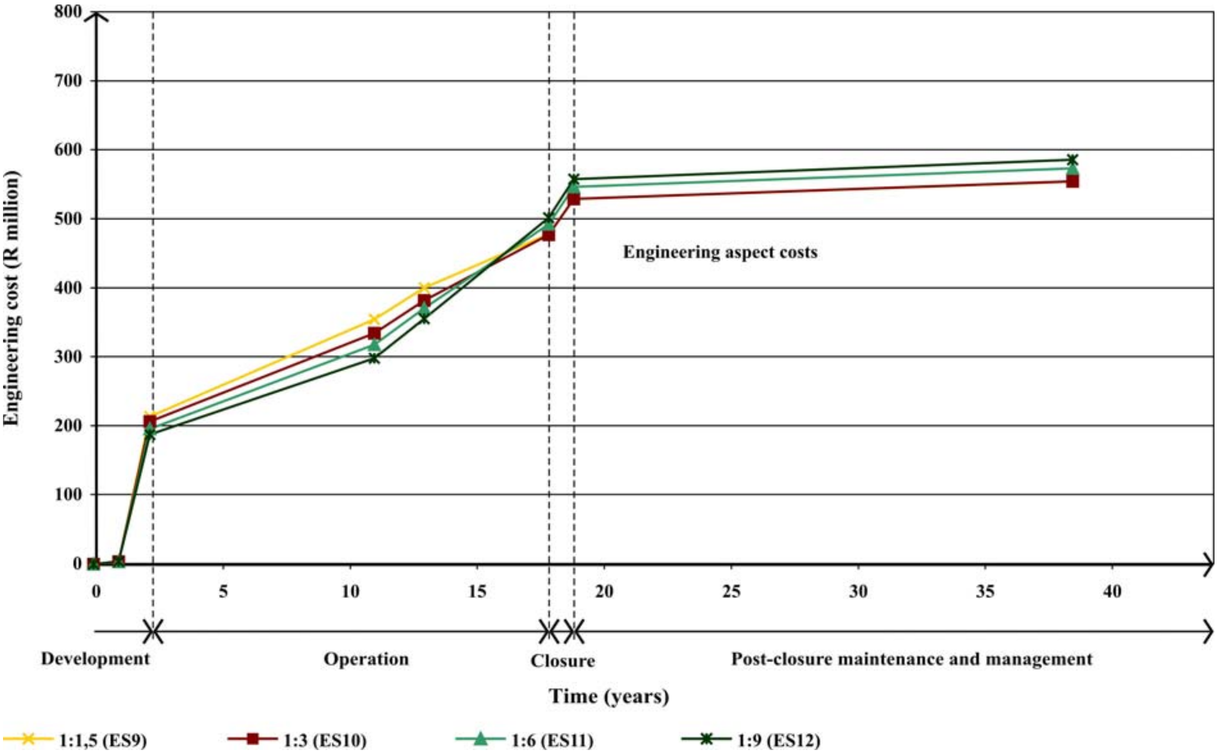

Figure 170: Cumulative engineering impoundment life-cycle costs indicated for scenarios ES9, ES10, ES11 and ES12.

The difference in total engineering costs of 6 % is negligible when compared to the total impoundment life-cycle costs of between R554 million and R586 million. This is an important observation as vegetation establishment may in certain instances favour flatter step-in side slopes which in turn will require the flattening of the overall impoundment embankment side slope.

Engineering cost items that significantly influence the impoundment life-cycle costs are the:

- starter wall, paddock wall, blanket drain, and elevated drain chimney construction costs;
- wall building and pipe work relocation, catwalk and platforms lifting, the increase in outer surface area which is grassed as the impoundment rises, elevated drain construction operation costs; and
- basin profiling, rehabilitation of the basin, and rehabilitation of the outer slopes closure costs as a result in changed impoundment configuration.

