A comparative evaluation of two rehabilitation options employed to rehabilitate industrially generated elemental seepage on a coal mine

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ABSTRACT

Mining has a very long history in South Africa and together with the mining activities comes environmental degradation. The mining sector makes use of a number of different procedures and products that causes this degradation of the environment. One of the products harming the environment which are critical for mining activities to commence is explosives. The environment is protected by law in South Africa; it is required that the environment must be rehabilitated after the mining of an area has stopped. Similar environmental laws are also applicable to other industries that can cause harm to the environment.

Land in South Africa, and all over the world, is an important asset for ecosystems and people alike. This makes the rehabilitation of degraded land and ecosystems of the utmost importance. In most cases where land was degraded by human activities, human intervention is needed to rehabilitate the area. This is mostly to speed up the process and to make sure future harm to the environment is minimalised. Scientific research is undertaken in order to set up guidelines and procedures for the rehabilitation of degraded sites. The aim of this research is to ensure that each site, with its site specific problems, has the chance to be rehabilitated to the best possible state.

Environmental impacts created by human activities were not always a concern and in numerous historical cases the environment was degraded without any thought of the implications. As an example, the effluent from industries was often not disposed of in an environmentally friendly way; this is discussed further in this study.

In this study, an explosives manufacturing company (EMC) leased land from a coal mining company for a period of twelve years. The explosives manufacturing plant was erected on top of a watershed within the borders of the coal mining site. Effluent from the manufacturing plant was disposed of by means of a “soak-away” which entails dumping the effluent and wash water into the soil where the contaminants penetrates the soil and soaks away. This resulted in a series of problems with the soil fertility and caused the vegetation on the site to deteriorate and eventually die off completely which left the area denuded from any vegetation in certain areas.

After an assessment of the area, a company specializing in the rehabilitation of degraded land drafted a rehabilitation plan. This plan is explained and examined in this study. The rehabilitation and monitoring was done by the same company that compiled the remediation plan and the site was deemed to be successfully rehabilitated in 2008. The success of the rehabilitation however was short lived (approximately 2 years), since the site again showed signs of denudation in 2010. Intervention was needed once again and a site visit was conducted in 2010 (by a different rehabilitation company) after which a different rehabilitation plan was drawn up and implemented.

This study entails the evaluation of the different rehabilitation procedures implemented by the two companies in question and explains the different views of each. The main objective of each of the rehabilitation companies was to rehabilitate the site to the predetermined state were neither the coal mine nor the EMC faces any liability in terms of environmental law. In the case of the first company, this was attempted by removing the contaminants from the growth medium after which the soil was ameliorated with different biological inoculants and chemical ameliorants. The site was then reseeded for vegetation establishment with the long term goal of creating a self-driven vegetation cover.

The site was rehabilitated and monitored after the second rehabilitation attempt and all the findings indicate that the rehabilitation of the site was successful. The second plan entailed removing the contaminants which the first attempt failed to remove due to a possible lack of understanding regarding the underlying geology of the site. The second procedure also used better amelioration techniques that provided a better result.

Key words: Rehabilitation, denuded, contamination, drainage, amelioration, vegetation.

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1 Thessalonians 5:18

“Give thanks in every circumstance, for this is God’s will for you in Christ Jesus.”

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LIST OF ABBREVIATIONS:

Ave. - Average

CEC - Cation Exchange Capacity

DTEC - Department of Tourism, Environment and Conservation

DWAF - Department of Water Affairs and Forestry

DME - Department of Minerals and Energy

EC - Electrical Conductivity

EMC - explosives manufacturing company

MPRDA - Mineral and Petroleum Resources Development act

NEMA - National Environmental Management Act

PCA - principle component analysis

PSD - particle size distribution

RC1 - first rehabilitation company

SABS - South African Bureau of Standards

SD - Standard deviation

Tot. - Total

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CHAPTER 1: INTRODUCTION

1.1 Background

1.1.1 Mining in South Africa

Mining has a long history in South Africa and for a very long time mining has had an enormous impact on the country's economy. Over time, the mining sector has grown larger than the agricultural sector in South Africa (in financial terms) and became the main developer of infrastructure and the main contributor to the economic growth of the country (Ngcofe & Cole, 2014).

Mining in South Africa goes back as far as the 1800s when copper mines were in operation in the Namaqualand region where the town of Springbok is today (Cairncross, 2006). Gold mining also started around this time in the Witwatersrand area in 1867 and later in the East Rand and West Rand located in the Gauteng province. The gold mining industry further expanded to the Klerksdorp area in the North West province and also to Welkom in the Free State province (Reichardt, 2012).

Diamonds were discovered in the Kimberley area in 1867 and so we can say that the mining industry was prosperous in South Africa during the 1800's. Sarsby & Meggyes (2010) stated that 55 different minerals where sourced in 2005 from 1113 operating mines in South Africa. The majority of these minerals were exported. The mining sector contributed around 8% of the entire country's gross domestic product during the first decade of the 21st century. In 2008 the world production of coal was 5845 mega ton (Mt) of which South Africa produced 236 Mt. The major mining companies responsible for this production were BHP Billiton and Anglo Coal (www.mbendi.com).

As mentioned above, the South African mining sector is comprised of several different elements. The second largest element, measured in monetary value, is coal. Coal comprises 6.1% of the total merchandise exports of South Africa (www.universalcoal.com). Coal is used by Eskom in South Africa to generate electricity and thus plays a major role in the economy both directly and indirectly. (Eberhard, 2011).

There is a price associated with the economic growth that mining, as the largest single industry in South Africa, brings to the country. Over the years mining has produced a legacy of wastes and contamination that negatively impacted the environment (McDonald, 2004).

1.1.2 Environmental impact and legislation of mining in South Africa

It is inevitable that ecosystems and landscapes will be degraded and polluted with the mining of these much needed natural resources (Bradshaw & Chadwick, 1980; McDonald, 2004). In South Africa the Mineral and Petroleum Resources Development act (MPRDA, 2002) states in section 38 (1) (d) that: "*The holder of a reconnaissance permission, prospecting right, mining right, mining permit or retention permit must as far as it is reasonably practicable, rehabilitate the environment affected by the prospecting or mining operations to its natural or predetermined state or to a land use which conforms to the generally accepted principle of sustainable development.*"

Other legislation regarding the rehabilitation of degraded land is also in place that forces mining and other companies to restore these sites. This includes the Constitution of South Africa (1996), the National Environmental Air Quality Act 39 of 1994, the National Environmental Management (NEMA) Act 28 of 1998 as well as the National Environmental Biodiversity Act 10 of 2004. All of this legislation was set in place in order to protect the environment from industries that cause it harm. The aim of this legislation is the prevention of environmental pollution and rehabilitation of the affected areas.

The Constitution of South Africa (Act 108 of 1996) states in section 24, "*everyone has the right to an environment that is not harmful to their health or well-being*". It also states that "*everyone has the right to have the environment protected, through reasonable and other legislative measures that prevent pollution and ecological degradation, promote conservation and secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development*".

Soil can be degraded by toxic industrial substances. This leaves environmental problems that have a large cost implication in order to correct. Soil is an important resource and it can be seen as re-useable but with regard to the scale of human lifetimes soil cannot be seen as a renewable resource (Brady & Weil, 2008).

It is also stated in NEMA, Act 107 of 1998, that degradation and pollution of the environment must be rehabilitated. The National Department of Tourism, Environment and Conservation (DTEC) and the Department of Minerals and Energy (DME) plans and budgets yearly for ownerless mines in order to rehabilitate them and minimize the environmental risk (Nel, 2006).

As seen above, the government of South Africa considers the mitigation of disturbed land very important. Thus, it will be a high priority for all companies in the affected sectors to comply with the legislation in order to protect the environment for generations to come as well as for business reasons, for example to obtain a mine closure certificate.

The mining sector uses a number of procedures that can create a negative environmental impact. One example of such a procedure is the production and misuse of explosives (Folchi, 2003) which create a cost effective way of clearing the unwanted material in order to get to the valuable and desirable resources. Even in the early developmental stages of mining explosives were used for blasting open the shafts to recover the ore beneath the ground.

The explosives used in the mining sector can become pollutants when released into the environment. Pollutants are defined by Newman (2015) as "*A substance that occurs in the environment at least in part as a result of man's activities, and which has a deleterious effect on living organisms*"

Pollution is known to migrate from one medium to another. One example is pollution in the air that pollutes the soil and water when precipitation takes place. Pollution in the soil can enter groundwater systems and cause contamination. We also see two different ways of how pollutants enter the environment. The first is known as point source pollution and the other nonpoint pollution. With point source pollution the pollutant is discharged from an identifiable source a nonpoint is where the pollution discharges from different points apart from each other and this makes it more difficult to control (Spellman, 2010).

As mentioned previously we see that one of the possible environmental pollutants from the South African mining industry can be explosives. This phenomenon is seen all over the world where the contaminants are released into soil and water. Explosives are known to be less biodegradable than other nitrates, which means under natural circumstances it will remain in the environment as a pollutant for a very long time (Spain, 2000).

1.2 Background of the specific study area

In this study we find that an explosives manufacturing company (EMC) leased a piece of land from a coal mining company on a mining site. The area was polluted by effluent from the explosives plant and this resulted in a complex set of legal issues. It was found that the EMC was liable for the rehabilitation of the site, and so the rehabilitation process was started.

The explosives company called upon an established rehabilitation company. This company performed a site assessment and a rehabilitation plan was drawn up for the specific site that was contaminated by the explosives effluent.

The rehabilitation plan was approved and executed where after the rehabilitation was considered to be successful. However, this success was short-lived (approximately 2 years) and the problem started to reappear.

1.3 Perspective and outline of dissertation

1.3.1 Problem statement

The use of explosives in mining is a much needed commodity. However, if explosives are released into the environment it can have a negative impact. Explosives contaminate the soil and water that it comes into contact with and therefor causes a problem that must be addressed.

As was mentioned before, this study is concerned with an EMC that leased land on a coal mining site. The EMC erected a manufacturing plant on the site at the top of watershed with the natural relief sloping to the south. An emulsion based explosives manufacturing plant started operating on the site in 1978 and was decommissioned in 1990. During the operation of the plant the spillages, effluents and plant and vehicle washings were disposed of by means of a soak-away to the south of the plant. The old soak-away was backfilled in 1991 and seeded to establish vegetation (Anonymous, 2003:1).

Down-slope, to the south of the plant, vegetation started to die off to such an extent that an area of 8.5 ha was completely denuded of all vegetation. The denudation of the area was caused by pollutants emanating from the explosives manufacturing plant and not the mining activities. This assumption can be made because of the fact that the closest mining related activities are more than a kilometre away and the mining commenced down slope from this specific denuded area.

Because the area is situated within the borders of a mining site, it is required to be rehabilitated in order for the mine to obtain a closure certificate. A closure certificate is needed by all mines when mining is no longer commencing. This document certifies that the mining company is no longer liable for the safety and environmental responsibilities and this means the mined land is environmentally rehabilitated to the prescribed state (MPRDA, 2002). If a mine which is not in use any more cannot obtain a closure certificate it has a large negative financial impact to the mining company.

This site under consideration in this study is required to be rehabilitated to a state which can be utilised as grazing. This will ensure that there is no liability remaining to the EMC or the coal mining company. The rehabilitation must be successful to a level that is acceptable to the relevant authorities in order for the mine to obtain mine closure (Anonymous, 2003:4).

1.3.2 Aim and objectives

The aim of this study was a critical analysis of a rehabilitation procedure recommended and implemented on the specific site. Further, to recommend and implement an alternative rehabilitation procedure in order to successfully rehabilitate the same site after failure in the first rehabilitation attempt.

The objectives of this study included the following:

- Critically evaluating the rehabilitation procedure initially used to rehabilitate the specific site.
- Implementing a different and more effective rehabilitation procedure on the same site.
- Assessing the differences between the two procedures and identifying the shortcomings of the procedures.
- Successfully completing the rehabilitation of the site to a state where it can be utilised as grazing with no liability to the explosives manufacturing company or the coal mining company.

1.4 Outline of dissertation

Chapter 1 serves as the introduction to the study. This chapter includes some background of the South African mining industry with regard to the history of mining in South Africa. The chapter also gives more information on the environmental impact and legislation of mining in a South African context. This chapter furthermore gives insight on the perspective and outline of the study with regard to the problem statement and the aim and objectives.

Chapter 2 provides an overview of the previous rehabilitation attempt and gives more information on the specific study area with regard to the previous rehabilitation procedure and how it was implemented. Some methodology about the procedure is also included.

Chapter 3 contains the materials and methods used in the study to obtain the data needed. This chapter also explains the procedures implemented in order to reach the end result of the rehabilitation.

Chapter 4 shows the results from the data obtained in this study and a discussion thereof. The aim of this discussion is to highlight the changes in the measurements over time. This chapter also contains a summary of applications implemented in order to correct the deficiencies, key ratios and excess elements.

Chapter 5 provides conclusions and recommendations with regard to the specific study.

Chapter 6 shows the references used in the study.

CHAPTER 2: OVERVIEW OF THE PREVIOUS REHABILITATION ATTEMPT

2.1 Study area: Site description

The specific site for this study is situated on a coal mine to the south of Emalahleni in the Mpumalanga province of South Africa in the grassland biome. To be more specific, the eastern Highveld grassland biome (Mucina et al, 2014). According to Thompson & Turk (2007) a biome is defined as "*a community of plants living in a large geographical area characterized by a particular climate*".

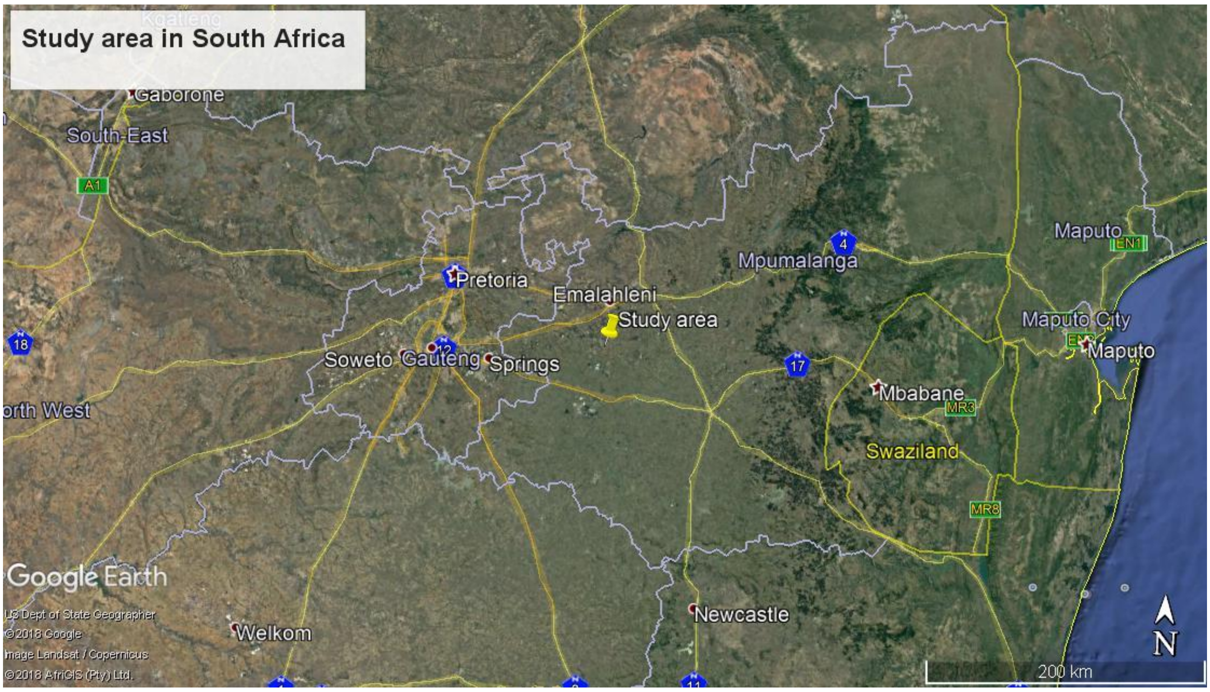

Figure 2.1: A geographical illustration of the location of the study area in South Africa.

