

Reconstituted soils: a probabilistic approach to resolve aspects relating to the sustainability and economic viability of the rehabilitation of mined lands

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Abstract

Exxaro KZN Sands is a heavy minerals mining and beneficiation operation on the east coast of South Africa. The pre-mining land use on the mineralised dunes consists of dryland commercial sugarcane farming. In terms of legislative requirements pertaining to mine closure several issues become evident when considering the concepts of sustainability and economic viability as applied to commercial dryland agriculture. Assuming that responsible farming practices will be maintained, the sustainability of the post-mining land can be influenced by physical changes to the farmed land (for example erosion) whilst economic viability can be affected by climatic fluctuation (in particular rainfall). In order to arrive at measurable and defined criteria in terms of anticipated yield, a probabilistic approach was taken to determine the impact of rainfall and cover thickness. The key mitigation measure is cover depth, which must be optimized from agricultural and financial perspectives. A probabilistic approach was used to derive a range of probable rather than absolute yields, and a 95% confidence level was used to calculate the impact of final cover thickness. This approach and the results for Hillendale Mine are discussed in this paper.

Changes in soil properties over time will influence both economic viability as well as sustainability. The mining company has influence over the landform and associated changes, and can consequently plan and design around these aspects. From a sustainability perspective erosion must be mitigated by means of suitable land use planning, and sufficient cover thickness must be allowed to sustain the farming practice over a period of time. The universal soil loss equation was used to calculate the impact of this aspect on cover thickness.

The demonstration of the sustainability and economic viability of mined lands is required by South African regulatory authorities prior to granting the final closure for mined lands. In this paper an approach aimed at translating these terms into practical and measurable criteria is provided.

1 Introduction

Hillendale Mine near Empangeni, South-Africa, provides a heavy mineral concentrate containing ilmenite, rutile and zircon. Mining activities commenced at Hillendale during April 2001 and due to the relative small size of the ore body the mining activities are planned to come to an end during 2010. Hydraulic mining methods are applied with the run of mine being split into three main streams at the Primary Wet Plant: heavy mineral concentrate, slimes and sand. The heavy mineral concentrate is trucked to a central processing complex close to Empangeni for further beneficiation. The sand is pumped back to backfill while most of the slimes are disposed in the residue dam.

The pre-mining land use was commercial sugarcane agriculture. In order to create favorable environmental conditions for sugarcane production a portion of the slimes is mixed into the sand and deposited over the backfilled dunes as a capping. Previous work (Hattingh and Viljoen, 2006) on this aspect has shown that a sand : slimes ratio containing 20 – 30% slimes retains sufficient water to support dryland sugarcane agriculture given the specific regional rainfall pattern. The key question that remains to be answered is how thick this sand-slime cap should be. The answer to this question is determined by the water retention capacity of the sand-slimes mixture in view of the nature of the underlying backfill and the necessary allowance for erosion. Dryland agriculture could be a risky business – especially with the fluctuating rainfall patterns characteristic of this area. The permeability of the underlying backfilled sand dunes (containing very little slimes compared to the original scenario) is such that excess rainfall infiltrating the soils will drain through the cap into the saturated zone without compromising the crop through waterlogging. On the other hand, during dry conditions the soil water (or plant available water) should be sufficient to ensure plant growth which is comparable with the undisturbed surrounding areas. The minimum sand-slimes mixture which complies with this criterion must be supplemented with additional depth to provide for erosion. Although good farming practices (such as extended plant coverage) minimise the extent of erosion, it will still occur and must be compensated for.

The quantification of the question on the thickness of the sand-slimes mixture is further complicated by the rapidly evolving South-African legislation relating to environmental issues. With increasing public awareness and subsequent increased expectations for long term post-mining sustainability, companies are under greater pressure to comply with legislation. The work as described in this paper forms part of a larger group of activities aiming at quantifying the standards to which rehabilitation must be conducted and measured in order to achieve mine closure for Hillendale Mine.

2 Sustainability and economic viability as concepts

The concepts of sustainability and economic viability as promoted by the regulators involved in mine closure is not easily translatable into quantifiable criteria against which the success of the mine closure process could be measured. However, from a public and regulatory perspective, these concepts are non-negotiable in terms of the rehabilitation of mined lands. The onus is on the private sector to propose such criteria for consideration. Providing the private sector can provide information to scientifically support such criteria, the authors believe this to be a sound approach. Hence the objective of this paper to quantify the thickness of the sand-slimes cap - which will be satisfying the specific needs of the given environment - via a scientific approach.

3 Mining and the surrounding environment

The Hillendale mining area represents a coastal dune sequence that accumulated north of the Tugela River, the largest river catchment in KwaZulu-Natal, South Africa (Pers. Comm., Dr G. Botha, Council for Geosciences, South Africa). The Hillendale orebody comprise of a thin basal coastal beach facies overlain by coastal barrier dune sands that preferentially concentrated the heavy mineral sand fraction. The coastal dune contains variable amounts of weatherable feldspar and ferromagnesian minerals that are broken down during pedogenic weathering in the vadose zone to form clay minerals and release solutes that are transported down the profile by groundwater movement. This process results in a relative enrichment in the soil profile, particularly the most intensely weathered and oxidized uppermost horizon.