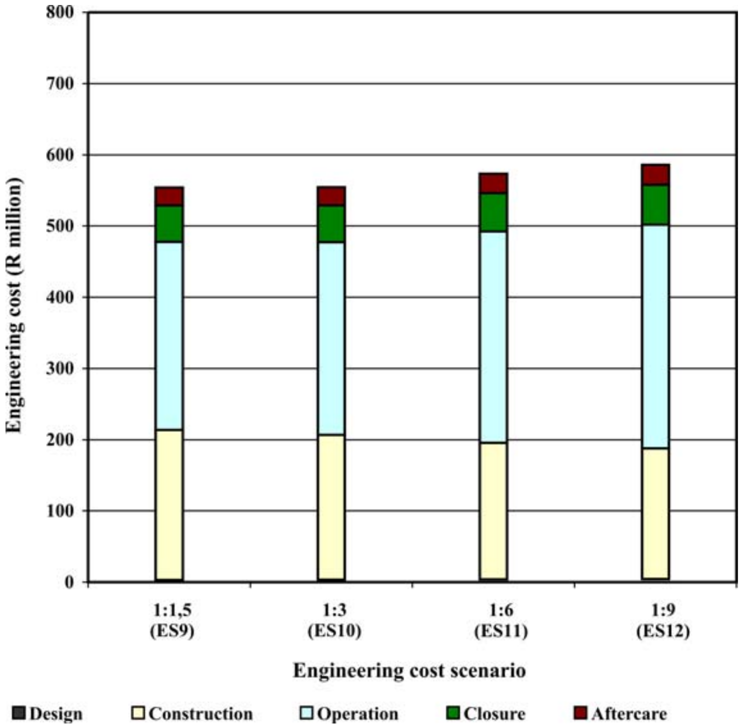

Figure 171: Comparative bar chart results for the engineering scenarios costs ES9, ES10, ES11 and ES12. The development cost is split into design and construction cost items.

There is a variance of about 30 % in the design, 15 % in the construction, 20 % in the operation, 10 % in the closure, and 13 % in the maintenance stage costs when comparing the flattest embankment slope option (1:9) to the steepest embankment slope option (1:1,5) modelled. The total cost of the 1:9 configuration is about R30 million more expensive that the 1:1,5 configuration. It is therefore cheaper to construct an impoundment with a steeper embankment side slope than to construct an impoundment with a flatter embankment side slope (Table 65). Engineering construction cost items that significantly influence the total construction cost are:

- starter wall construction;
- elevated drain chimneys construction; and
- return water dam (RWD) construction

Table 65: Significant construction cost items for scenarios ES9, ES10, ES11 and ES12.

	Engineering costs (R million)			
Description	**ES9 (1:1,5)**	**ES10 (1:3)**	**ES11 (1:6)**	**ES12 (1:9)**
Starter wall construction	92,5	88,1	80,7	75,0
Elevated drain chimneys construction	25,0	22,7	19,0	16,4
RWD embankment construction	12,3	12,4	13,0	13,5
Toe wall construction	1,1	1,2	1,5	1,7
Blanket drain construction	2,8	2,9	3,1	3,2
Delivery and distribution piping installation	14,6	14,7	14,8	14,9

The rehabilitation costs (Table 66) to cover just the side slopes with a grassed armouring is about R7 million for an impoundment with an overall embankment side slope of 1:1,5, approximately R11 million for slope of 1:3, R18 million for a 1:6 slope and R26 million for an embankment overall slope of 1:9. If for argument sake an overall embankment slope of 1:6 is required to sustain grass, the additional engineering cost compared to the slope of 1:3 will be about R20 million.

Table 66: Comparison of closure stage cost items for the various embankment side slopes modelled.

	Grassed armouring costs (R million)			
Closure stage cost items	**ES9 (1:1,5)**	**ES10 (1:3)**	**ES11 (1:6)**	**ES12 (1:9)**
Basin profiling	5,2	4,2	2,7	1,7
Tailings impoundment basin cover	37,2	34,4	29,0	23,8
Tailings impoundment embankment slope cover	6,4	10,9	19,7	28,0
Total	48,8	49,5	51,5	53,4

Figure 172 illustrates an important observation in that the embankment slope does not have the same significant impact on engineering cost as change in cover has. It can however be expected that an impoundment with a very flat embankment slope will increase in costs whereas an impoundment with a steep embankment slope will not vary significantly in engineering cost from an impoundment with a 1:1,5 embankment slope.