The Highveld grassland bioregion is the largest grassland area in South Africa and it contains the highest number of vegetation types of all the grasslands found in South Africa. This specific site is located in the higher rainfall parts of the South African Highveld (Mucina et al., 2006).

According to climate-data.org the average annual rainfall of the Emalahleni area is around 693mm and most of the precipitation comes in the summer months. The climate is classified as warm and temperate.

To the east of the mining site we find where the old explosives manufacturing plant was situated on top of a watershed with the denuded area downslope to the south of the plant as illustrated in figure 2.2. The site is divided into different sections (Figure 2.2) namely:

i) The plant or plant footprint: This is where the plant was situated when it was still in production.

ii) The prills silo: Situated to the west of the plant on the area where the storing facilities was situated before decommission of the plant

iii) The soak away: Placed just south of the plant where disposal of effluent and wash water took place

iv) The denuded area: To the South of the plant below the farmed field. This area is where the contaminants affected the soil and caused the denudation of vegetation.

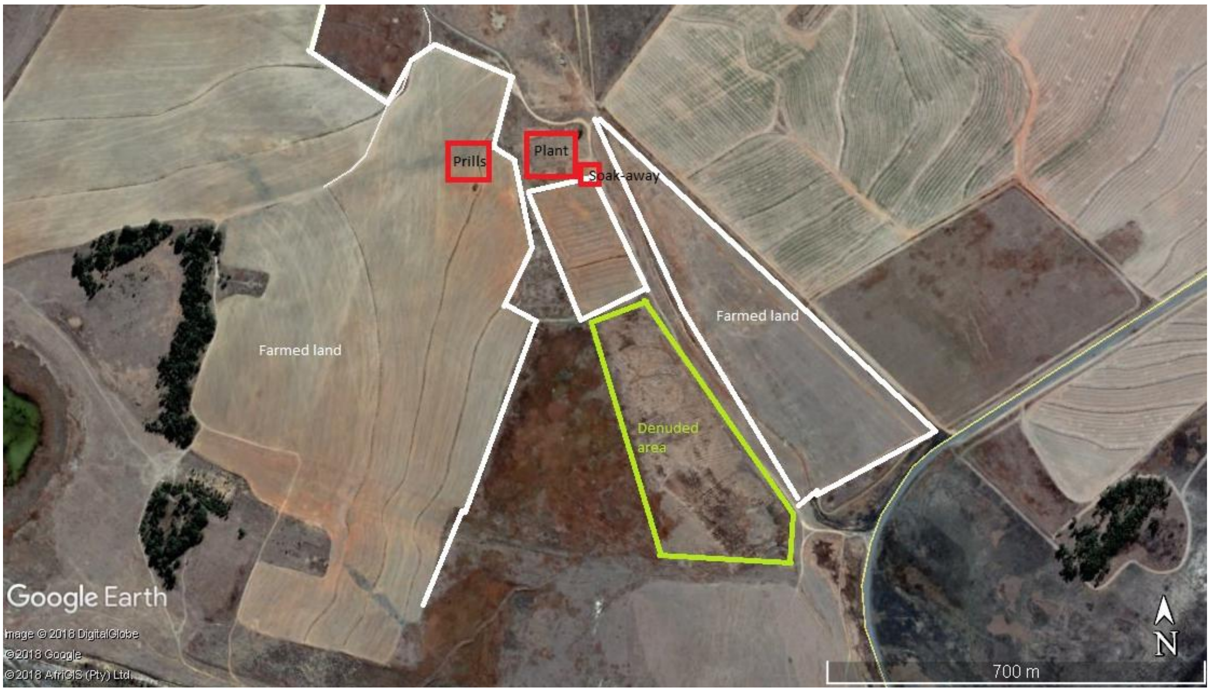

Figure2.2: A site map illustrating the different sections of the study area.

2.2 First rehabilitation attempt

The following section is a summary of different anonymous and confidential reports (Report No. 1-6) of the first rehabilitation effort at the study site. The reports were written between 2003 and 2008, starting with a site assessment report and ending with a completion report in 2008. The completion report stating that the site had been rehabilitated successfully.

The first report (Report no. 1), issued in September 2003, was entitled "*Conceptual rehabilitation plan".* In this report the first rehabilitation company (RC1) stated the site history and the plan that was devised to rehabilitate the problem areas. Together with the first report, RC1 issued report no. 2 also in September 2003 which was entitled "*Methodology statement".* This report gave an overview of what they needed to do on the different areas of the site in order to rehabilitate it. This was conditional upon the approval of the rehabilitation plan by the client, namely the EMC. The methodology statement included pricing for amelioration of the growth medium and pricing for all the different areas.

The third report (report no. 3) was issued in October 2003 and was entitled *"Scope of work for the remediation of the site".* This report contained a detailed rehabilitation plan for all the areas on the site accept for the plant footprint, namely the denuded area, the old soak-away, and prills silo. This report explained what needed to be done in terms of amelioration as well as soil preparation and also the reasons why each process should have been implemented.

The fourth report (report no. 4, September 2004), was named "*Addendum to scope of work for the rehabilitation of the site – Remediation of the plant footprint".* The report contained the same information as the scope of work report for the remediation of the site, but only with regard to the plant footprint (after the plant has been demolished). Report no. 5 was issued during February 2005 and this report was entitled "*Environmental rehabilitation of plant – methodology statement",* and the report contained a detailed plan for demolishing the physical structure of the decommissioned manufacturing plant.

The final report (Report no. 6) was issued in October 2008 and the title of this report is "*Completion report for rehabilitation of the site*". This report stated the rehabilitation history that was done on the site, the monitoring process and the conclusion that the site was successfully rehabilitated to the predetermined standards.

2.2.1 Historical overview of the first rehabilitation procedure

In 1996 RC1 conducted a site visit and evaluated the area. They came to the conclusion, by means of soil analysis, that the denudation of the area was caused by the excessively high levels of nitrogen salts and sulphate in some areas of the site. Another site visit was conducted by the same company in 1997. There was little change in the results of the soil analysis between the two visits. Thereafter, in 1999, more soil samples were taken and most of the sampling points showed a decrease in contamination in terms of nitrogen salts and sulphate, but the levels of acidification showed an increase on the entire area. They stated that the reason for this could be the horizontal movement of the pollutants and the pollutants accumulated in some poorly drained areas and that it would take many years for the site to be cleaned up under natural conditions.

During 2002 RC1 undertook monitoring of the site and found that the levels of contamination had decreased from 1999 but the amount of nitrate and ammonia were still high enough to maintain the salinity of the soil and to prevent plant growth. It was reported that: "*Information recently discovered has indicated that the denuded areas are not a result of toxicity of the chemicals that are present in the soils, rather it is their contribution to the total salinity of the soil which impacts on the osmotic potential of the soil*." This implies that the moisture gradient is created so that water moves from the plant to the soil. Because of this, the plant cannot retain water. RC1 took the Electrical Conductivity (EC) value of below 400mS/m as a target value for the rehabilitation.

2.2.2 First attempt to rehabilitate the old soak-away

The old soak-away (Figure 1.2) was backfilled and seeded in 1991. The seeding was not completely successful because the vegetation that was established was patchy. Monitoring on the area was done by RC1 and they found that the salinity decreased significantly, but some hot spots were still present where the EC was higher than the target value of 400mS/m. The proposed remedy was to mix the soil in order to get a better overall salinity. This was done by ripping the soil at a depth of 500mm and thereby mixing the more contaminated soil with the soil that shows a lower EC value. The ripping was also done in order to create a more hospitable microbial environment by means of better aeration in the soil. Their hope was that this would create a more suitable substrate for plant growth and also increase the permeability of the soil which would help with the leaching of the contaminants.

In addition to the above, compost was added (500 m^3 per ha) before the ripping of the soil in order to enhance the microbial environment further by adding a food source to for the soil microbes. Studies have shown that compost increases the microbial biomass (Saison et al., 2006) and this was one of the desirable outcomes that the company wanted to achieve. Compost also enhances permeability for leaching of contaminants and serves as a long term source of plant nutrients in the soil. The area was then seeded with a number of grass species. The application of 50kg seeds per ha was used with the following species selected: *Eragrostis curvula* (Making up 40% of seed mix); *Eragrostis tef (*Tef*); Digetaria eriantha (*Smuts Finger grass*);* and *Chloris gayana* (Rhodes grass). It was recommended that the grass should be cut or burned in order to prevent the contaminants from re-entering the soil when the grass dies and decomposes.

In the above-mentioned, the microbes are seen as important because they were added to the soil for the purpose of de-nitrification and the plants also play a role in the uptake of the contaminants according to RC1. The area was seeded with the maximum historical amount of summer rainfall. Denitrification is a dissimilatory reduction process that is done by the metabolism of essential aerobic bacteria, of nitrogen oxides namely nitrate (NO_3^-) and nitrite (NO_2^-) to a gas stage (nitric oxide, NO_3 and nitrous oxide), (Knowles, 1982).

The hand over criteria for the rehabilitation process that was identified by RC1 for the old soak-away was determined to be average soil salinity with a value of less than 400mS/m in the upper 300mm of the soil. Furthermore, the summer basal cover of vegetation should have been at least 60% of the total area.

The old soak-away was monitored by RC1 by measuring the residual salt concentration in the growth medium and also the success of vegetation. The residual nitrogen concentrations were measured in the soil six months after the rehabilitation procedure took place. This was done by determining the EC by means of field tests. The tests were done on a 5 by 5m grid across the old soak-away and if the EC exceeded 400mS/m soil samples were collected to determine the cause of the salinity. Monitoring continued until no area on the old soak-away exceeded 400mS/m where after the rehabilitation of the soak away was seen as successful in terms of the identified salinity levels.

The vegetation monitoring was done by using the line transect method and three transects were used to monitor the success of the vegetation. The areas where plants intersected the line where recorded in addition to the bare patches. This was done in order to determine the proportion of bare areas and the proportion of areas covered with vegetation. This process took place at the end of the first growing season, in March 2004 to be precise. After that, the monitoring was repeated after every summer and every winter until 2008.

At the time of the report in 2003, RC1 stated that the maintenance would be largely dependent on the result of the monitoring that was required. If they found that the hotspots that were present at the time of the report were still present in 2005 they would have ripped the area and more compost would have been added (this was most likely the case). Field trials were also conducted as monitoring in order to see if the added microbes were successful in the denitrification of the growth medium. After the first five years of growth, monitoring would have determined whether it would be necessary to re-seed the old soak-away area after September 2004. If this was the case, a higher proportion of *Eragrostis curvula* would have been used in the seed mix in order to establish a community with more climax grasses.

2.2.3 The first attempt to rehabilitate the excavation of the prills silo

The first rehabilitation company evaluated the area and found that the base of the excavation was contaminated. Because of the pollution, it was unlikely that the area could support plant growth. The contamination present was localised to a hotspot next to the sump of the prills silo where the contaminants discharged. The area was rehabilitated by making use of a procedure that entailed adding freeze-dried bacterial cultures to the soil. This was done in order to get a more concentrated microbial population in the soil. A carbon rich source (compost) was added to the soil in order for the carbon to act as an energy source for the microbes when they metabolise the nitrates for de-nitrification. The excavation was then backfilled with stockpiled soil provided by the mine with two layers of compacted laterite half way up the excavation. The excavation was then filled with 800mm of topsoil on top of the compacted layers which serves as a growth medium.

The methodology statement that RC1 provided stated the following to describe the work to be undertaken:

Firstly, 100mm of clean topsoil was placed in the base of the excavation where after 500m^3 of compost was placed and spread over the area. The next step was to place 200mm of clean topsoil on top of that. Thereafter 500mm of un-compacted laterite was placed upon this topsoil. Two layers of laterite were placed and compacted in 200mm loose layers (compacted to MOD ASSHTO 95%) on top of the un-compacted laterite. The excavation was then backfilled with un-compacted laterite up to 750mm from the surface and filled with 800mm of clean topsoil before the area was seeded with the following species in the seed mix: *Eragrostis curvula (*making up 40% of the total seed mix); *Eragrostis tef* (Tef); *Digetaria eriantha* (Smuts Finger Grass); *Chloris gayana* (Rhodes grass). Seed mix was to be applied at 50kg per ha.

This rehabilitation method described by RC1 was implemented in order to separate the contaminated area and the pollution from the topsoil. The freeze-dried bacteria were for de-nitrification (turning the nitrate pollutants into nitrogen gas as discussed previously). The compost that was added was used as a source of carbon and the compacted layers of laterite were used to stop water from reaching the contaminated zone and also to stop the contaminants from reaching the growth medium.

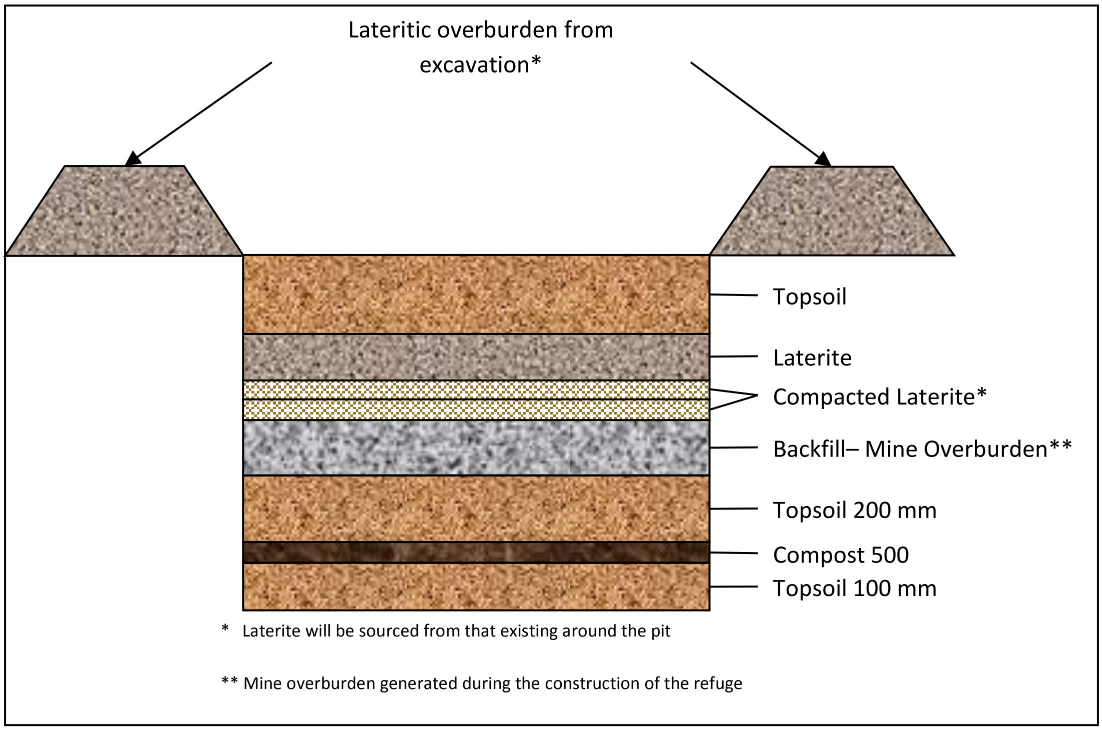

Figure 2.3: An illustration of the physical rehabilitation at the prills silo excavation by RC1.