The Mhlathuze River to the north of the ore body incised the northern section of the dune, with the result that steep slopes (approximately 34% of the total area consists of slopes of 20%) occur on the north-western edge of the dune, with more gentle slopes to the south-east. During mining and backfilling a unique opportunity occurs to flatten the steep slopes to some extent during the backfilling and shaping process.

A long term analysis of rainfall in the area is presented in Table 1 (Hattingh and Viljoen, 2006). From the table it can be seen that the mean rainfall is 1146 mm, however, there is a 1 in 10 chance that the rainfall can be as low as 798 mm in any given year, or as high as 1474 mm in any given year.

Table 1 Percentage of time a rainfall amount is exceeded, and the maximum, minimum and mean monthly rainfall amounts (mm)

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
Maximum	314	448	619	424	421	619	547	421	564	370	165	701	2356
10%	170	197	190	220	284	239	186	133	115	104	109	190	1474
20%	120	140	141	161	185	131	91	87	63	60	57	104	1261
50%	96	115	111	119	104	100	71	48	45	40	44	69	1107
Mean	104	117	122	127	138	126	90	70	59	52	50	89	1146
70%	72	82	75	78	68	68	45	30	20	23	27	40	900
90%	42	37	53	50	33	27	16	11	12	8	10	12	798
98%	25	21	31	29	19	17	11	0	2	1	0	7	685
Minimum	13	10	0	13	6	12	0	0	0	0	0	5	550

4 Modeling sugar cane yield

In order to arrive at completion criteria or standards against which the success of the rehabilitation of mined lands is concerned, it was attempted to obtain the historical yields recorded in the mining area. This proved to be difficult, for although the sugar mill as well as local farmers kept records, the provenance for specific harvests were difficult to trace with certainty. Factors complicating this search included transfer of ownership of farmland, inconsistent identification of farmed areas, incomplete records regarding the application of fertilizer and pesticides, and incomplete reporting in terms of dates planted, varieties used, and the number of ratoons before renewed planting. Due to these factors it was decided to use a theoretical approach and rather determine expected yield on the basis of a comparative assessment, as well as using a probabilistic approach instead of a fixed yield. Expected yields are therefore expressed in terms of the confidence of exceedance of a specific yield rather than fixed numbers.

Two aspects required consideration, comprising the texture (ratio of sand to slime) as well as the thickness of the sand-slime cap. Since the intention is to construct a bulk mixing plant aimed at producing this mixture, it was further decided to attempt to leave as large an operating envelope in terms of mixture composition as possible. The reason for this is that process control on this type of facility is difficult, and if there is scope for a large operating envelope, it should be used. The theoretical exercise was therefore divided into the two aspects, with the first question to be answered relating to the composition of the mixture.

4.1 Determining the optimum mixture ratio

Several methods are available to estimate soil hydraulic properties (water retention) from known physical properties. The range of water retention of interest for crop production is between 10 and 1500 kPa of soil water pressure (soil matrix potential), which is the range generally referred to as plant available water. The pressure value of 10 kPa usually corresponds to volumetric soil water content at field capacity (FC; this can go up to 33 kPa for clayey soils), whilst the pressure value of 1500 kPa corresponds to volumetric soil water content at permanent wilting point (PWP). Water across this range can be extracted by most plant species, although yield losses can be expected at soil water potential values much lower than 1500 kPa. In this context, a dedicated model (RETC version 6.0, Van Genuchten, 1980) was used to estimate plant available water from soil texture.

The RETC code can be used to predict the soil water retention curve from available data, including soil physical properties, measured soil water retention data or unsaturated hydraulic conductivity, and makes use

of several mathematical methods for determining soil water retention properties. In this study, the soil water retention mathematical model of Van Genuchten (1980) was used. The Rosetta model, included in RETC, is used to determine the parameters required by RETC to calculate the soil water retention function. In order to determine these parameters, Rosetta makes use of textural class, textural distribution, bulk density and one or two water retention points as input (Schaap et al., 1998, Schaap and Leij, 1998a). We used textural distribution data and bulk density.

The soil water retention of a range of soil textural properties was calculated using the Van Genuchten (1980) model in the range between volumetric soil water content at field capacity (FC) and permanent wilting point (PWP) (plant available water). All calculations were done for a 2 metre soil depth, based on previous work (Hattingh and Viljoen, 2006). The results are presented in Figure 1.

The output of the Van Genuchten model proved to be sensitive to particle size distribution. From the data obtained it is clear that an operating range consisting of less than 80 % sand would be fairly suitable for rehabilitation, if soil water retention is the only criterion.