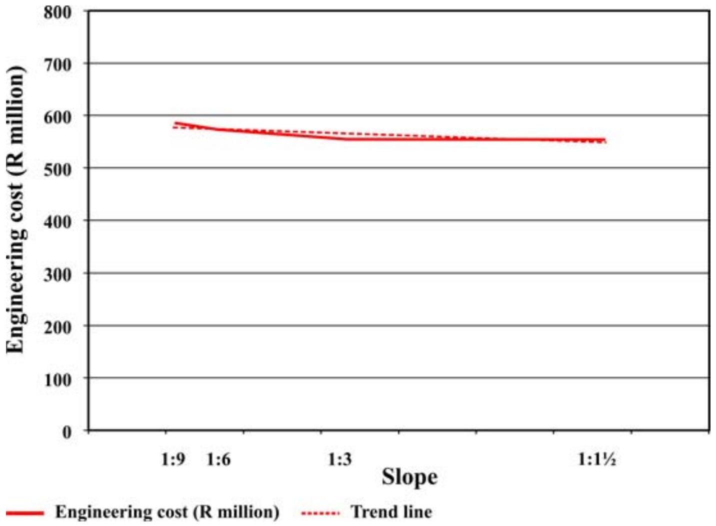

Figure 172: Change in engineering cost for changes in slope for a grassed armouring covered impoundment.

Visual

The mean visual perception comparative bar chart results in Figure 141 (p. 245) illustrates that there is no definitive relation between overall embankment side slope and its effect on visual perception distance as there is no apparent trend from these results. This may well be because only two overall embankment side slope configurations were tested in the experiment namely 1:3 and 1:6. It was however observed that cover type significantly influences the visual perception distances.

It was therefore decided to use the 1:3 embankment visualisation results presented in Table 56 (p. 249) for combination with engineering costs in Figure 173. The detection perception zone influence surface areas for the scenario VS5 (1:3 slope and grassed armouring cover) is 7 400 ha and for the purpose of this example this number will be used for the scenarios being compared.

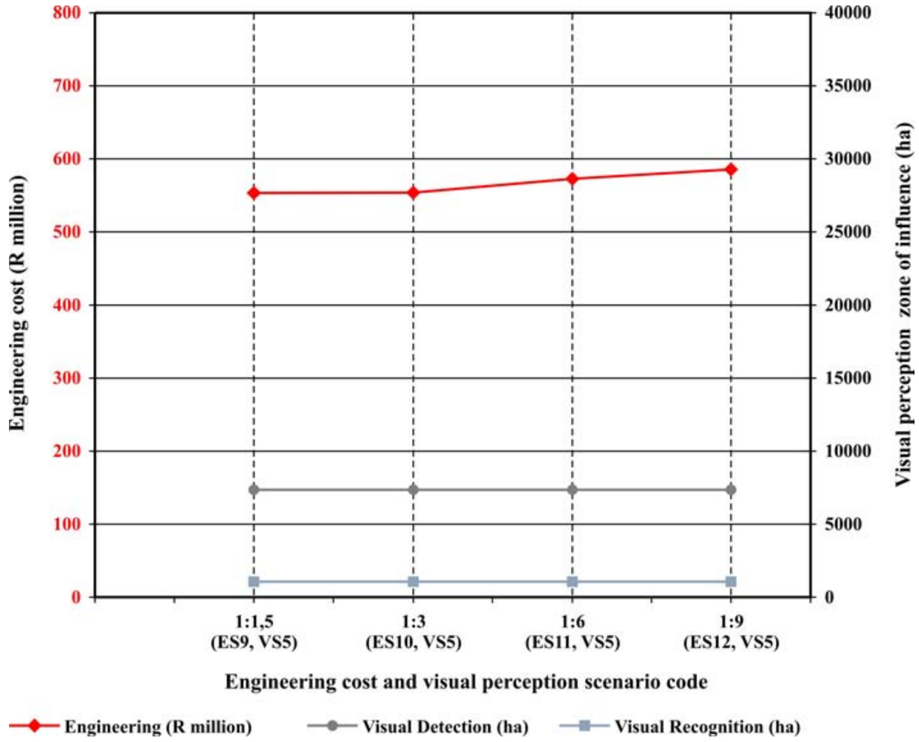

Figure 173: Combining visual perception zone of influence and engineering costs for change in slope.

Air

Figure 174 shows an increase in air quality zone of influence surface area with a decrease in embankment slope. The air quality influence areas for the 25 µg/m^3 PM10 isopleths are 1200 ha (AS9), 1300 ha (AS10), 1500 ha (AS11) and 1750 ha (AS12). This represents an increase of 0,1 %, 3,5 %, and 6 % for AS10 (1:3), AS11 (1:6) and AS12 (1:9) respectively when compared AS9 (1:1,5). The increase in air quality influence area is attributed to the change in impoundment surface area exposed to wind erosion.