The handover criteria selected by RC1 for the excavation at the prills silo was only to establish a basal vegetation cover of at least 60%. The reason why this was the only hand over criteria for this area is that the pollution was only present below the surface and the top soil added would not have a high EC value.

Vegetation monitoring was done after completion of the mentioned procedures by means of the line transect method. Two transects were used to monitor the success with the same proportional bare patch to vegetation method described under the old soak-away monitoring. This was also undertaken at the end of the first growing season in March 2004 and thereafter at the end of each summer and winter until 2008.

The monitoring required at the time of the report would have determined if the re-seeding of the area would be necessary after the first year of growth in September 2004. If re-seeding were necessary, a higher proportion of *Eragrostis curvula* would have been included into the seed mix.

2.2.4 The first rehabilitation attempt of the denuded area

RC1 evaluated the denuded area and stated that, from their historical knowledge of the practices in the area, the main sources of pollution were the old soak-away and the excavation at the prills silo. The company constructed a conceptual model of the area that shows the laterite layer below the surface and the area where the pollution daylights. Based on this conceptual model of the underlying geology they assumed that the pollution entered the soil trough shallow seepage, mostly in the area where the old soak-away was situated, and moved below the soil surface on the laterite layer under the farmers field to the point where it daylights at the top of the denuded area.

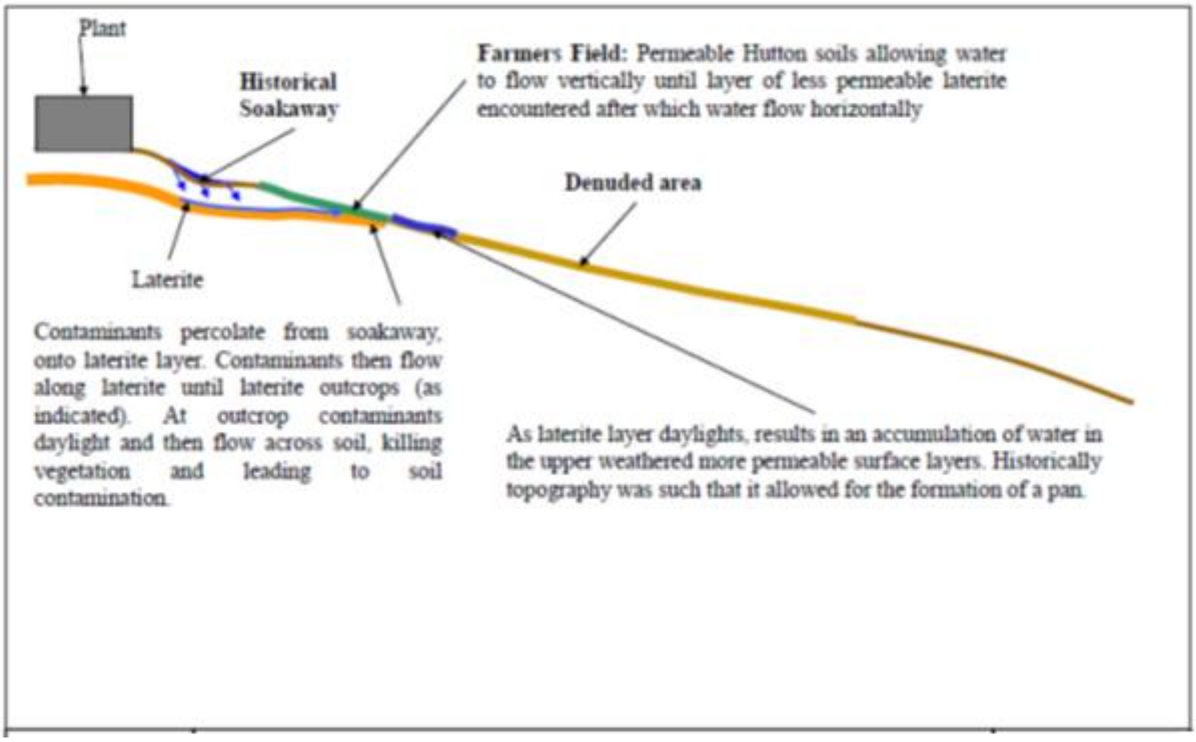

Figure 2.4: The first rehabilitation company's understanding of underlying geology.

With the above mentioned perception of the underlying geology thought to be present in the area RC1 constructed two cut off trenches (1000mm in width at a depth of 2000mm) on the farmers field in order to intercept the pollution between the source (old soak-away) and the denuded area. This was done to reduce the ongoing pollution of the denuded area and these two connected trenches drained into a holding tank ($10m^3$). The local farmer emptied the tank once every week and used the content as fertiliser.

The scope of work on the denuded area entailed that two trenches were excavated; 2000mm deep and 1000mm wide with a trench length of 750m. Geofabric was laid in the excavation and extended 1000mm up each side of the excavation. On top of that, a 100mm layer of 19mm washed stone was placed in the Geofabric and 65mm of Geopipe was laid on the stone. The pipe was then covered with stone with an average cover of 100mm and the overlap of Geofabric was used to enclose the stone fill. Thereafter, 200mm of double washed filter sand was placed on the stone fill and the trenches were backfilled with the remaining topsoil to surface level. Both drains were connected with a main drain that was discharged into the holding tank, which was buried 5000mm deep and the excavation was backfilled.

Other rehabilitation procedures were also implemented on the denuded area at the same time. These procedures entailed ripping the area to a depth of 500mm to enhance the permeability of the soil for better leaching conditions and the ripping against the contour created an irregular surface that reduced surface runoff (less erosion) and increased the amount of water that infiltrated the soil. This also created a physically suitable growth medium for plants to establish.

After the area was ripped, compost was added together with a freeze-dried bacteria culture to the denuded area. Contour berms of 300mm in height were also constructed at regular intervals over the denuded area. This was done in order to reduce surface runoff and increase the amount of water that infiltrated the soil. Thereafter, the area was seeded with a number of pasture species namely *Eragrostis curvula* (Making up 40% of the total seed mix); *Eragrostis tef* (Tef); *Digetaria eriantha* (Smuts Finger Grass); *Chloris gayana* (Rhodes grass). Seed mix was to be applied at 50kg per ha.

There was no hand over criteria identified for the farmer's field because the infrastructure was put in place in order to stop the sources of contamination rather than treating the contaminated area. This area was considered to be successfully rehabilitated when the vegetation was established on the denuded area. This drain was decommissioned when the water drained into the tank had a nitrogen concentration of less than 30mg/l. The denuded area was required to have a soil salinity of less than 400mS/m and a basal vegetation cover of 60% or more.

The water in the holding tank (placed in the farmer's field, upslope from the denuded area and downslope from the old soak away) was tested twice a year to determine the amount of ammonia and nitrogen in solution. This was done in order to determine when the residual contamination in the subsurface no longer presented a risk of causing contamination on the denuded area.

The residual nitrogen concentrations and the success of the vegetation were monitored in this area. RC1 monitored the nitrogen concentrations in the medium by soil sampling six months after the rehabilitation procedure was implemented. The monitoring consisted of field tests to determine the EC of the medium and the tests were conducted on a 5m by 5m grid across the denuded area. Where the EC exceeded 400mS/m, soil samples were taken to determine the cause of the high salinity. Monitoring continued every 6 months until no areas showed an EC value of higher than 400mS/m. Vegetation was monitored once again by the line transect method discussed previously. Three transects were used in this case. The monitoring started in March 2004 and was repeated twice a year thereafter. The monitoring of the area continued until 2008.

Once again, the ongoing maintenance was dependant on the monitoring results obtained from the area. If hotspots were still found in 2005 the area would have been ripped again and more compost would have been added. Field trials were done to determine whether de-nitrification of the medium by means of the added microbes was successful and the vegetation monitoring would have determined whether it was necessary to re-seed the area after the first year in September 2004. If this was the case a higher proportion of *Eragrostis curvula* would have been included into the seed mix.

Figure 2.5: Physical rehabilitation measures illustrated on the site map with the RC1 drainage channels in green and contour berms in orange.

2.2.5 The first rehabilitation attempt of the plant footprint

In 2003, when the rehabilitation procedures were implemented on the other areas, the plant infrastructure was still present on the site. The plant was decommissioned and removed in 2003 and the rehabilitation procedure was started. RC1 stated that the plant footprint would have the same characteristics of pollution as the other areas because of spills and accidents that might have occurred during the time of operation.

The methodology used for the disposal of the plant started with the disposal of the concrete from the plant that was excavated and moved to a waste disposal site. Thereafter, the excavation was backfilled with the laterite provided from the mine stockpile.

The plant footprint was rehabilitated thereafter by ripping the area to a depth of 500mm before 500m^3 of compost were placed on the area. The area was seeded for revegetating the area with a seed mixture containing *Eragrostis curvula* (making up 40% of the seed mix); *Eragrostis tef* (Tef); *Digetaria eriantha* (Smuts Finger Grass); *Chloris gayana* (Rhodes grass). Seed mix was to be applied at 50kg per ha. The above-mentioned procedures (ripping and adding of compost) were done for the same reasons as mentioned previously with the other areas.

The hand over criteria selected was the same as with the other areas (i.e. a soil salinity value of less than 400mS/m and at least 60% basal cover of vegetation).

Residual nitrogen concentrations in the growth medium were monitored here as well as the success of vegetation. Six months after the completion of the rehabilitation work monitoring started and concentrations of residual nitrogen was measured. The monitoring consisted of field tests to determine the EC on a 5m X 5m grid across the area of the plant footprint. Where the EC exceeded 400mS/m samples were taken to determine the cause of the salinity and monitoring continued until there were no areas with an EC higher than 400mS/m.

The vegetation was monitored by the line transact method as described previously and this monitoring continued until 2008. Once again the maintenance depended on the monitoring at the time. If they found that the hotspots were still present in 2005 the area would have been ripped and compost would have been added again.

Field trials were commissioned in order to determine whether the microbes were successful in the de-nitrification in the soil and monitoring of vegetation would have determined if re-seeding would be needed after the first year of growth. If this was the case a higher proportion of *Eragrostis curvula* would have been added to the seed mix.

2.2.6 Issuing of the completion report by RC1

In 2003, RC1 started with monitoring, this showed an increase in biomass and an increase in the overall soil quality for plant growth. Monitoring continued and in 2008 the RC1 issued a completion report stating that the rehabilitation of the site was successful. The reason that they saw the rehabilitation as successful was because of the better soil quality and the removal of all sources of pollution. They also stated that the remaining pollution present in the soil would have been removed by means of the cut off drains, de-nitrification from the soil microbes, leaching and plant uptake.

Between 2003 and 2007 the EMC contracted a local farmer to maintain the site after the rehabilitation procedures had been implemented. In January 2008 the rehabilitation of the site was complete, but before that ongoing maintenance was implemented on an annual basis. The maintenance entailed the establishment of *Phragmites* reeds on the wet patches of the denuded area. Ploughing was done on the denuded area to a depth of 200mm in order to loosen the growth medium and reseeding was done on the area with the seed mix already discussed. The erosion control berms were repaired when needed. A section of the Geopipe was replaced because of damage done to it in a veld fire. Controlled burning of the veld was done to remove the weeds that had accumulated on the site.

During the ongoing monitoring RC1 found that despite of cut off drains that were installed down slope of the plant in the farmers field there were still groundwater day-lighting in the denuded area. They stated that the cut off drains only isolated approximately 25% of the groundwater catchment. This lead to wet patches on the denuded area and RC1 was of the opinion that these saturated patches were independent of the plant activities and that they will remain there and have an impact on the vegetation.

During the first growth season from 2003 to 2004 the vegetation was established with a basal cover of over 60% and the predominant species was *Eragrostis tef.* In the next growth season from 2004 to 2005 the basal cover still exceeded 60% but some wet patches appeared on the denuded area and these patches had 0 to 20% basal cover, depending on the specific area considered within the denuded area. These wet patches occupied ±2% of the entire denuded area at that time, and the other 98% had a change in species dominance from *Eragrostis tef* to pioneer species such as *Bidens pilos* and *Tagetes minuta*.

In 2005 to 2006 the wet patches increased in size and a fire changed the predominant species again to *Eragrostis curvula* and *Chloris gayana*. In late 2005 *Phragmites* reeds were planted on the wet patches with only partial success. From 2006 to 2008 the predominant species remained *Eragrostis curvula* and *Chloris gayana* and almost no vegetation was visible on the wet areas which covered ±8% of the total area at that time.

The soil was also monitored; samples were analysed from the bottom of the slope on the denuded area, the middle of this slope, the top of this slope and approximately 5m upslope from the start of the denuded area. The samples showed that the pH has increased overall and that there were no areas with a pH value lower than 6. This indicates a substantial increase, since the pH value was around 4.5 in 2002. The EC values declined dramatically but the EC was higher on the higher parts of the slope. The nitrates and ammonia in the soil has also decreased over time. However, the ammonia levels decreased at a faster rate, which was an indication that nitrification (ammonia to nitrates) was proceeding faster than the de-nitrification. RC1 stated that this was due to the annual ripping of the soil that created oxidizing conditions and that de-nitrification will become more rapid because of the fact that the ripping of the soil was stopped at that time.

After the completion report was issued by RC1 the site degraded again and this shows that the first rehabilitation procedures were not as successful as it seemed at that time.

CHAPTER 3: MATERIALS AND METHODS

3.1 Rehabilitation of the site

In 2010 the first site visit was conducted. This was done after being called in by the EMC because of doubts as to the success if the first rehabilitation attempt. After the site visit, it was found that the rehabilitation done by the RC1 was not successful. This conclusion was based on the fact that the denuded area was showing signs of denudation again and that the pollutants on the site would take a very long time to remove under natural conditions. At that time, it was clear that the surface and subsurface water that enters the denuded area of the site needed to be reduced because the water carried the remaining pollution on the site to the denuded area. Together with the reduction of the water, it was required to utilize pH adjusting, chemical and organic material for amelioration in order to create better conditions to sustain plant establishment and plant growth in the soil.

The rehabilitation procedure implemented took place in a phased approach. This decision was taken in order to make the necessary detail of information available and to ensure that the rehabilitation was done in a cost effective manner. Phase 1 was the investigation, analysis, planning and recommendations of what was required for successful rehabilitation. The construction of the subsoil drains and the initial in situ treatment of the soil were done during Phase 2. The treatment of the soil and re-vegetation of the site was finalised during Phase 3. This took place after the subsurface drains removed enough contaminants and the analyses showed the pollution has decreased to acceptable values.

3.2 Rehabilitation procedure implemented on the site

During the first site visit some relevant information was obtained from the mine personnel and the local farmer leasing the area at that time. The location of the borehole and some other information were collected from the people mentioned above. Soil samples were taken of the growth medium and were analysed by the Eco Analytica laboratory in Potchefstroom.