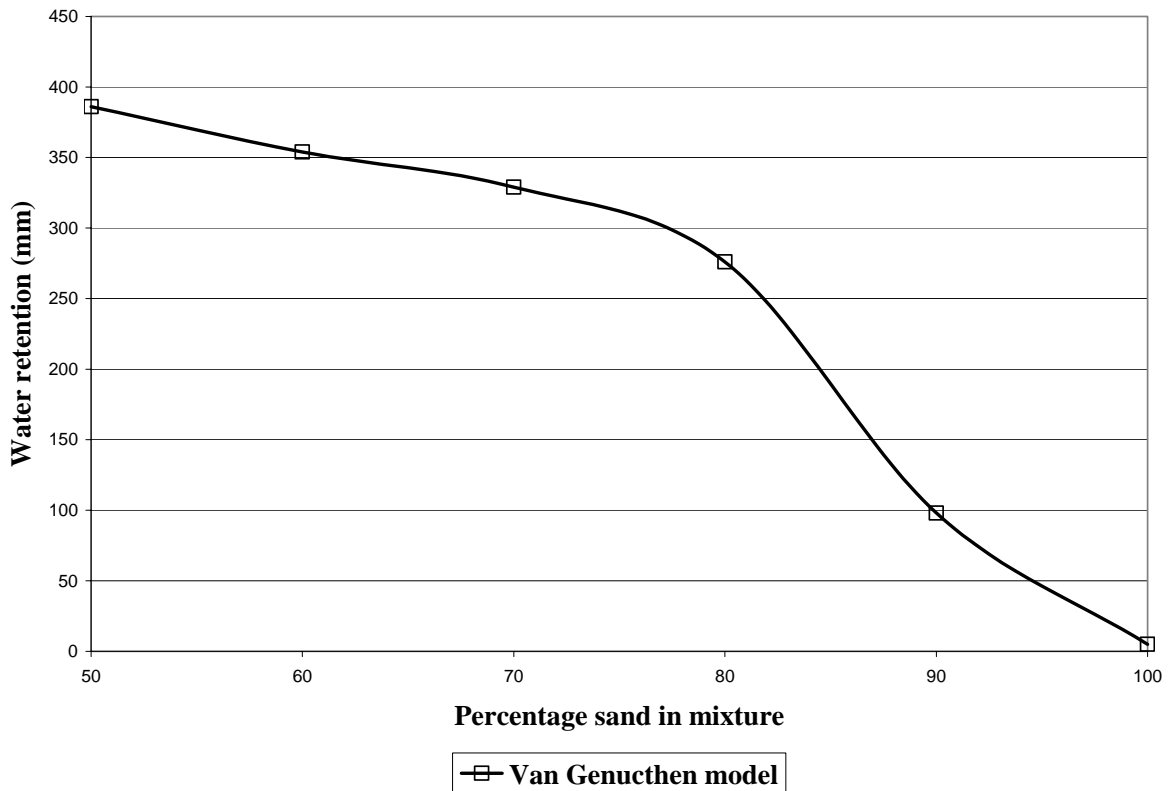


Figure 1 Soil water retention of a series of mixtures of sand and clay, using the van Genuchten mathematical model

4.2 Determining the optimum thickness

In the second step of this study, the SWB soil-crop-atmosphere model (Annandale et al., 1999) was used in order to determine the effect of soil water storage (retention) on dryland sugarcane water use and yield. The SWB model requires weather, crop and soil data as input. The crop growth parameters for sugarcane were extensively researched by the South African Sugar Experimental Station in Umhlanga (Thompson, 1991; Annandale et al., 1999). These specific crop parameters were included in SWB during the development phase of the model (Annandale et al., 1999). They resulted from extensive research and validation exercises. The only simulation variables were therefore soil water retention (field capacity and permanent wilting point) and soil depth. In running these sensitivity analyses, it was assumed that water use and yield are

affected only by soil water retention and depth, whilst all other environmental conditions were constant. It was also assumed that all agronomic practices and factors were optimal with water (soil water storage, rainfall amount and distribution) being the only variable affecting sugarcane yield. The maximum depth of the rooting system, which is one of the specific crop growth parameters required in SWB (Figure 4), was varied to match the depth of the soil profile.

Runoff reduces the amount of water that is available for plant growth and as such is an important factor affecting the prediction of sugarcane yields at the Hillendale site. Simulated runoff data for the ACRU model (Shulze, 1994) for the Hillendale Mine Catchment were developed for the purpose of this exercise. This model originated from a distributed catchment evapotranspiration based study by the Agricultural Catchments Research Unit (a unit within the Department of Agricultural Engineering of the erstwhile University of Natal, Pietermaritzburg, South Africa, <http://www.beeh.unp.ac.za/acru/>), and is generally used in the water decision making process in afforested areas in South Africa. These data were used to derive a reasonable runoff percentage factor as input into the SWB model. The calibration result is shown in Figure 2. The most acceptable data fit was achieved with a SWB runoff factor of 48mm. The discrepancy between the SWB and ACRU model is attributed to the runoff equations in the SWB model which do not take rainfall intensity into account. This runoff figure is an average runoff parameter for the catchment which does not consider site specific issues like slope or trashing from sugarcane, and was used in the sensitivity analyses and subsequent Monte Carlo simulations.