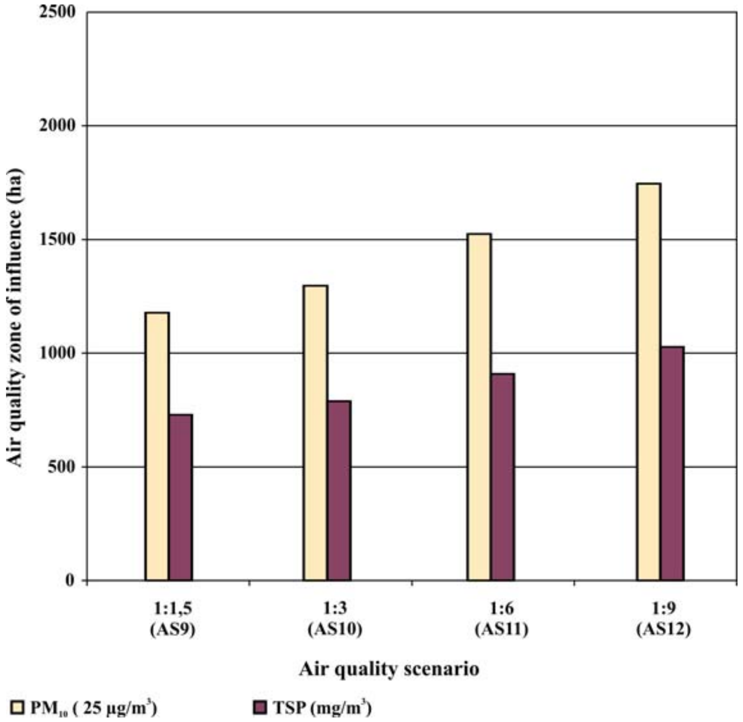

Figure 174: Influence of change in slope on air quality zone of influence.

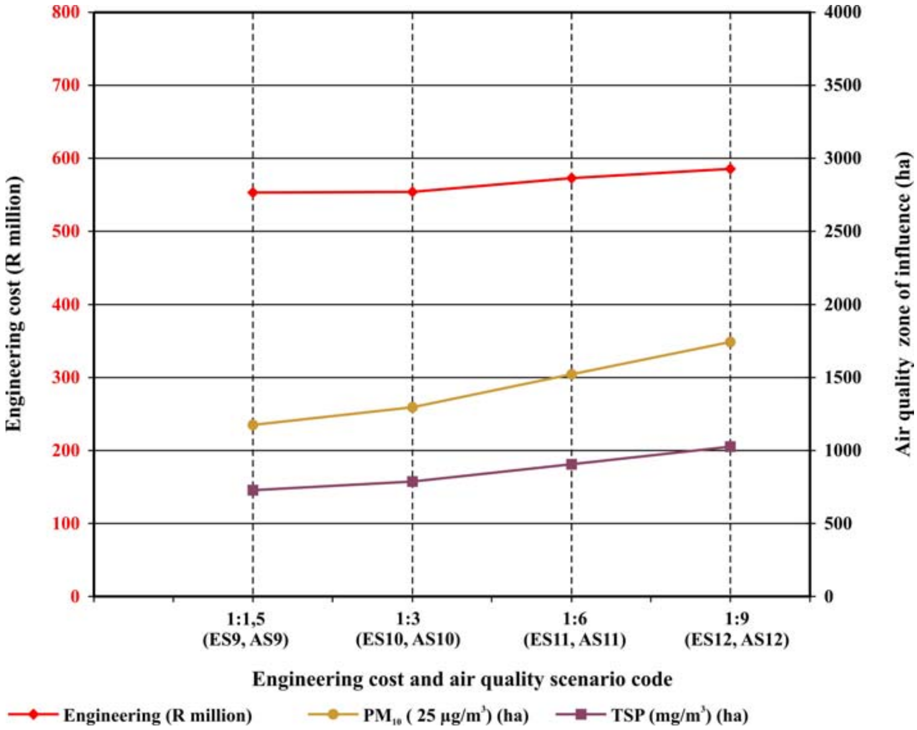

Figure 175: The combination of air quality zone of influence and engineering costs for changes in embankment slopes.