Five samples were collected on the historical sample sites (one on each). These soil samples were taken from the plant footprint, the old soak-away, the footprint at the prills silo, ¼ of the way down slope on the denuded area and ¾ of the way down slope on the denuded area. The rationale behind this was to determine the overall state of the site in terms of soil chemistry and pollutant levels in order to get a better view of what the problems were that needed to be addressed. The reports from RC1 were made available in order to see what has been done and to make more informed recommendations. Figure 3.1 is an illustration of the sampled area and where the samples have been taken.

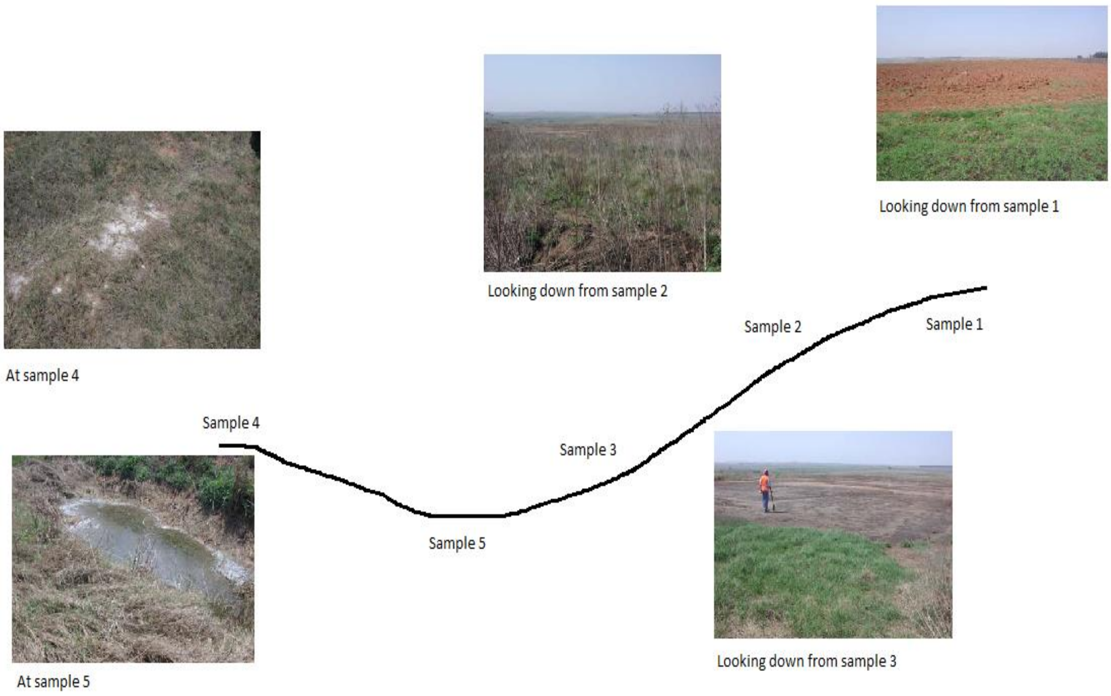

Figure 3.1: Cross section display of where the first five samples were taken during the initial site visit in 2010.

3.3 Sampling of the site

Soil samples were taken at an approximate depth of 20cm by making use of a ground auger. Each sample weighed around 500g. Three soil samples were collected at each of the five sampling points on the site during later site visits, but with the initial site visit in 2010 only one sample was taken from each sampling point. Three water samples of 250ml were taken from the collection pond at a depth of 10cm in bottles provided by the laboratory.

3.4 Soil analysis procedures used

The 1:2 water extraction procedure (as described in detail by Van Rensburg & Pistorius, 1998) was used to determine the water-soluble basic cation friction in the growth medium as well as the trace elements present. The water-soluble basic cation friction entails Ca^{2+}, Mg^{2+}, K^+ and Na^+ and the trace elements entails Fe, Mn, Cu and Zn. The quantification was done by means of atomic absorption spectrophotometry with the Spectr. AA – 250 Varian, Australia (Ramiriz-Munoz, 1968). The 2:1 water extraction procedure is described by Rhodes (1982).

P-Bray 1 analysis was done (as described by Bray &Kurtz, 1945) to determine the P concentration. This was done by using a solution of 0.03 mol l^{-1} ammonium floride in 0.025 mol l^{-1} HCl (Bray 1 solution) with a soil to extractant ratio of 1:7.5g ml^{-1}.

The anions, phosphates, nitrates, sulphates and chloride were determined by using an Ion Chromatograph (Metrohm 761, from Switzerland) and the ammonium concentrations were determined by using an ammonium selective electrode as described by Banwart et al. (1972). The bicarbonate HCO_3^- in the growth medium was determined by the potentiometric titration method with a pH end-point of 4.5 and using a standard 0.005M HCl solution as described by Skougstad et al. (1979). Boron concentrations were determined by the azomethine-H method (Barrett, 1978).

The extractible bases were determined by using the Spectr. AA – 250 (Varian, from Australia) following extraction with ammonium acetate solution as described by Thomas (1982). Base saturation was calculated by determining the ratio between total exchangeable cations which are Ca, Mg, K and Na to the exchangeable capacity of the growth medium (Buys, 1986)

The CEC (cation exchange capacity) was determined by the stepwise replacement of the cations from exchange sites by adding sodium acetate and thereafter ammonium acetate. The suspension was placed in leach tubes and leached with ammonium acetate in order to replace the Na^{2+} on the exchange complex with ammonium and the Na concentration of the leachate, which was determined by the AA – 250 (Varian, from Australia), was then used to calculate the CEC.

Both the pH (H_2O) and the pH (KCl) were determined by adding 50ml of deionised water or KCl to 20g of the media. The suspension pH was determined by means of a calibrated pH meter (Radiometer pHM 80, Copenhagen). The supernatant for measurement of the EC was prepared by adding 50ml of deionised water to 50g of the growth medium and then determined with a WTW LF92 conductivity meter. The available phosphate was determined by the adding of 75ml p – Bray solution to 10g of the growth medium and the phosphate concentration was analysed with a Continuous Flow Analyses System (Skalar, Netherlands) at 340 to 650nm in a 15mm tubular flow cell.

The organic carbon content was determined by using the Walkley-Black method as described by Walkley (1935). As described by Rhodes (1982), the exchangeable acidity is quantified by applying KCl to the filtrate and titrating the product with NaOH.

The PSD (Particle Size Distribution) was determined by the percentages sand, silt and clay method. This was analysed by separating the sand friction from the percentage silt and clay and, thereafter, the clay percentage was quantified by means of the Hydrometer as described by Gee and Bauder (1986).

3.5 Sequence of implementation of the rehabilitation procedure

The rehabilitation procedures discussed were implemented in the following order:

The first procedure implemented was the installation of the subsurface drains where after the area 1 and area 2 (See figure 3.2 below) was ripped to a depth of 500mm. The third step was the formation, repair and cleaning of the drain along the road to prevent surface water flowing over the rehabilitated area. After this, an application of 30 tons of dolomitic lime per hectare was spread on area 1 before the rainy season. The next step entailed the forming of contouring on area 1 to channel the surface water to the drain along the road. An application of 20 tons dolomitic lime per hectare was spread on area 2 before the rainy season with an application of 30 tons well-cured organic material on area 2 and 300kg super phosphate per hectare. After this, area 2 was seeded with seed mixture as indicated before. The monitor and addressing of area 1 was done in the next phase during the winter months.

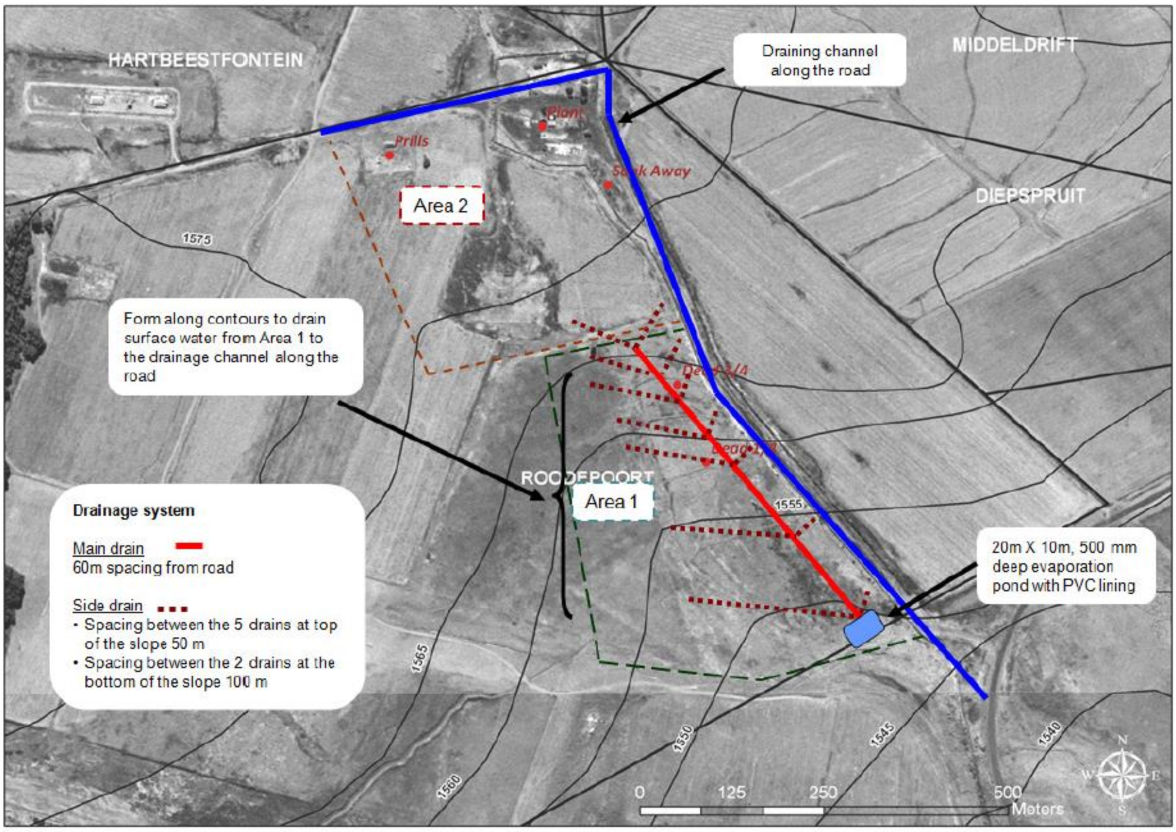

Figure 3.2: Site plan displaying the position of the cut off drains installed within the denuded area (area 1).

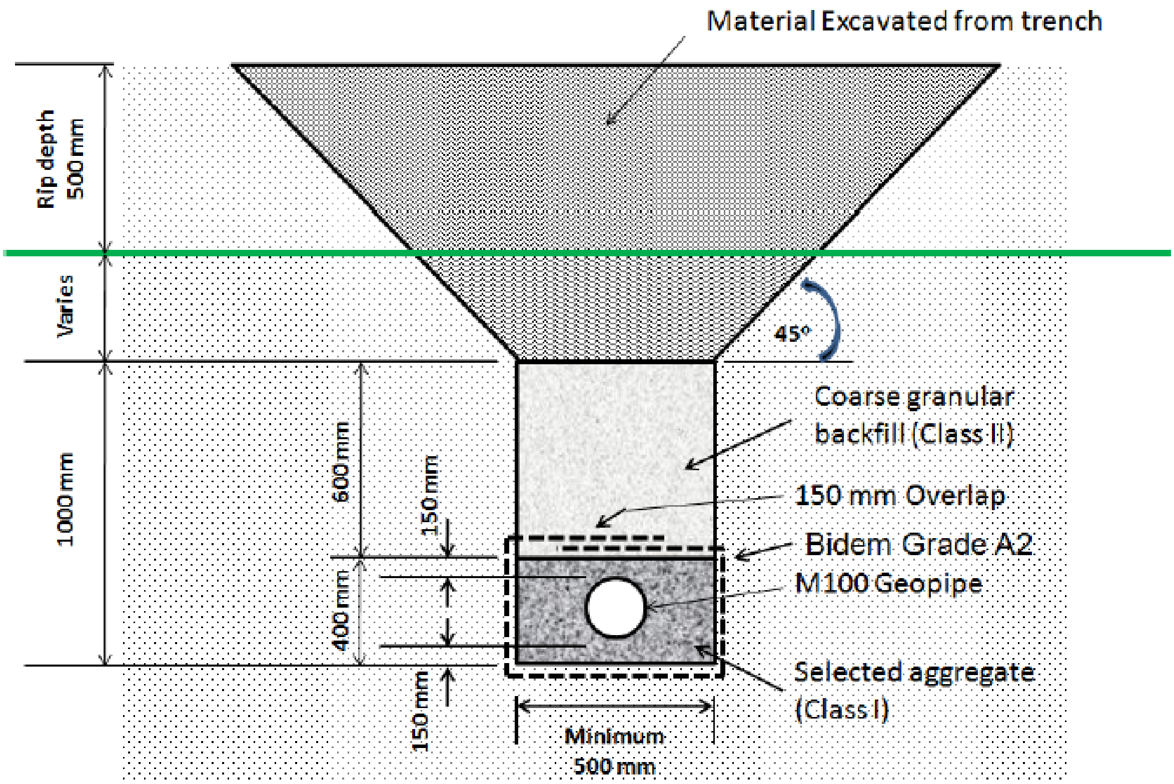

Figure 3.3: Cross section of the main cut off drain and illustrations of the imbedding.

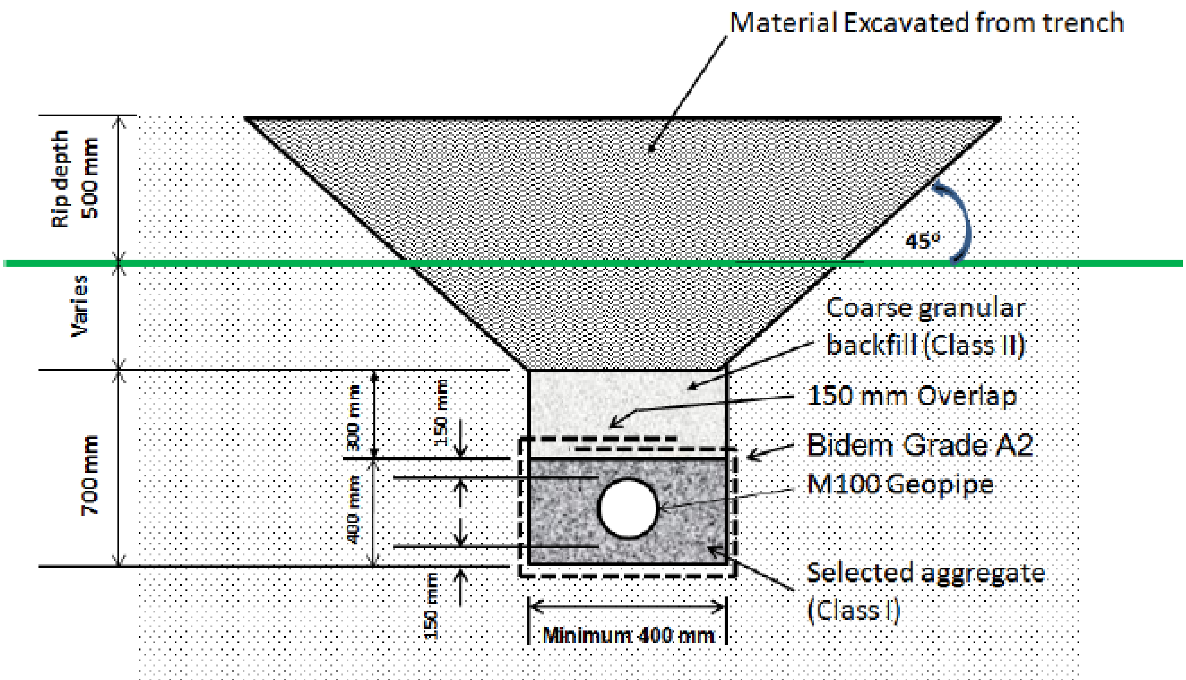

Figure 3.4: Cross section of the side cut off drains and illustrations of the imbedding.