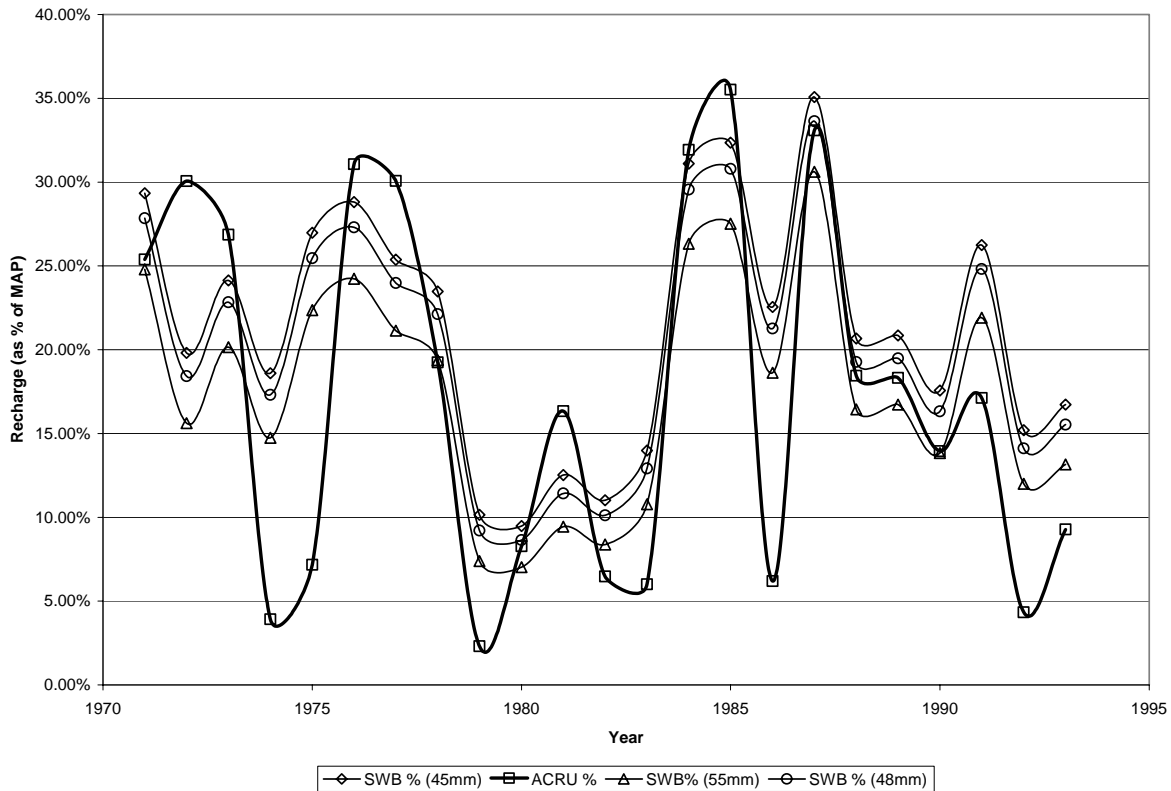


Figure 2 Calibration of SWB data versus ACRU data, for various recharge percentages (against mean annual precipitation). Refer to the text for explanations of the abbreviations used.

Sugarcane yield in these simulations was determined indirectly from evapotranspiration by using the equation of Thompson (1976):

$$Y = 9.53(ET/100) - 2.36 \tag{1}$$

Where:

Y = Yield in t/ha

ET = Evapotranspiration in mm/a

The rainfall recorded on a daily basis at Richards Bay by the SA Weather Bureau from 1970 to 2003 was used for the sensitivity analyses as well as the Monte Carlo simulations. It was decided that this would be more predictive of future rainfall patterns than an artificially constructed rainfall dataset.

A sensitivity analysis determines the sensitivity of the model simulations to variations in specific input parameters. This allows the identification of the input parameters that require further investigation or the parameters that need to be considered during Monte Carlo simulations. During the sensitivity analysis, the input parameter in question is systematically varied while the other parameters are kept constant. The simulated deviations from the calibrated or assigned values are used to measure the influence of a specific input parameter. The parameters that were considered during the sensitivity analysis included precipitation, runoff, silt clay percentages and soil depth. The results of the sensitivity analyses are shown in Figure 3. It can be seen from this figure that the most sensitive parameter is precipitation followed by runoff and soil depth. The model was more sensitive to decreases in silt clay percentages and soil depth rather than increases in these two parameters. This trend is attributed to the decrease of available soil moisture for plant growth below a soil thickness of 2m and a silt clay percentage of 30%.