The modelling of the change in slope scenarios for the same grassed armouring cover indicates that there is an increase in the air quality influence surface by flattening the embankment slope and as mentioned previously is likely the result of an increase in impoundment exposed surface area. It may well be that by flattening the embankment slope configuration that a reduction in air quality influence areas will be achieved as flatter step-in slopes are likely to be more resistant to surface runoff erosion and be less draughty which create a better environment for vegetation establishment and the sustaining thereof. It can also be expected that an improved grass cover will increase the management control efficiency in terms of wind erosion which will result in a reduction in emissions off the impoundment.

The air quality models used did not allow for an increase in emission control efficiency with the decrease in overall embankment side slope with regard to improved grass coverage. The results do however indicate a possible increase of between 10 % and 50 % in the air quality influence zone surface area and lead to the conclusion that flattening impoundment embankment side slope may well not be better in terms of the potential increased influence on the surrounding environment. In other words, the objective for flattening embankment slopes must be clearly defined as this could exacerbate and not alleviate issues relating to air quality related impacts.

Water

The mass load sulphates measured in tonnes for the various water modelling scenarios are WS9 (1 480 t), WS10 (1 575 t), WS11 (1 760 t), and WS12 (2 260 t). The flattening of embankment slope results in the increase in engineering costs as well as the increase in sulphate discharge calculated as mass load.

Comparing the two extreme slopes modelled, i.e. the 1:1,5 and the 1:9 slope configuration, a difference in R32 million (6 %) in the total engineering life-cycle costs and 780 t (50 %) in sulphate discharge per annum is observed.

For the purpose of this example the 1:1,5 (steepest embankment slope modelled) is the best case scenario and the 1:9 (flattest embankment slope modelled) is the worst case scenario as it is not only the most expensive but potentially discharges the most sulphates into the environment.

The results presented in Figure 151 (p. 255) indicate that cover as well as slope influences the sulphates released into the environment (calculated as mass flux). The previous discussion focussed on the influence of change in slope to illustrate the effect that an engineering design decision, in terms of impoundment embankment slope, could potentially have on the receiving environment. Similarly, Section 5.3.1 illustrates how a change in cover can have an effect on the mass flux. Both slope and cover influence the potential impact on the environment. Also, both these attributes have a direct bearing on the post-closure land use of an impoundment.