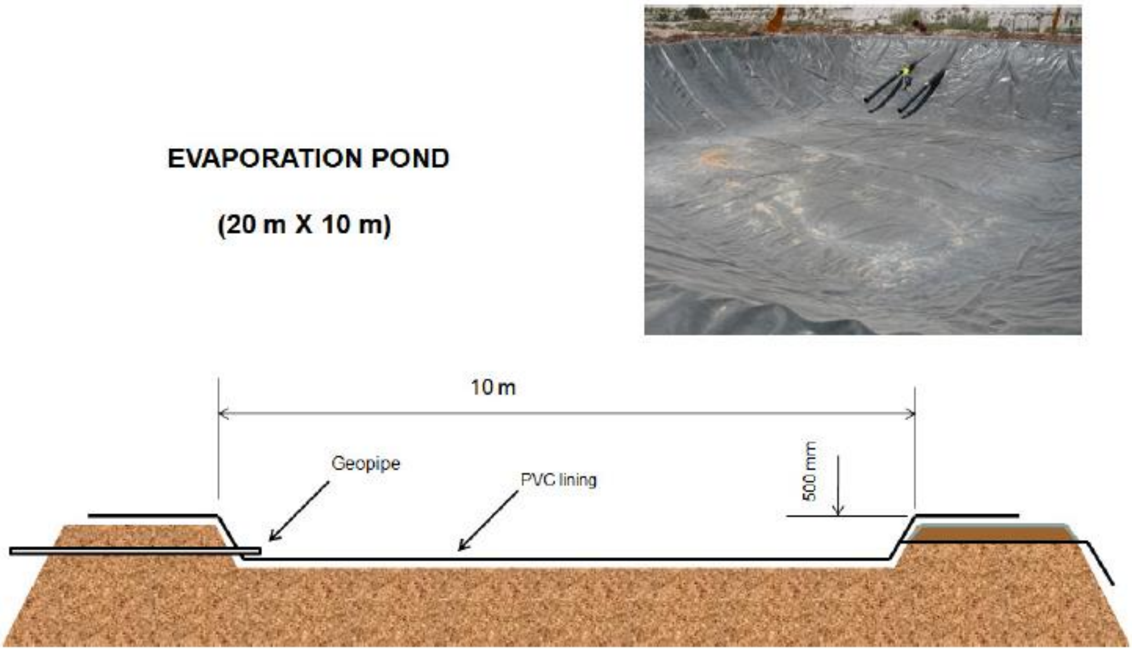

Figure 3.5: Cross section of the evaporation pond where the drainage system empties into.

Specifications on lying and bedding of Geopipe:

The purpose of the bedding was to provide a surface on which the Geopipe can be placed in order to separate the pipe from the surrounding rocks and clay material. Geopipe is a flexible pipe which does not have a large load bearing capacity. Therefore the quality of the backfill would have determined the strength of the pipe. With a reasonable material, the bedding thickness needed to be 100mm but when using softer or saturated material the bedding thickness should be between 150 and 200mm according to the SABS 1200 standards.

The proper compaction of the bedding material was essential to ensure that the gradient of the pipe could be maintained. The side fill was also very important and special care was taken with the placement of the haunch areas under the Geopipe. If the backfill material was not placed under the pipe, voids would have formed and the flexible pipe would have deformed into the voids. The compaction of the material was done at 90% Mod AASHTO. Fortunately, granular soils are easily graded and it provided uniform support to the Geopipe. The granular soil accommodates the haunch support material, which was compacted next to and above the Geopipe after it was laid.

Because the Geopipe is flexible it can carry a greater load. This is because of the fact that the pipe can deform horizontally and vertically without breaking. If the trench was too wide or to deep it may have caused instability and this could create problems with the laying of the Geopipe and also backfilling. If the trench collapses before proper bedding took place the pipe would have deformed. This is largely dependent on the soil type and the depth of the trench and in some cases trench support systems might be needed, however, this was not the case on this site.

Deformation of Geopipe is not seen as a problem but rather a requirement. The correct placement of bedding and padding should be implemented so that the deformation of the pipe does not exceed the limits. The backfilling of the trench was done in a symmetric manner in order to prevent the lateral movement of the pipe as this can cause problems with alignment. No dumping of soil in an indiscriminate manner to backfill the trench was done because this would have a negative influence on the integrity of the pipe. Furthermore, rocks pressing against the pipe should be avoided.

A layer of selected aggregate was placed above the pipe for protection against rocks and to provide support for backfilling. Hand compaction was used on the first 300mm of medium above the pipe. The selected backfill specifications (SABS 1200: Earthworks) divided the material into two classes. Class 1 is a clean, crushed rock or stone aggregate in the range between 9 and 38mm with little or no fines (particles smaller than 0.075mm). Class 2 is coarse grained, granular, free-draining, non-cohesive soils graded between 0.6 and 38mm with less than 5% fines.

Figure 3.6: A photograph displaying the lying of Geofabric during construction of the drainage system.

Figure 3.7: Imbedding of Geopipe during construction of the drainage system.

Figure 3.8: Backfilling of trenches after installation of drainage system.

Figure 3.9: Completed evaporation pond with drainage pipes entering on the right.

3.6 Implementation procedure of soil amelioration

The implementation of the rehabilitation procedure was done in October 2015 to utilise the maximum amount of summer rainfall. The procedure used entailed the broadcasting 15 tons of lime/ha, there after the broadcasting 1.7 tons of rock phosphate per ha. Potassium and zinc fertilizers were broadcasted at a rate of 350 kg/ha. The applied ameliorants were incorporated into the soil by means of a chisel plough and roller. Contouring of the erosion affected areas and controlling preferential flow patterns was implemented. Microbial inoculation at a rate of 4L/ha and application of the humic acid at a rate of 25kg/ha with fulvic acid at a rate of 7.5kg/ha were done by using a tractor and agricultural sprayer. After this the site was seeded by broadcasting the seeds (25kg/ha) and rolled by a rolling implement and tractor. Monitoring of the site was the next step. The indigenous seed mixture that was used contained *Cynodon dactylon, Pennisetum clandestinum, Eragrostis curvula, Eragrostis tef, Digitaria eriantha* and *Sorghum bicolor.*

3.7 Vegetation monitoring

The vegetation establishment survey was conducted by means of the wheel point method as explained by Tidmarsh and Havenga (1955). The previously denuded area was divided into 5 transects on which a wheel that marks each meter with a clicking sound was implemented to determine species on the transects. The species within 10cm from the mark where identified and recorded on each of the 5 transects.

Quadrants where then spaced evenly on each transect with a size of 1m^2 each. Within each of the quadrants, all the plants were identified and counted.

3.8 Data analysis

The data obtained from the soil sampling were analysed with the multivariate analysis method referred to as principle component analysis (PCA) in CANOCO version 4 (Ter Braak & Smilauer, 1998). Data analyses entailed nonparametric methods because the data were not normally distributed and the data was highly skewed due to the high null values and the data showed heterogeneous variances among groups.

Standard deviations and means were calculated by using Microsoft Office Excel 2010 together with the Student's one sided t-tests at a nominal significant level of 5% for equality of means.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Soil and water data obtained from 2010, 2011, 2013 and 2016

4.1.1 Results and discussion of the data obtained in 2010

During the first site visit in 2010, only one sample was taken on each of the designated sample areas. This was done in order to get an overview of the area and the problems that was present at that time (as described by Conklin, 2004). The information obtained from the resulting analyses was used to set up a conceptual rehabilitation plan. The reason for the plan being conceptual was to address the problems at hand. It was not possible at that time to plan for the future with precision with regard to the soil chemical amelioration that would be needed.

The results of the 1:2 water extraction procedure provide a good indication of water soluble elemental concentrations as well as other elements that are available for plant uptake. The elemental concentrations seen in this procedure can also be seen as the elements that can be transported by water and leach into the environment.

Table 4.1: Macro-elements, measured with the 1:2 water extraction procedure, present in the soil (mmol l^{-1}) at the sampled areas during 2010.

Macro-elements										
Sample ID	Ca	Mg	K	Na	PO_4	SO_4	NO_4	NH_4	Cl	HCO_3
	Millimol per litre									
Sample 1	0.14	0.88	0.42	0.10	<0.01	1.17	0.17	0.02	0.10	0.00
Sample 2	0.87	0.65	1.18	0.20	<0.01	0.51	3.54	0.21	0.13	0.00
Sample 3	7.86	10.84	1.64	3.25	0.05	0.41	78.49	38.34	1.42	0.00
Sample 4	0.27	0.13	0.35	0.07	0.01	0.34	0.14	0.05	0.34	0.10
Sample 5	5.35	3.04	0.93	3.53	0.02	0.96	19.77	1.03	0.64	0.00

Table 4.2: Micro-elements (µmol l^{-1}) and other data (pH, mS/cm and ppm), measured with the 1:2 water extraction procedure, present in the soil at the sampled areas during 2010.

Micro-elements and other data								P-Bray 1
Sample ID	Fe	Mn	Cu	Zn	B	pH	EC	ppm
	Micromol per litre						mS/cm	
Sample 1	4.10	1.10	0.10	0.25	<1	4.46	0.26	12.62
Sample 2	31.91	11.52	0.20	0.73	12	4.32	0.47	57.23
Sample 3	1.28	499.76	0.10	5.74	4	4.32	8.20	78.60
Sample 4	11.03	0.60	0.81	1.26	<1	5.17	0.13	26.32
Sample 5	3.08	164.22	0.35	2.86	<1	4.15	2.26	13.00

Tables 4.1 and 4.2 above shows the results of the samples and the following can be inferred:

Sample 1 was taken on the plant footprint and the macro-elemental concentrations revealed slightly elevated SO_4 and no HCO_3. This indicated that the sampling site was completely devoid from any buffering capacity. These problems can easily be addressed by applying the correct amount of dolomitic lime and by doing so the Ca deficiency would also be corrected. By applying a fertilizer with a NO_3 basis, the P and K concentrations will address the macro-elemental concerns. The dolomitic lime will also correct the low pH of the area and this will address the slightly elevated Mn concentration.

Sample 2 was collected half way down the slope from sample 1 and this area showed only sparse vegetation. The analyses showed that the area was slightly nutrient poor and elevated K and NO_3 concentrations were seen here. The norm values for vegetation establishment for a 1:2 water extraction are Ca: 1.8, Mg: 0.6, K: 0.8, Na: <1.0, SO_4: 0.9, NO_3: 2.1, Cl: <1.0 and HCO_3: 0.8 mmol l^{-1}. (Bergmann, 1992)

Sample 3 was taken on the slope that was completely devoid of any vegetation (denuded area). This area on the site showed clear signs of leaching and eutrophication. Eutrophication is the process by which a water body becomes increasingly rich in aquatic plant life because of plant nutrient pollution in the water body (Ansari, 2011). The analyses of the sample showed clear signs of amelioration that was done on the site previously because of the particularly elevated Ca and Mg concentrations in the growth medium. The N concentration in this area is phytotoxically high (both NO_3 and NH_4) and together with that the Na and Cl concentrations exceeds the adsorption capacity of this area completely. Furthermore, with the low pH value of the area and the depleted buffering capacity the Mn, and to some extent the Zn, in the area was at phytotoxically high concentrations (Bergmann, 1992).

Sample 4 was taken on the opposite bank of the slope and does not show chemical traces from the mining activity but the area is slightly nutrient poor. This problem can easily be addressed by applying the correct amount and combination of inorganic and organic fertilizer.

Sample 5 was taken at a pond in the natural stream at the bottom of the slope and showed a combination of chemical residue from the mining activities and the pollutants (fertilizer/explosives) leaching from the source at the top of the slope. Elevated Na, NO_3, NH_4 Mn and Zn concentrations were seen in the analyses together with a low pH and a high EC value of 2.26mS/cm which should be 1.8 to 2.0mS/cm for plant establishment and growth. (Bergmann, 1992)

Figure 4.1: Visible Eutrophication due to the N leaching at the natural stream to the south of the denuded area. The stream is around 1.5m wide.

Figure 4.2: Vegetation producing anthocyanin due to salt and Mn load adjacent to the denuded area (east).

Table 4.3: Nutrient status (mg/kg), pH and EC (mS/m) of the soil measured with the Ammonium acetate extraction analysis at the sampling areas during 2010.

Nutrient Status								
Sample ID	Ca	Mg	K	Na	P	pH(H_2O)	pH(KCl)	EC mS/m
	mg/kg							
Sample 1	275.0	146.0	104.5	23.5	12.6	5.21	4.34	31
Sample 2	417.5	141.5	134.5	65.5	57.2	4.78	4.23	53
Sample 3	1051.0	635.0	159.5	191.0	78.6	4.52	4.33	266
Sample 4	455.5	206.0	174.5	68.0	26.3	6.04	5.09	45
Sample 5	446.0	227.0	92.5	148.5	13.0	4.48	4.22	392

Table 4.4: Exchangeable cations (cmol(+)/kg), measured with the ammonium acetate extraction analysis, present in the soil at the sampling areas during 2010.

Exchangeable cations									
Sample ID	Ca	Mg	K	Na	CEC	S-Value	Base saturation (%)	pH(H_2O)	pH(KCl)
	(cmol(+)/kg)								
Sample 1	1.37	1.20	0.27	0.10	5.96	2.94	49.43	5.21	4.34
Sample 2	2.08	1.16	0.34	0.28	8.26	3.88	46.94	4.78	4.23
Sample 3	5.24	5.23	0.41	0.83	13.71	11.71	85.40	4.52	4.33
Sample 4	2.27	1.70	0.45	0.30	6.22	4.71	75.78	6.04	5.09
Sample 5	2.23	1.87	0.24	0.65	9.94	4.98	50.07	4.48	4.22

The ammonium acetate extraction procedure gives us an indication of the total elemental concentrations in the growth medium. The exchangeable cation ratios should be Ca 65 : Mg 25 : K 8 : Na 2 as norm values (MVSA, 1997) but in this case it was 46 : 41 : 9 : 3, 54 : 30 : 9 : 7, 45 : 46 : 4 : 7, 48 : 36 : 10 : 6 and 45 : 38 : 5 : 13 respectively for the five different samples. These results showed that the medium had a significant Ca requirement and that the Na concentration was far too high. This is an important factor to take into account for vegetation establishment as the Na inhibits K adsorption in a competitive manner. If this problem is not addressed the vegetation will be prone to stress from drought and appear yellow, which is a symptom of N or P deficiency (Bergmann, 1992).