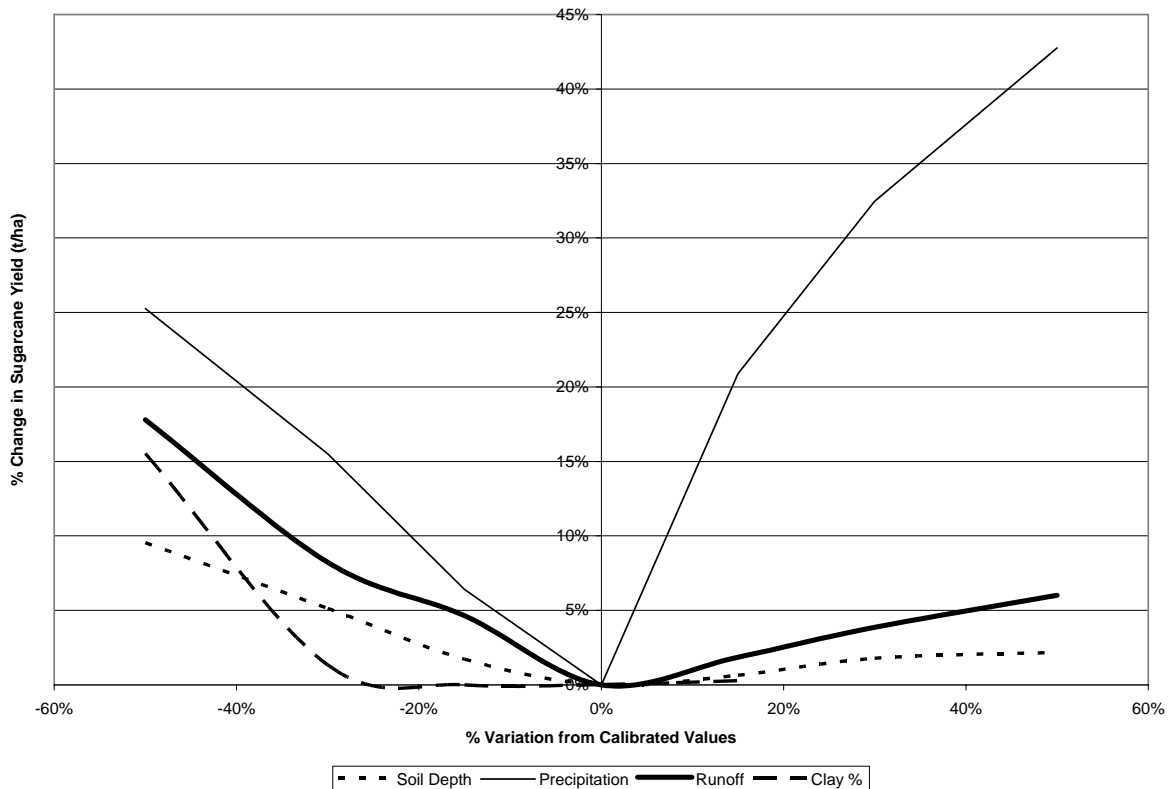


Figure 3 Sensitivity analysis of various input parameters in the Soil Water Balance (SWB) model, with the percentage change in sugar cane yield in tons per hectare (t/ha)

There is considerable uncertainty regarding the distribution of the SWB model input parameters. For this reason, Monte Carlo simulations were undertaken to address this uncertainty for the simulated sugarcane yields for this study. Random values are generated for selected input parameters from population distributions to be used in subsequent simulations. The results of the model simulations are analyzed as a probability density function to determine the likely variation in sugarcane yields. This is typically reported

for an exceedance probability percentage of 5% (95% confidence limit) for variations in historical precipitation. The varied rainfall patterns in the historical rainfall record for similar MAP figures are reflected in the varied sugarcane yields. For this reason, the results of the Monte Carlo simulations were smoothed using a 3 point moving average for the historical rainfall record. This is considered to be the best compromise between illustrating an increase in yield for increased precipitation while also illustrating the degree of yield variation that may occur due to varying rainfall patterns. The results of the Monte Carlo simulation are shown in Figure 4.

It can be seen from this figure that sugarcane yields increase with increasing soil depth. However, it is also evident that increased precipitation results in a staged increase in sugarcane yield, as is noted in the work by Bezuidenhout et al. (2006). It is also clear that this first approach to generating adequate rainfall data is causing some complications which the model can not physically handle. In an ideal world the curves in Figure 4 would be smooth, however, significant deviations are introduced through artifacts in the rainfall data used.