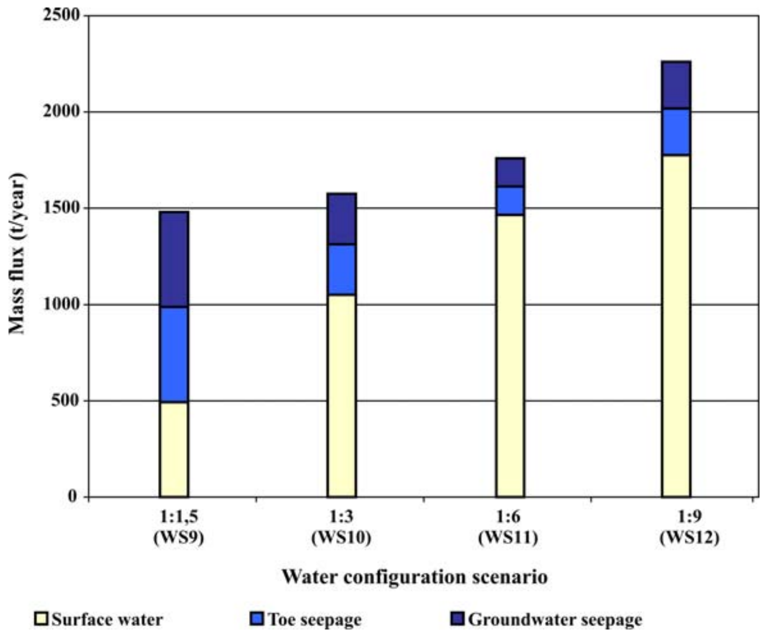

Table 67: *Influence of changes in slope on mass flux.*

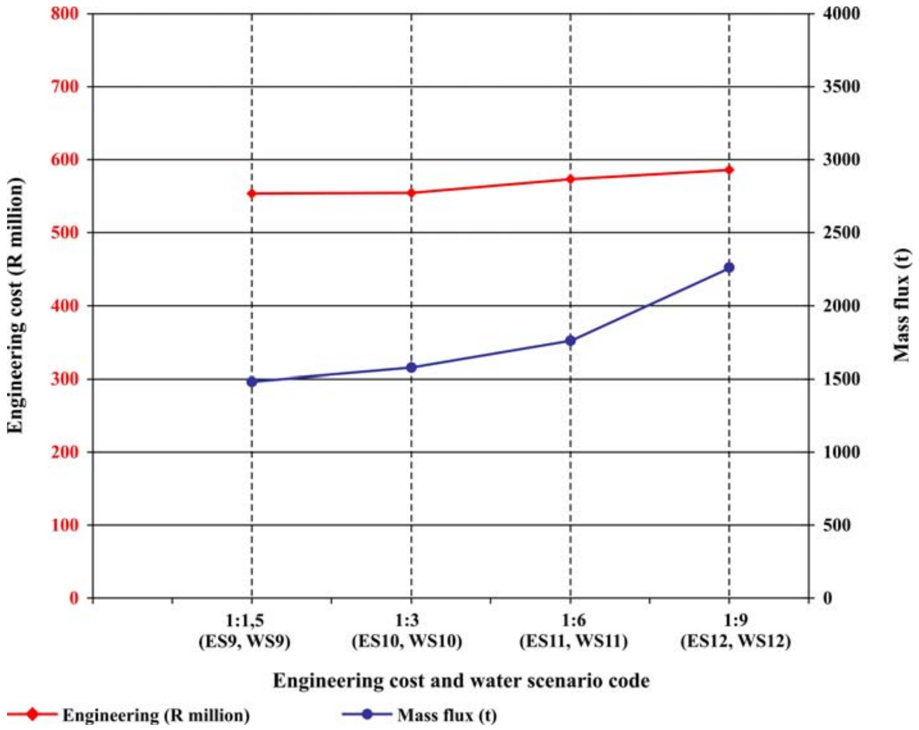

Figure 176: *The combination of sulphates expressed as mass flux and engineering costs for different slopes.*

Combination of results

It may well be that the post-closure land use objective is to reinstate some form of grass cover that can sustain grazing. However, land use is both a function of cover and access (slope). The change in slope will directly influence access to the top of the impoundment. If one assumes that access has to be unrestricted the overall embankment slope should be less than 1:3 and the step-in slopes less than 1:3,5.

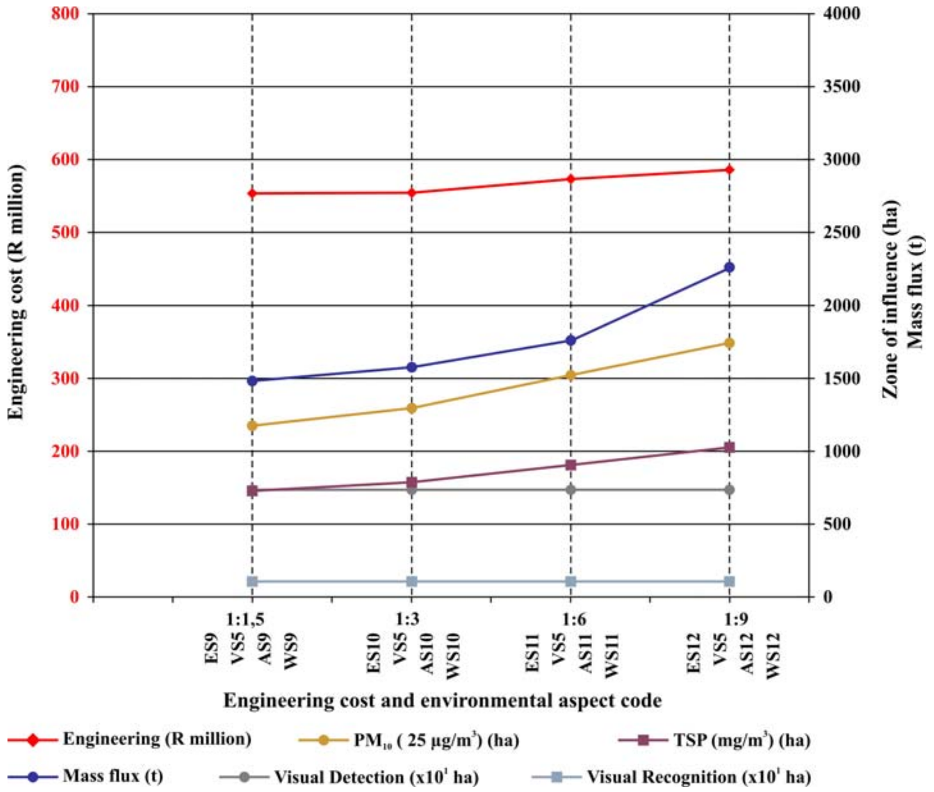

Figure 177: The combination of environmental aspect influences and engineering scenario costs for changes in embankment slopes.