The pH(KCl) analyses showed that the pH is below 5.5 and this can result in potential micro-elemental toxicity to plants (Sparks, 2003). The cation exchange capacity (CEC) fell in the 0 to 5 cmol(+) kg^{-1} range for most samples, which is a very low value. This can be addressed by adding organic material to the medium (Bjorklund & Mello, 2012). CEC is seen as the sum of all the exchangeable cations that can be absorbed by the soil (Brady & Weil, 2008). The percentage base saturation value of sample 3 was close to 100%, this should not be the case under normal circumstances. Sample 3 seemed to be an exception to the rule because of the higher clay content present as seen in Table 4.5.

Table 4.5: Particle size distribution (PSD) of the soil determined in 2010.

Sample	> 2mm	Sand	Silt	Clay
	%	% < 2mm		
1	0.4	82.0	2.5	15.4
2	0.8	86.6	4.7	8.6
3	0.2	86.9	4.6	8.4
4	10.3	82.5	5.3	12.2
5	17.9	77.5	6.0	16.5

In Table 4.5 we see that the particle size distribution of all samples are dominated by the sand friction and is, therefore, characterized by the low nutrient status and the limited water holding capacity. This can be seen in the CEC values of the samples.

Figure 4.3: Visible signs of surface runoff and erosion on the denuded area.

Figure 4.4: Very shallow water table on the denuded area close to the ¼ denuded sampling point due to saturation of the soil. (The size of the hole is 30 x 30 x 30cm).

Figure 4.5: N pollution on surface at the natural stream down slope from the denuded area.

By looking at the soil sample analysis it is clear that all sources of pollutants were not removed and that the remaining pollutants will not be taken up by plants, removed by de-nitrification or removed by the drainage trenches installed by RC1 in the near future. As a result, further rehabilitation is required.

4.2 Addressing the problems on the site

The site was divided into two areas for the rehabilitation of the site *viz.* Area 1; the denuded area down slope from where the plant was situated (south of the plant) and Area 2; the combination of the other sites mentioned previously (plant footprint, prills silo and the old soak-away).

Samples were taken on each sampling point at different depths to determine the depth to where contaminants were present in the soil. It was believed that contaminants were rising through the medium by capillary action. Samples were taken at the surface, 0.5m, 1m, 1.5m and 2m.

The historical sample sites were used again in the second rehabilitation project in order to have a reference from the data collected by RC1. These sampling points provide a reference for monitoring from 2002 when RC1 implemented their rehabilitation procedures up until now. For sampling area 1 the practical sites one quarter down the slope into the denuded area (with sample identification 1/4 denuded) and three quarters down the slope into the denuded area (with sample identification 3/4 denuded) were used because these sites are situated inside the worst affected area on the site. For sampling area 2 the sites at the prills silo, old soak-away and plant footprint was used.

After the site was visited in 2010 and information was collected using the means mentioned above, soil and water data was collected in 2011, 2013 and 2016 respectively. This was done to determine if the subsurface drains were working properly and to do possible adjustments to the amelioration plan for the site.

As mentioned previously, the site was divided into five different areas with regard to sampling points. The plant footprint, the prills silo and the old soak-away, all in area 1, as already discussed, were sampled in order to determine if the contamination has stopped in those areas and to revegetate these specific areas. The other two sampling points were taken one quarter way down the denuded area and three quarters down the slope on the denuded area. These samples are called ¼ denuded and ¾ denuded respectively.

4.3 Data ordination (2010 analysis)

The data obtained from the 2010 soil sampling were analysed with the multivariate analysis method principle component analysis (PCA) in CANOCO version 4 (Ter Braak & Smilauer, 1998). Data analyses entailed nonparametric methods because the data were not normally distributed and the data was highly skewed due to the high null values and the data showed heterogeneous variances among groups.

Table 4.6: Key to sample identities as used in the statistical ordination of the data.

Full site name	Abbreviated name
Prills 0.0m	Pr_0.0
Prills 0.5m	Pr_0.5
Prills 1.0m	Pr_1.0
Prills 1.5m	Pr_1.5
Prills 2.0m	Pr_2.0
Soak-away 0.0m	S_Aw_0.0
Soak-away 0.5m	S_Aw_0.5
Soak-away 1.0m	S_Aw_1.0
Soak-away 1.5m	S_Aw_1.5
Soak-away 2.0m	S_Aw_2.0
Plant 0.0m	Pl_0.0
Plant 0.5m	Pl_0.5
Plant 1.0m	Pl_1.0
Plant 1.5m	Pl_1.5
Plant 2.0m	Pl_2.0
¼ Denuded 0.0m	1_4D_0.0
¼ Denuded 0.5m	1_4D_0.5
¼ Denuded 1.0m	1_4D_1.0
¼ Denuded 1.5m	1_4D_1.5
¼ Denuded 2.0m	1_4D_2.0
¾ Denuded 0.0m	3_4D_0.0
¾ Denuded 0.5m	3_4D_0.5
¾ Denuded 1.0m	3_4D_1.0
¾ Denuded 1.5m	3_4D_1.5
¾ Denuded 2.0m	3_4D_2.0

Of all the ordination data analyses conducted, it was decided that the ordination based on the exchangeable cations should be selected as being the most representative of the dataset. Statistical analysis based on the groupings were obtained from area 1 (as the 1_4D sample series), whilst the rest of the samples were designated as area 2 (Pl_1.0 and Pl_1.5 was grouped into group 2 as well as the remaining members of that group).

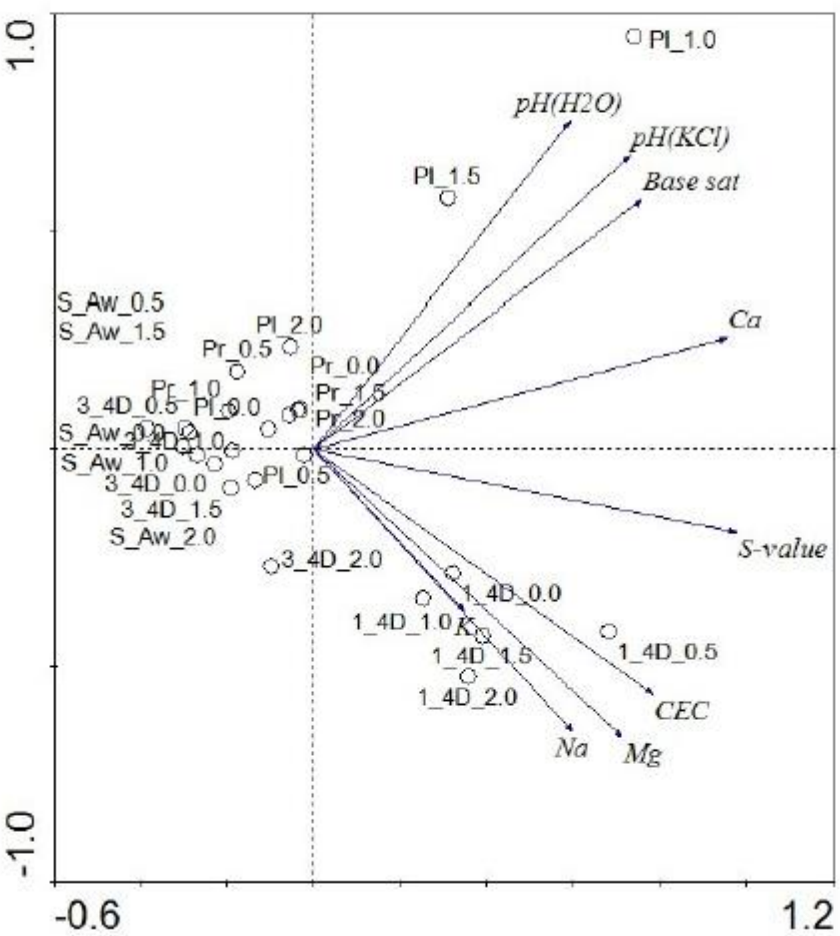

Figure 4.6: Display of data ordination (PCA).

Data ordination (PCA) based on the exchangeable cations from the ammonium acetate extraction procedure.

4.4 Results and discussion of the data obtained in 2010 throughout the growth medium (2010)

The results of the 1:2 water extraction procedure that provides an indication of the elemental concentrations that is soluble in water, and for that reason, available for plant uptake and leachable, are the following:

The area 1 samples showed extremely high concentrations in terms of Ca, Mg, K, Na, NO_3 and NH_4 (Bergmann, 1992).

Sampling area 1 was completely devoid from any buffering capacity as represented by the HCO_3 concentration.

This was a clear indication that the acidification process was still active at that time and that the contaminants were still present in this area. The norm values of these elemental concentrations are as follows: Ca: 1.8, Mg: 0.6, K: 0.8, Na: <1.0, NO_3: 2.0 and NH_4: 0.4 mmol l^{-1}.

Table 4.7: Mean macro-elements (mmol l^{-1} ± SD), measured with the 1:2 water extraction procedure, present in the soil at the sampled areas during 2010.

Macro- elements								
Sample ID	Ca	Mg	K	Na	PO_4	SO_4	NO_3	NH_4
	mmol l^{-1} ± SD							
Area 1	9.50±0.94	6.98±1.41	2.79±0.62	3.06±0.63	0.02±0.01	0.88±0.09	56.58±9.21	18.90±4.61
Area 2	0.57±0.54	0.35±0.38	0.22±0.13	0.16±0.24	0.01±0.00	0.39±0.18	4.5±7.94	2.19±4.12

Table 4.8: Mean micro-elements (µmol l^{-1} ± SD) and other data (pH, mS/cm, ppm and %), measured with the 1:2 water extraction procedure, present in the soil at the sampled areas during 2010.

Micro-elements					
Sample ID	Fe	Mn	Cu	Zn	B
	Micromol per litre				
Area 1	1.48±10.28	211.94±45.43	0.42±0.17	6.65±2.09	3.40±4.69
Area 2	6.13±9.01	30.86±48.98	0.17±0.12	0.80±0.57	0.72±1.50

Other data	pH	EC	P-Bray1	C	N
		mS/cm	*ppm*	*%*	*%*
Area 1	4.18±0.13	5.87±0.92	32.38±24.13	1.47±0.57	0.01±0.01
Area 2	4.42±0.78	0.54±0.77	15.94±13.89	1.19±0.27	0.04±0.20

The samples of sample area 2 were slightly nutrient poor but still showed signs of elevated NO_3 and NH_4. In these samples there were trace amounts of HCO_3 present in the soil and this indicated that the acidification process had almost reached its end and that the leaching of contaminants had decreased in these areas (Brady & Weil, 2008).

By looking at the micro-elements from the 1:2 water extraction we see that the area 1 samples showed extremely elevated Mn and Zn concentrations and Mn is phototoxic to plants (Fernando & Lynch, 2015). The norm value for Mn concentration in the soil for a 1:2 water extraction that is acceptable for plant growth is 0.9 µmol l^{-1}. In the area 2 samples the Mn was also very high but in terms of the micro-elemental concentrations it was the only element that warrants some concern.

In the table for other data it is clear that the pH values of both area 1 and area 2 samples are very low. The elevated EC values showed in the area 1 samples were much higher than that of the area 2 samples (Van Rensburg & Maboeta, 2004). The norm range value for the EC is between 0.5 and 0.8mS cm^{-1} for the 1:2 water extraction.

The ammonium acetate extraction procedure gives a good indication of the total elemental concentrations in the medium. The results of this procedure revealed that the exchangeable cation ratios deviate from the norm values to a large degree. The norm percentages of the exchangeable cation ratios (Ca:Mg:K:Na) are: 65:25:8:2. In group 1 the ratios were 48:36:6:10 and 62:17:9:10 for area 2. This indicated that the Ca in area 1 is significantly lower than the norm value and the Na concentration was significantly higher than the norm value.

Table 4.9: Mean nutrient status (mg kg^{-1} ± SD), pH and EC (mS m^{-1}) present in the soil at the sampling points, by utilising the ammonium acetate extraction analysis during 2010.

Nutrient status								
Sample ID	Ca	Mg	K	Na	P	pH(H2O)	pH(KCl)	EC
	mg/kg							mS/m
Area 1	537.00 ±114.05	242.70 ±43.97	132.80 ±32.27	121.20 ±10.81	32.38 ±24.13	4.76 ±0.25	4.32 ±0.21	1773.40 ±201.16
Area 2	285.48 ±210.16	48.33 ±26.88	82.10 ±37.80	53.95 ±25.25	15.94 ±13.89	4.96 ±0.84	4.25 ±0.80	150.35 ±208.50

Table 4.10: Mean exchangeable cations (cmol(+)/kg ± SD) (% and pH) in the soil at the sampling points, measured by utilizing the ammonium acetate extraction analysis during 2010.

Exchangeable cations									
Sample ID	Ca	Mg	K	Na	CEC	S-Value	Base saturation	pH(H2O)	pH(KCl)
	cmol(+)/kg						%		
Area 1	2.68 ±0.57	2.00 ±0.36	0.34 ±0.08	0.53 ±0.05	9.75 ±1.05	5.54 ±1.01	56.94 ±8.54	4.76 ±0.25	4.32 ±0.21
Area 2	1.42 ±1.05	0.40 ±0.22	0.21 ±0.10	0.23 ±0.11	4.22 ±1.01	2.27 ±1.10	52.58 ±16.85	4.96 ±0.84	4.25 ±0.80

The average pH(KCl) of the area 1 and the area 2 samples were well below 5.5 and this could cause problems with potential heavy metal toxicity and result in the observed elevated micro-elemental concentrations. The average cation exchange capacity (CEC) for both area 1 and area 2 samples were in the range between 0 to 10 cmol(+) kg^{-1}. These values were very low and indicated that the medium was in need of organic material. The base saturation of sample areas 1 and 2 were both significantly lower than 100%. This was due to the low CEC values of both sample areas, and also due to the low pH values present in the medium of both groupings at that time.

The physical soil analyses of the medium showed that the particle size distribution (PSD) was ±80% for the sand friction, ±10% for the clay friction and ±6% for the silt friction. This indicated that the soil composition was adequate for the rehabilitation procedures prescribed and the rehabilitation commenced without any special requirements. The permeability of the soil was deemed adequate for the functioning of subsurface drains.

4.5 Summary results and discussion of soil analysis (2011)

Tables 4.11 to 4.14 reflect the average of the results obtained of the soil analysis conducted in May 2011:

Table 4.11: Mean macro-elements, measured by utilizing the 1:2 water extraction procedure, present in the soil (mmol l^{-1} ± SD) at the sampled areas during 2011.

Macro-elements										
Sample ID	Ca	Mg	K	Na	PO_4	SO_4	NO_3	NH_4	Cl	HCO_3
	Millimol per litre									
¼ Denuded	10.14 ±0.32	7.17 ±1.93	3.04 ±0.71	3.29 ±0.75	0.02 ±0.01	0.91 ±0.11	61.18 ±9.51	21.18 ±4.79	0.41 ±0.06	0.00 ±0.00
¾ Denuded	1.38 ±0.13	1.02 ±0.33	0.26 ±0.08	0.54 ±0.15	0.01 ±0.00	0.20 ±0.04	16.71 ±2.60	8.24 ±1.06	0.08 ±0.04	0.00 ±0.00
Plant	0.55 ±0.42	0.12 ±0.03	0.21 ±0.15	0.03 ±0.01	0.01 ±0.00	0.61 ±0.20	0.09 ±0.06	0.02 ±0.01	0.06 ±0.05	0.23 ±0.40
Prills	0.12 ±0.10	0.12 ±0.08	0.18 ±0.10	0.02 ±0.00	0.01 ±0.01	0.28 ±0.20	0.09 ±0.05	0.02 ±0.00	0.08 ±0.06	0.01 ±0.01
Soak-away	0.18 ±0.03	0.15 ±0.07	0.20 ±0.09	0.03 ±0.01	0.01 ±0.00	0.40 ±0.06	0.04 ±0.02	0.02 ±0.00	0.06 ±0.02	0.00 ±0.00

Table 4.12: Mean micro-elements (µmol l^{-1} ± SD) and other data (pH and mS/cm), measured with the 1:2 water extraction procedure, present in the soil at the sampled areas during 2011.