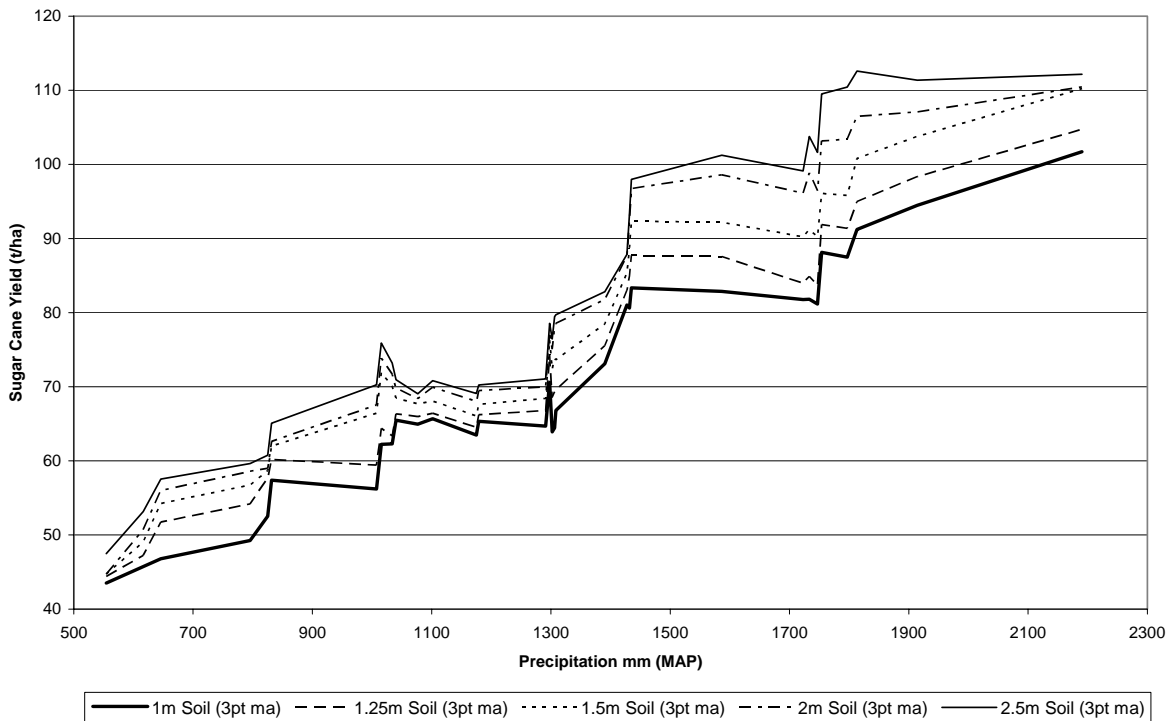


Figure 4 Results of the yield simulations for various layer thicknesses, as a function of rainfall, calculated as 3-point (3-pt) moving averages. Mean Annual Precipitation (MAP) expressed in millimeters (mm); sugar cane yield expressed in tons per hectare (t/ha).

5 Determination of erosion

The South African Sugarcane Research Institute (SASRI) has conducted extensive research into erosion modeling and subsequently developed the nomograph used today for land use planning in the South African sugar industry. The land use nomograph was developed using the Universal Soil Loss Equation (USLE) to predict the soil loss for all possible combinations of factors that include Tillage (T), Strip Planting (SP), Conservation Terraces (CT) and Burned or Trashed crops (BT) (Platford, 1987). Thus the panel width (W) required when designing a land use plan for sugarcane fields, taking land slope and soil conditions into account, can be represented by the following equation:

$$W = f(T, SP, CT, BT) \text{ (Platford, 1987)} \quad (2)$$

The rehabilitated area of the Hillendale mine will be sloped at 1%, 10% and 20% sections according to the macro-topographical relief of the area. In order to determine the soil loss from each section, the Universal Soil Loss Equation (USLE) was utilized and multiple simulations were run using the Monte Carlo method to derive sensitivity analysis for the different parameters used and to obtain probabilities in terms of the volumes of soil lost to erosion.

The Universal Soil Loss Equation (USLE) is used to calculate long term average annual soil losses as follows:

$$A = R \times K \times LS \times C \times P \quad (3)$$

Where:

A = Soil loss in $t \text{ ha}^{-1} \text{ annum}^{-1}$

R = Rainfall erosivity

K = Soil erodibility

LS = Topographic factor

C = Crop management

P = Practices factor

Rainfall erosivity (R) is defined as the total rainfall kinetic energy (E) multiplied with its maximum 30 minute intensity (I_{30}). The Richards Bay area has been classified as the N-region (Smithen, 1981) with a minimum value of 300 and a maximum value of 458 for EI_{30} . An empirical formula was developed for this region and uses the average yearly rainfall (P), where $R = 0.65 P - 192.46$. Using the formulae the erosivity for the Hillendale area is above the maximum permissible value and the erosivity is therefore reduced to the maximum value of 458. This value also corresponds well with the iso-erodent map developed for South Africa (Smithen and Schulze, 1982). Maher (1990) suggests a value of 400 for the N-region.

Soil erodibility (K) in South Africa is generally assigned based on experience, rainfall simulator data and estimations from the soil erodibility nomograph (Wischmeier *et al*, 1974). Most literature studies on erosion state that the erodibility is more related to topsoil texture than the soil series itself. For the Hillendale mining area the virgin soil erodibility is estimated at 0.2 based mainly on the prevalence of the Hutton soil series in the farmed areas. The rehabilitated soil erodibility is in the region of 0.1 to 0.14 using the soil erodibility nomograph (Wischmeier *et al*, 1974).

The topographic factor (LS) is estimated using the land use plan developed for the various slopes identified for the rehabilitation sections. The 20% slope is evaluated for the purpose of this paper. Average panel widths (W) according to the land use plan range from 40 to 60 metres. The topographic factor is therefore 4.8 to 5.7 using the LS graph as given in Platford (1987).