Land use is determined collectively by a host of intrinsic attributes (El-Swaify and Yakowitz, 1998:11). These attributes, whether physical, chemical, or biological, can favour, limit, or completely inhibit certain activities and include attributes such as climate, soils, and landform characteristics which are discussed in Section 2.13.5.

Slope characteristics may favour or restrict land use; as they determine:

- accessibility,
- trafficability,
- stability against surface erosion and mass movement of material,
- potential runoff and flooding, and
- exposure to climatic influences, particularly wind, rain and solar radiation.

Slope can have a limiting effect on the use of land. Figure 77 (p. 152) shows slope requirements for various land uses. Level or gently sloping sites are usually necessary for industrial and commercial buildings and sports fields. Grazing land is generally limited to slopes of less than 1:3 with a preferred slope of about 1:5 for impoundment embankments because of the performance and safety restrictions posed by the operation of machinery such as tractors. The criteria, regarding soil depth and slope as summarised from the Chamber of Mines Rehabilitation Guidelines (CM, 1981) for the following land capability classes are:

- Arable land: soil depth will not be less than 0,6 m and the slope will not exceed 7 % (1:14).
- Grazing land: soil depth will be at least 0,25 m an the slope will not exceed 30 % (1:3).
- Wilderness land: soil depth is less than 0,25 m but more than 0,15 m.

Theoretically the top of the impoundment, depending on the final engineered cover, will not pose any restrictions in terms of land capability. It is however the embankment configuration that could limit the use as a result of slope steepness. When keeping the geometric volume and height of the impoundment constant at 105 600 000 m^3 and 37,3 m respectively, the impoundment embankment configurations of the scenarios modelled can be summarized as:

Overall embankment slope ratio	**1:1,5**	**1:3**	**1:6**	**1:9**
Overall embankment slope angle	33,7 °	18,4 °	9,5 °	6,3 °
Step-in slope ratio (rounded)	1:1	1:2,5	1:5,5	1:8,5
Step-in slope angle	45 °	21,8 °	10,3 °	6,7 °

It is also not the overall embankment slope that is important but the step-in slope angle. Thus to reinstate a slope of a minimum of 1:3,5 and preferable 1:5, which is required for grazing, an overall embankment slope of 1:6 will be necessary. A post-closure impoundment configuration consisting of an overall embankment slope angle of 1:6 and 300 mm armouring will cost about R570 million, have a potential detection perception zone of influence area of about 7 400 ha, an 25 $\mu g/m^3$ PM_{10} air quality influence area of about 1 500 ha, and a sulphate mass load of 1760 t. There is an increase of about R19 million (3,5 %) in engineering costs when comparing the 1:6 and 1:3 embankment slope scenarios. This additional cost will be required in order to configure the embankment slope suitable to sustain grazing. It does however come at a cost – a cost to the environment in that the air quality influence area may increase by 230 ha and the sulphate mass load increase by 185 t. The detection visual perception influence area is estimated to be about 7 400 ha. However, this may be justified if it can be demonstrated that the impoundment embankment configuration can sustain the intended post-closure use.

5.3.3 Summary

The previous two sections in this chapter describe the influence that change in tailings impoundment cover types and slopes has on the environment. The quantified environmental aspects are combined with engineering costs and summarised in Figure 169 (p. 276) for the change in cover type and Figure 177 (p. 285) for the change in slope. Visual and air quality influence zones and water pollutant as mass loads are compared to engineering costs. The graphical representation of the combination of environmental aspects and engineering costs effectively communicates the relative change in environmental aspect influences for different closure alternatives. This can be used to inform rational decision making. The trends may have been expected but the question still remains how to use the environmental aspects and take the process to the next stage of ascribing costs and benefits to the environmental improvements. In other words, describing changes in absolute terms and not only relative terms. Once this can be done, the environmental aspects can be integrated with engineering costs. The following section integrates the environmental impacts with engineering costs.