Micro-elements and other data							
Sample ID	Fe	Mn	Cu	Zn	B	pH	EC
	Micromol per liter						mS/cm
¼ Denuded	1.53±1.19	240.20±33.56	0.44±0.19	7.37±2.56	5.56±5.14	4.27±0.03	6.33±0.95
¾ Denuded	4.75±0.77	110.41±19.80	0.12±0.08	1.59±0.20	1.28±1.17	3.87±0.11	1.72±0.27
Plant	4.59±2.46	2.27±1.93	0.14±0.04	0.23±0.22	0.57±0.49	5.38±1.83	0.16±0.08
Prills	21.93±16.43	1.99±0.97	0.27±0.13	0.64±0.54	0.00±0.00	4.56±0.32	0.08±0.04
Soak-away	0.74±0.63	8.50±1.89	0.14±0.07	0.79±0.16	0.00±0.00	4.22±0.07	0.09±0.01

Table 4.13: Mean nutrient status (mg kg^{-1} ± SD), pH and EC (mS m^{-1}) present in the soil at the sampling points, by utilising the ammonium acetate extraction analysis during 2010.

Nutrient status								
Sample ID	Ca	Mg	K	Na	P	pH(H_2O)	pH(KCl)	EC
	mg/kg							mS/m
¼ Denuded	561.67 ±151.93	235.33 ±60.37	136.33 ±44.64	119.50 ±14.76	47.16 ±18.60	4.88 ±0.27	5.84 ±0.48	1809.67 ±267.91
¾ Denuded	168.33 ±18.43	73.50 ±11.79	28.50 ±6.08	59.17 ±26.99	23.92 ±18.48	4.39 ±0.15	5.36 ±1.23	476.67 ±132.25
Plant	555.67 ±430.47	53.00 ±3.04	92.33 ±20.25	56.67 ±15.88	24.23 ±11.61	5.78 ±1.34	5.92 ±1.21	55.67 ±34.93
Prills	256.50 ±42.44	37.67 ±8.52	121.50 ± 21.98	27.50 ±17.59	30.49 ±20.32	5.24 ±0.23	5.50 ±0.10	38.67 ±5.77
Soak-away	141.67 ±16.62	11.67 ±2.84	87.83 ±25.26	47.00 ±16.93	9.33 ±3.78	4.32 ±0.09	4.24 ±0.00	28.67 ± 2.31

Table 4.14: Mean exchangeable cations (cmol(+)/kg ± SD) (% and pH) in the soil at the sampling points, measured by utilizing the ammonium acetate extraction analysis during 2011.

Exchangeable cations									
Sample ID	Ca	Mg	K	Na	CEC	S-value	Base saturation %	pH (H_2O)	pH (KCl)
	cmol(+)/kg								
¼ Denuded	2.80 ±0.76	1.94 ±0.50	0.35 ±0.11	0.52 ±0.06	9.42 ±1.26	5.61 ±1.42	59.35 ±10.49	4.88 ±0.27	5.84 ±0.48
¾ Denuded	0.84 ±0.09	0.60 ±0.10	0.07 ±0.02	0.25 ±0.12	3.74 ±0.56	1.77 ±0.20	47.58 ±1.85	4.39 ±0.15	5.36 ±1.23
Plant	2.77 ±2.15	0.44 ±0.03	0.24 ±0.05	0.25 ±0.07	5.18 ±0.49	3.69 ±2.08	70.46 ±36.83	5.78 ±1.34	5.92 ±1.21
Prills	1.28 ±0.21	0.31 ±0.07	0.31 ±0.06	0.12 ±0.08	4.41 ±0.68	2.02 ±0.39	45.84 ±4.37	5.24 ±0.23	5.50 ±0.10
Soak-away	0.71 ±0.08	0.10 ±0.02	0.23 ±0.06	0.20 ±0.07	2.71 ±0.20	1.23 ±0.19	45.31 ±4.16	4.32 ±0.09	4.24 ±0.00

As mentioned in the previous chapter, the 1:2 water extract shows the elemental concentrations of in the soil that is soluble in water and thus available for plant uptake. From the 2011 data it is evident that the K concentrations exceeded the norm value of 0.84mmol l^{-1} at the ¼ denuded area sampling site, but in contrast the other four sampling sites showed low K concentrations. The Na norm value of <2 mmol l^{-1} was also exceeded at the ¼ denuded area sampling site. At each of the sampling sites the PO_4 concentrations were found to be below the norm value of 0.03 mmol l^{-1}. Potentially, phytotoxic values of 61.18 mmol l^{-1} and 16.71 mmol l^{-1} at the ¼ denuded and ¾ denuded sampling sites, respectively, for both NO_3 (norm value is 2.1 mmol l^{-1}) and NH_4 (norm value is 0.03 mmol l^{-1}) characterized both these sampling sites in terms of the data collected during 2011. In the three remaining sampling sites, the NO_3 values are below the concentrations required for optimal plant establishment and growth. At each of the sampling points the HCO_3 values indicated that the soil was devoid of any buffering capacity at that time (2011) with values well below the norm value of 0.8 mmol l^{-1} typifying the sites.

With regard to the micro elemental concentrations as reflected by the 1:2 water extract data, the Mn concentrations stood out as a possible element of concern with elevated average levels of 240.20 μmol l^{-1} and 110.41 μmol l^{-1} respectively, at the ¼ denuded and ¾ denuded sampling points. This was substantially higher than the norm value of 1 μmol l^{-1} to a maximum value of 3 μmol l^{-1}. This was significant as Mn in these concentrations is potentially phytotoxic to plants (Bergmann, 1992). The Zn concentration typifying the ¼ denuded area was also elevated above the norm value (1 μmol l^{-1} to a maximum value of 3 μmol l^{-1}) to a level of 7.37 μmol l^{-1}. The pH of all the sampling points were lower than the norm of 6.3 with the EC values at the ¼ denuded area as well as at the ¾ denuded area that showed very high values.

Analysis of the results from the ammonium acetate extraction procedure was done by the calculation of the exchangeable cation ratios. This provides us an indication of the ratios between the different cations in the ratio of Ca:Mg:K:Na. The norm ratio values for this analysis is 65:25:8:2 and is calculated by using the following equation:

$$\frac{100\ Ca}{S}:\frac{100\ Mg}{S}:\frac{100\ K}{S}:\frac{100\ Na}{S}.$$

The S-value is indicated for each sample and is calculated as follows:

$$S - value\ =\ Ca\ +\ Mg\ +\ K\ +\ Na,$$

(MVSA, 1997).

Table 4.15: Mean exchangeable cation ratios (cmol(+)/kg ± SD) from the ammonium acetate extraction procedure in the 2011 samples.

Sample ID	Ca	Mg	K	Na
	(cmol(+)/kg ± SD)			
¼ Denuded	49.91±2.84	34.58±2.35	6.24±0.65	9.27±0.87
¾ Denuded	47.46±2.21	33.90±3.70	3.95±1.30	14.12±5.03
Plant	75.07±10.96	11.92±4.26	6.50±3.99	6.78 ± 3.53
Prills	63.37±1.49	15.35±2.23	15.35±3.35	5.94 ± 2.60
Soak-away	57.72±4.30	8.13±6.50	18.70±3.99	16.26±2.95
Norm Values	65	25	8	2

In comparison to the norm ratio it was clear that the Ca percentages were low at the ¼ denuded, ¾ denuded and the soak-away sample points while the Na percentages were much higher than the norm value of 2%. The pH(KCl) was also above 5.5, which can result in micro-elemental toxicities in plants. This is due to the fact that the micro-elements become soluble under these conditions (FERTASA, 2016). The low CEC value is also indicative of a limited binding capacity on the exchangeable matrix that can potentially be problematic for different physical soil properties.

4.6 Summary results and discussion of soil analysis (2013)

Table 4.16: Mean macro-elements (mmol l^{-1} ± SD), measured with the 1:2 water extraction procedure, present in the soil at the sampled areas during 2013.

Macro-elements										
Sample ID	Ca	Mg	K	Na	PO_4	SO_4	NO_3	NH_4	Cl	HCO_3
	Millimol per litre									
¼ Denuded	3.76 ±1.91	0.44 ±0.38	0.05 ±0.04	0.29 ±0.12	0.01 ±0.01	0.22 ±0.11	7.89 ±5.00	0.04 ±0.03	0.07 ±0.06	0.47 ±0.64
¾ Denuded	13.02 ±11.95	7.08 ±7.47	1.08 ±1.03	2.06 ±1.96	0.02 ±0.02	0.60 ±0.44	41.52 ±40.50	0.20 ±0.19	0.38 ±0.34	0.38 ±0.28
Plant	2.32 ±1.313	0.44 ±0.26	0.38 ±0.20	0.45 ±0.30	0.00 ±0.00	0.95 ±0.09	4.84 ±3.39	0.12 ±0.19	0.09 ±0.06	0.00 ±0.00
Prills	0.09 ±0.03	0.07 ±0.03	0.35 ±0.16	0.07 ±0.02	0.00 ±0.00	0.32 ±0.05	0.16 ±0.11	0.13 ±0.09	0.08 ±0.04	0.05 ±0.00
Soak-away	0.15 ±0.08	0.07 ±0.03	0.20 ±0.18	0.07 ±0.01	0.01 ±0.01	0.31 ±0.07	0.11 ±0.10	0.08 ±0.12	0.07 ±0.06	0.05 ±0.00

Table 4.17: Mean micro-elements (µmol l^{-1} ± SD) and other data (pH, mS/cm), measured with the 1:2 water extraction procedure, present in the soil at the sampled areas during 2013.

Micro-elements and other data							
Sample ID	Fe	Mn	Cu	Zn	B	pH	EC
	Micromol per liter						mS/cm
¼ Denuded	15.42±15.87	50.13±72.64	0.31±0.12	0.35±0.37	16.83±9.98	5.87±1.33	0.89±0.47
¾ Denuded	15.55±23.38	44.10±71.19	0.62±0.11	0.70±0.13	19.10±8.63	6.11±0.94	4.35±4.17
Plant	0.78±0.39	154.98±122.24	0.91±0.40	9.30±4.50	2.97±2.73	4.07±0.04	0.68±0.35
Prills	25.28±10.41	1.08±0.70	0.06±0.03	0.28±0.12	9.56±9.21	4.75±0.08	0.09±0.03
Soak-away	34.53±6.65	1.65±0.82	0.42±0.03	0.93±0.18	10.01±6.19	4.88±0.03	0.09±0.03

Table 4.18: Mean nutrient status (mg kg^{-1} ± SD), pH and EC (mS m^{-1}) present in the soil at the sampling points, by utilising the ammonium acetate extraction analysis during 2013.

Nutrient status								
Sample ID	Ca	Mg	K	Na	P	pH(H_2O)	pH(KCl)	EC
	mg/kg							mS/m
¼ Denuded	1214.33 ±985.37	63.33 ±37.33	22.33 ±6.75	9.50 ±1.32	50.43 ±7.43	5.81 ±1.70	5.48 ±1.86	178.33 ±92.65
¾ Denuded	1327.00 ±694.82	266.83 ±164.61	97.33 ±51.81	48.83 ±38.76	62.75 ±38.76	5.73 ±0.70	5.62 ±1.39	1114.00 ±934.46
Plant	147.17 ±61.92	13.83 ±9.00	53.17 ±12.39	11.83 ±8.13	46.66 ±17.22	3.96 ±0.14	3.75 ±0.10	123.67 ±47.54
Prills	146.67 ±25.18	31.67 ±5.53	115.00 ±3.00	3.17 ±1.89	25.58 ±16.83	4.93 ±0.01	4.02 ±0.07	17.67 ±2.52
Soak-away	302.67 ±45.62	40.83 ±3.25	91.33 ±28.11	1.67 ±1.26	72.08 ±31.32	5.04 ±0.10	4.06 ±0.10	22.33 ±7.02

Table 4.19: Mean exchangeable cations (cmol(+)/kg ± SD) (% and pH) in the soil at the sampling points, measured by utilizing the ammonium acetate extraction analysis during 2013.

Exchangeable cations									
Sample ID	Ca	Mg	K	Na	CEC	S-value	Base saturation %	pH (H_2O)	pH (KCl)
	cmol(+)/kg								
¼ Denuded	6.06 ±4.37	0.52 ±1.30	0.06 ±0.11	0.04 ±0.14	13.38 ±2.24	6.68 ±5.84	48.40 ±49.58	5.81 ±0.85	5.48 ±1.57
¾ Denuded	6.62 ±0.83	2.20 ±0.03	0.25 ±0.13	0.21 ±0.04	13.34 ±1.42	9.28 ±0.70	74.33 ±8.02	5.73 ±0.49	5.62 ±0.16
Plant	0.73 ±0.23	0.11 ±0.03	0.14 ±0.07	0.05 ±0.01	11.62 ±1.03	1.04 ±0.21	8.94 ±2.36	3.96 ±0.10	3.75 ±0.15
Prills	0.73 ±2.71	0.26 ±0.32	0.29 ±0.04	0.01 ±0.02	12.41 ±2.21	1.03 ±3.01	4.93 ±18.65	4.93 ±1.07	4.02 ±0.95
Soak-away	1.51 ±5.57	0.34 ±1.58	0.23 ±0.15	0.01 ±0.19	12.56 ±1.10	2.09 ±6.39	5.04 ±48.66	5.04 ±1.38	4.06 ±1.77

As was the case in 2011, the 1:2 water extract data for 2013 still reflected potential K deficiencies at the majority of the sampling points. Furthermore, it became clear that the K decreased dramatically from the toxic levels from 2011 at the ¼ denuded sample point. The same held true for the Na concentrations, but the Na concentration increases at the ¾ sampling point over the same period. The NO_3 values decreased dramatically at the ¼ denuded sampling point but was still at very high levels at that time (2013). An increase in the NO_3 concentration became apparent in the ¾ denuded samples down slope and a potentially problematic increase was noted at the plant sampling point in terms of the NO_3 value. NH_4 concentrations decreased from phytotoxic values in 2011 to acceptable values within the norm value range for this sampling period. There was a slight increase in the HCO_3 values of almost all sampling sites but all was still critically low in 2013.

The micro-elemental and other data (1:2 water extract) still mirrored the concerns in terms of high Mn values although it decreased from 2011 in the ¼ denuded sample point and the ¾ denuded sample point. The plant sampling point revealed a dramatic increase in Mn concentrations in the 2013 data as well as the Zn concentration at the plant sampling site. In terms of the pH values (water extractable) an increase was seen at the ¼ denuded area and the ¾ denuded area to an acceptable value but a decrease was seen at the plant area while the other two sampling sites (prills and soak-away) remained almost unchanged.

Table 4.20: Mean exchangeable cation ratios (cmol(+)/kg ± SD) from the ammonium acetate extraction procedure in the 2013 samples.