Crop management (C) is the most important factor to consider during the soil loss exercise mainly due to the range of this variable. Extensive research by SASRI limits the factor to between 0.05 and 0.15 mainly due to large canopy and considerable above ground residues that the perennial sugarcane provides. Maher (1990) has classified this factor according to the planting date of the crop and differentiated between midlands and coastal sugarcane. Since Hillendale mine lies in the coastal zone the factor will vary between 0.09 for sugar cane planted in September to 0.11 for areas planted in February.

Support practices (P) such as strip planting, contour tillage, reduced tillage, thrashing and the construction of water carrying terrace banks have reduced the amount of soil loss in the sugarcane industry. The Hillendale mine rehabilitation plan entails an initial phase of conventional tillage to ensure restoration of the soil in terms of organic composition and other elements. After this phase the mine will commence with minimum tillage as their preferred practice. Strip planting and the construction of water carrying structures form part of the land use plan envisaged for the area. Sugar cane burning will not be conducted in order to reduce the impact of erosion. The combined factor for Practices (P) of 0.43 (conventional tillage) decreasing to 0.1 (minimal tillage), was determined after assuming strip planting, water carrying terraces and thrashing.

The two scenarios as identified were simulated using a Monte Carlo package (Simulacion 4.0, developed by J.R. Varela, <http://www.cema.edu.ar/~jvarela/simulacion.htm>) on the Universal Soil Loss Equation (USLE). In total 5000 simulations were conducted on each scenario, and the results are depicted in Figures 5 and 6.

The conventional tillage simulations (Figure 5) showed that 99% of the iterations estimated a soil loss of less than 16.9 t/ha/year. The results for minimum tillage (Figure 6) showed that 99% of the iterations estimated a soil loss of less than 4.3 t/ha/yea. The sensitivity analyses are presented in Table 2, and show that soil erodibility is the most important parameter in the scenario where conventional tillage is being practiced. There is a significant decrease in the soil loss from the initial phase to the final phase exclusively due to the Practices factor altered due to changes in the type of tillage between the phases. The estimation of the Soil erodibility (K) gave a lower value for the rehabilitation soil mixture than the virgin soil conditions in the area. This estimation will in future work be verified with a rainfall simulator to ensure the correct K-value for the rehabilitation soil mixture.

There has been extensive research in South Africa on how the various parameters affect the soil loss in a practical approach. A project on a small catchment near La Mercy in South Africa by Maher (1990) has concluded that soil loss is affected to a lesser extent by the soil type and rainfall intensity but to a greater extent by crop cover and management practices.

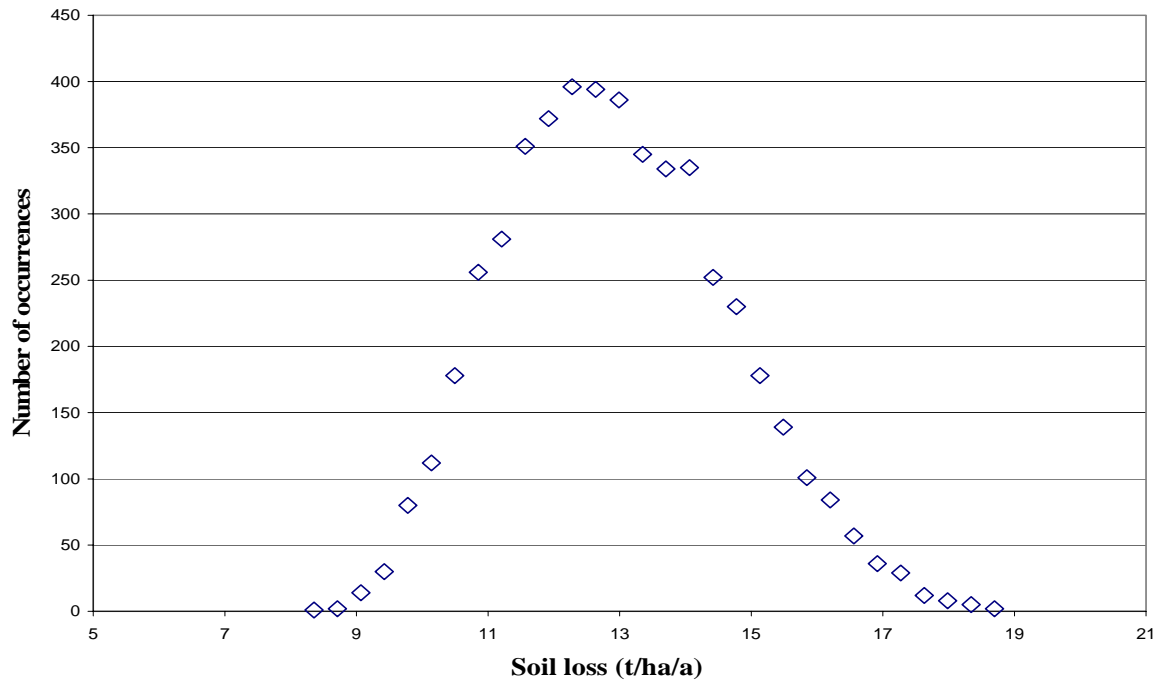


Figure 5 Distribution of results in the Monte Carlo simulation of erosion resulting from conventional tillage, using the Universal Soil Loss Equation

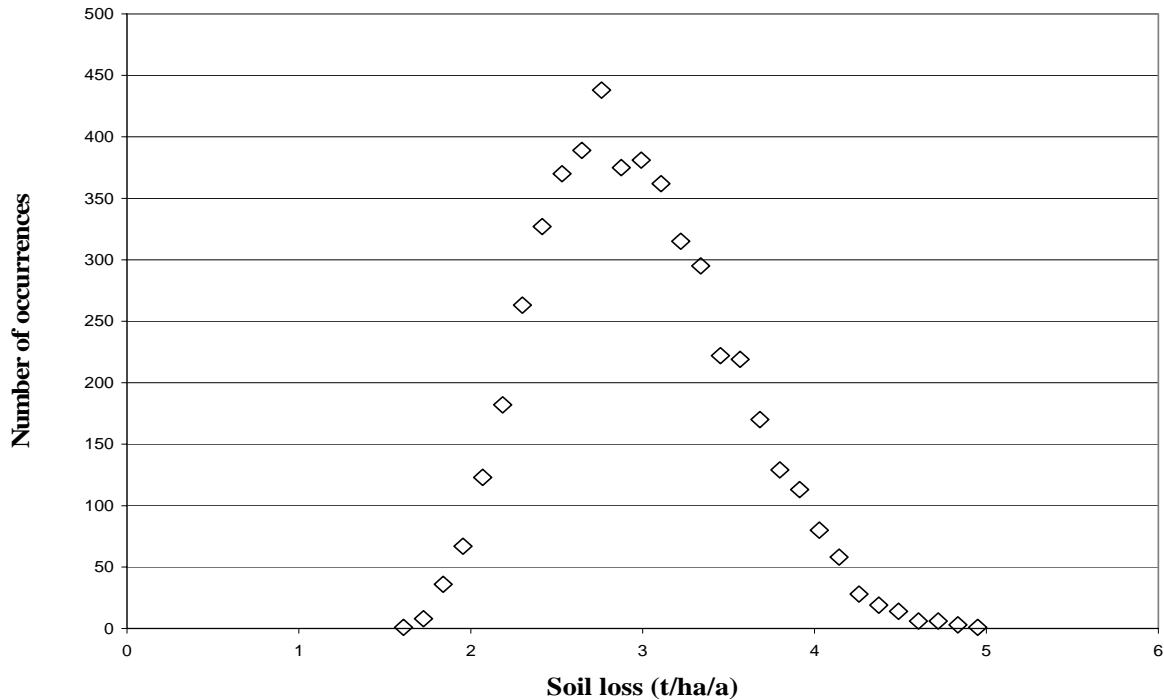


Figure 6 Distribution of results in the Monte Carlo simulation of erosion resulting from minimum tillage, using the Universal Soil Loss Equation. Soil loss is represented in tons per hectare per year (t/ha/a).

Table 2 Sensitivity analysis by means of correlation factor between variables for the initial (conventional tillage) and final (minimal tillage) scenarios

Variables	Conventional Tillage: Correlation coefficient	Minimal Tillage: Correlation coefficient
Rainfall erosivity	0.2936	0.1959
Practices factor	0.3212	0.7377
Topographic factor	0.3612	0.2584
Crop management	0.4165	0.2870
Soil erodibility	0.7104	0.5178

6 Conclusions

In terms of the replacement of a soil suitable to grow sugarcane, the key physical properties to be considered include layer thickness and constitution. The ratio of sand to clay is important in terms of soil water retention, which decreases considerably once the sand portion starts exceeding 80%. Between 70 and 80 % sand this ratio is unlikely to be as strong a limiting factor as rainfall, given the dependence of this crop on rainfall as illustrated in Figure 4. From previous work (Hattingh and Viljoen, 2006) the conservative theoretical cover thickness at which there should be no difference between soil water properties in the natural and post-mining environments equates to two metres. This work was aimed at refining this thickness further. It is concluded that a minimum layer thickness of 1 metre will give substantially lower yields at the lower end of the rainfall spectrum than the 2 metre layer, and it is recommended that a layer thickness of at least 1.25 metres be used for the purpose of rehabilitation.

As far as erosion is concerned, it is evident that the land use practice is critical in the mitigation of this component. A detailed land use plan therefore has to be drawn up, and needs to be strictly followed. As far as the provision for erosion in layer thickness is concerned, preliminary calculations show that erosion losses, assuming the measured bulk density of the mixture of 1.57 g/cm^3 , will range from 0.27 mm per year (for the minimal tillage scenario) to 1.08 mm per year (conventional tillage scenario) on the 20% slopes. From a sustainability perspective the cover thickness should therefore be increased with the incremental loss (as a function of agricultural practice) multiplied by the period over which erosion needs to be considered. As an example, for a century an additional 108 mm cover thickness over and above the 1.25 metres would be required for conventional tillage.

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