	Ca	Mg	K	Na
¼ Denuded	90.72±2.66	7.78±1.74	0.90±0.48	0.60±0.71
¾ Denuded	71.34±1.39	23.71±5.19	2.70±4.02	2.27±0.37
Plant	70.20±2.00	10.58±3.39	13.47±2.69	4.81±1.20
Prills	56.16±0.13	20.00±0.05	22.31±0.01	0.77±0.01
Soak-away	72.25±0.23	16.27±0.03	11.01±0.07	0.48±0.01
Norm Values	65	25	8	2

In general the Ca percentages showed an increase from the 2011 analysis. We see a dramatic decrease in Na percentages, however, these percentages was still high at the ¾ denuded area and the plant sampling point. The CEC values revealed an increase, but the pH values had a negative change and decreased further over this period.

4.7 Summary of the results obtained in the 2016 data

Table 4.21: Mean macro-elements (mmol l^{-1} ± SD), measured with the 1:2 water extraction procedure, present in the soil at the sampled areas during 2016.

1:2 Water extract										
Macro-elements										
Sample ID	Ca	Mg	K	Na	PO_4	SO_4	NO_3	NH_4	Cl	HCO_3
	Millimol per litre									
¼ Denuded	2.08 ±0.24	0.35 ±0.05	1.40 ±0.16	0.12 ±0.03	0.04 ±0.01	0.29 ±0.16	4.33 ±0.92	0.04 ±0.03	0.07 ±0.06	0.73 ±0.40
¾ Denuded	13.94 ±1.06	7.31 ±2.42	2.30 ±0.41	2.80 ±0.86	0.03 ±0.01	1.35 ±0.22	44.13 ±6.33	0.35 ±0.09	0.48 ±0.09	0.60 ±0.13
Plant	2.58 ±0.42	0.37 ±0.09	0.70 ±0.06	0.50 ±0.04	0.03 ±0.01	0.77 ±0.12	5.19 ±0.83	0.18 ±0.12	0.08 ±0.02	0.45 ±0.05
Prills	0.55 ±0.21	0.16 ±0.05	0.42 ±0.10	0.16 ±0.04	0.02 ±0.01	0.28 ±0.08	0.89 ±0.33	0.13 ±0.09	0.13 ±0.08	0.50 ±0.05
Soak-away	0.50 ±0.07	0.14 ±0.04	0.35 ±0.08	0.12 ±0.06	0.01 ±0.01	0.29 ±0.09	0.55 ±0.07	0.08 ±0.05	0.09 ±0.04	0.63 ±0.10

Table 4.22: Mean micro-elements (µmol l^{-1} ± SD) and other data (pH, mS/cm), measured with the 1:2 water extraction procedure, present in the soil at the sampled areas during 2016.

Micro-elements and other data							
Sample ID	Fe	Mn	Cu	Zn	B	pH	EC
	Micromol per litre						mS/cm
¼ Denuded	11.17±6.30	17.41±13.94	0.31±0.12	0.30±0.33	11.58±4.16	5.96±0.33	0.65±0.07
¾ Denuded	5.95±5.71	23.43±28.49	0.55±0.03	0.60±0.15	12.33±3.06	6.50±0.42	4.80±0.67
Plant	0.78±0.39	37.11±18.64	0.77±0.35	7.82±3.87	3.32±1.53	6.04±0.06	0.74±0.10
Prills	21.95±8.98	1.05±0.75	0.06±0.03	0.26±0.15	7.00±2.00	6.61±0.23	0.22±0.04
Soak-away	27.81±7.69	1.29±0.20	0.38±0.07	0.87±0.26	9.69±6.74	6.27±0.57	0.19±0.03

Table 4.23: Mean nutrient status (mg kg^{-1} ± SD), pH and EC (mS m^{-1}) present in the soil at the sampling points, by utilising the ammonium acetate extraction analysis during 2016.

Nutrient status								
Sample ID	Ca	Mg	K	Na	P	pH(H_2O)	pH(KCl)	EC
	mg/kg							mS/m
¼ Denuded	494.00 ±5.27	70.83 ±2.08	179.33 ±2.02	3.33 ±0.29	56.28 ±0.34	5.85 ±0.07	5.21 ±0.05	61.33 ±1.53
¾ Denuded	1340.50 ±10.48	85.67 ±2.47	241.50 ±4.58	5.33 ±1.04	28.27 ±0.17	7.56 ±0.06	7.13 ±0.25	63.00 ±14.80
Plant	997.17 ±3.55	140.83 ±2.08	188.33 ±2.47	4.50 ±0.50	61.00 ±0.17	6.53 ±0.05	5.95 ±0.09	48.00 ±3.00
Prills	3296.00 ±5.89	149.33 ±1.61	158.17 ±3.01	11.67 ±1.04	26.68 ±0.21	8.19 ±0.04	8.03 ±0.07	52.67 ±1.15
Soak-away	3408.00 ±7.09	329.33 ±2.02	241.67 ±3.88	23.33 ±1.04	35.32 ±0.20	8.07 ±0.06	7.97 ±0.11	169.33 ±3.06

Table 4.24: Mean exchangeable cations (cmol(+)/kg ± SD) (% and pH) in the soil at the sampling points, measured by utilizing the ammonium acetate extraction analysis during 2016.

Exchangeable cations									
Sample ID	Ca	Mg	K	Na	CEC	S-value	Base saturation %	pH (H_2O)	pH (KCl)
	cmol(+)/kg								
¼ Denuded	2.47 ±0.03	0.58 ±0.02	0.46 ±0.01	0.01 ±0.00	8.93 ±0.09	3.52 ±0.03	39.46 ±0.11	5.85 ±0.07	5.21 ±0.05
¾ Denuded	6.69 ±0.05	0.71 ±0.02	0.62 ±0.01	0.02 ±0.00	7.11 ±0.12	8.04 ±0.08	113.05 ±2.06	7.56 ±0.06	7.13 ±0.25
Plant	4.98 ±0.02	1.16 ±0.02	0.48 ±0.01	0.02 ±0.00	10.75 ±0.15	6.64 ±0.02	61.73 ±0.82	6.53 ±0.05	5.95 ±0.09
Prills	16.45 ±0.01	1.23 ±0.01	0.41± 0.01	0.05 ±0.00	13.08 ±0.07	18.13 ±0.05	138.62 ±0.46	8.19 ±0.04	8.03 ±0.07
Soak-away	17.01 ±0.02	2.71 ±0.02	0.62 ±0.01	0.10 ±0.00	14.69 ±0.06	20.44 ±0.04	139.10 ±0.31	8.07 ±0.06	7.97 ±0.11

In 2016 the 1:2 water extract data indicated an increase in K at each of the sampling points. At the ¼ denuded sampling point the value increased to a acceptable concentration, but the ¾ denuded sampling point still showed excess K while the other 3 samples was still slightly below the norm of 0.84 mmol l^{-1}. The Na at the ¾ denuded sample point still exceeded the norm value and even showed a slight increase. The NO_3 values all showed an increase from 2013 to 2016 accept for the ¼ denuded area in which the value decreased. The NO_3 values still exceeded the norm value of 2.1 mmol l^{-1} at the ¼ denuded, ¾ denuded and plant sampling points with the ¾ denuded point at an extremely high value of 44.13 mmol l^{-1} on average.

The HCO_3 values increased from almost 0.00 mmol l^{-1} to values with a minimum of 0.45 which is much closer to the norm value of 0.83 mmol l^{-1}.

The micro-elements and other data of the 1:2 water extract revealed another decrease in the Mn concentrations from 2013 to 2016. However, these values were still much higher than the norm in the ¼ denuded area, the ¾ denuded area as well as the plant sampling point. The Zn concentration decreased but was also still high at the plant sampling point. All the pH values showed an increase to a value within the acceptable norm value with the EC value of 4.80 mS/cm (which is still high) present at the ¾ denuded sample point.

Table 4.25: Mean exchangeable cation ratios (cmol(+)/kg ± SD) from the ammonium acetate extraction procedure in the 2011 samples.

	Ca	Mg	K	Na
¼ Denuded	70.17±0.52	16.48±0.45	13.07±0.04	0.29±0.03
¾ Denuded	83.21±0.20	8.83±0.19	7.72±0.11	0.25±0.05
Plant	75.00±0.22	17.47±0.23	7.23±0.11	0.31±0.03
Prills	90.74±0.11	6.79±0.05	2.27±0.04	0.28±0.02
Soak-away	83.22±0.06	13.26±0.09	3.04±0.04	0.49±0.02
Norm Values	65	25	8	2

From these ratios we can see that, from 2013 to 2016, the Na percentages were reduced to acceptable levels for plant growth and a similar conclusion can be drawn regarding the rising Ca percentages. The pH values also showed an increase to more favourable conditions.

4.8 Summary results and discussion of water analysis (2013)

Table 4.26: Mean macro-elements (mg/l ± SD) present in the water samples taken from the collection pond in 2013.

Macro-elements										
Sample ID	Ca	Mg	K	Na	PO_4	SO_4	NO_3	NH_4	Cl	HCO_3
	Milligram per litre									
Pond water	272.93 ±6.17	125.82 ±3.04	35.97 ±1.17	60.08 ±1.31	<0.01 ±0	74.78 ±1.30	1960.15 ±53.06	100.83 ±3.40	14.03 ±1.61	1.02 ±0.35

The target water quality range for this analysis is specified by DWAF (Department of Water Affairs and Forestry of South Africa) (1996). Here we saw the drainage system that had been constructed was working effectively because of the high concentrations of NO_3 and NH_4 that was leaching from the soil. The norm value for NO_3 is <26.56 mg/l and in this case it was elevated to an average value of 1960.15 mg/l. The NH_4 norm value is <1.29 mg/l and in this sample an average value of 5.59 mg/l was seen. Ca and Mg has norm values of <32 mg/l and <30mg/l respectively and it was much higher in this case.

Table 4.27: Mean micro-elements (mg/l ± SD) present in the water samples taken from the collection pond in 2013.

Micro-elements and other data							
Sample ID	Fe	Mn	Cu	Zn	B	pH	EC
	Milligram per litre						mS/cm
Pond Water	0.42±0.02	12.46±0.43	0.03±0.01	0.14±0.00	0.03±0.00	4.65±0.04	3.37±0.09

The DWAF norm value for Fe is <0.1 mg/l and in this sample the value measured was 0.42 mg/l on average. The Mn should be <0.05 mg/l but here we see an elevated average value of 12.46 mg/l. The pH of the water was low with a value of 4.65 on average while the norm is 6 or higher. The EC value of 3.37 mS/cm is also elevated when compared to the norm of <0.7 mS/cm.

4.9 Overall discussion of data obtained in 2011, 2013 and 2016

The samples taken from the site showed an undesirable acidity and, in some cases, the pH(H_2O) values were significantly below the desired margins of 6.5-7 with values of below 4 in 2011 and 2013 respectively. The acidity became more suitable for vegetation establishment in 2016 but amelioration of the growth medium was still needed in order to fully correct the pH and the nutrient imbalances. Together with the low pH values a very low buffer capacity, or even a complete lack of buffer capacity was recorded in the soil in 2011. The buffer capacity was still low in 2013, but in 2016 the bicarbonate levels increased to values closer to the norm value of 0.83mmol l^{-1}. The acidic conditions in the soil created an environment where metals like Mn and Fe were soluble and they were present in phytotoxic concentrations. This was seen in the water analysis data from the samples that were collected from the collection pond in 2013. The pH levels needed to be corrected in in order to prevent the liberation of metals and keep these contaminants from entering the natural stream downslope of the area. In order to achieve this, a lime application of 15 tons per hectare was recommended.

The results seen in the plant, prills and soak-away areas were difficult to monitor. This is due to the fact that, after the rehabilitation procedures of RC1, these areas were used by a local farmer to produce maize. The drainage system that was implemented was effective in reducing the undesirably high levels of inorganic solids in the ¼ denuded area to acceptable levels that made a revegetation program possible. In contrast, the plant, prills and soak-away areas showed signs of increase in these inorganic solids, but this could be accounted for by the land use for maize production.

Nutrient imbalances and deficiencies have been identified by means of soil analysis. This analysis includes the following: Ca shortages, Ca: Mg imbalances, K shortages, P shortages, Zn shortages, excessive Na and an organic matter deficiency. The Ca shortage and the Ca: Mg imbalance was corrected by the lime application while the problems associated with K, P and Zn were corrected by the application of potassium sulphate, soft rock phosphate and zinc sulphate. The lime application had another function, that of displacing the excessive Na from the colloidal fraction in the soil to be leached as Na_2SO^4. The organic matter fraction was increased by applying both humic and fulvic acids that is water soluble and also degradable by microorganisms. The humic and fulvic acids applied to the soil also ads carbon to the growth medium which is a source of energy for soil microbes and also a vital element with regard to soil health (Waring et al., 2014; Brady & Weil, 2008).

The gully erosion on the site was caused by a lack of vegetation (Montgomery, 2007) together with poor soil structure (Brady & Weil, 2008). This problem was addressed by tillage of the soil against the natural gradient, construction of contour berms and vegetation establishment. The vegetation establishment on the site was not only done to prevent soil erosion, but also to restore the natural succession of vegetation with regard to the predetermined specifications needed to rehabilitate the site.

The microbial activities in the soil (bacteria and fungi) play an integral role in soil health, plant health and also the utilization of nutrients by plants. The microbial inoculation of the soil plays a large role in the success of the rehabilitation of the site for the previously mentioned reasons. With the nutrients present in the soil together with the low pH values we saw the growth medium as an abiotic environment, this situation needed to be corrected (Miransari, 2012). The micro-organisms that were introduced into the soil are beneficial to the health of the soil and the plants established in it (Waring et al., 2014).

4.10 Changes in values between 2011 and 2016

Table 4.28: P-values associated with t-tests in the 1:2 water extraction procedure (macro-elements) data for the denuded area between 2011 and 2016.

Sample	K	Na	PO_4	NO_3	NH_4	HCO_3
¼ Denuded	0.003	0.000	0.011	0.000	0.000	0.044
¾ Denuded	0.006	0.022	0.032	0.006	0.000	0.008

Table 4.29: P-values associated with t-tests in the 1:2 water extraction procedure (micro-elements and other data) data for the denuded area between 2011 and 2016.

Sample	Mn	Zn	EC
¼ Denuded	0.000	0.001	0.000
¾ Denuded	0.010	0.000	0.005

Table 4.30: P-values associated with t-tests in the ammonium acetate (Exchangeable cations) data for the denuded area between 2011 and 2016.

Sample	Ca	CEC	pH(H_2O)	pH(KCl)
¼ Denuded	0.224	0.077	0.000	0.005
¾ Denuded	0.000	0.001	0.000	0.029

With Student’s one sided t-test for equality of means at a nominal significant level of 5%, all the p-values below 0.05 indicate statistically significant differences between the sample means. Virtually all of the tests reject the null hypothesis of equality of means. As a result we infer that there are substantial differences between the results of measurements between 2011 and 2016. This indicates that the rehabilitation program has resulted in statistically significant changes in the composition of the soil. This, in turn, provides strong statistical evidence to support the claim that the rehabilitation program has improved the quality of the soil.

4.11 Vegetation survey (monitoring of the site)

Due to the fact that the sample sites at the plant footprint, prills silo and old soak-away were used for crop production by a local farmer; the area was not seeded with the prescribed seed mix, however, the amelioration was implemented. The vegetation assessment was done in September 2016. This assessment included only the previously denuded Transects, which were numbered from 1 to 5, starting from the farmers field (up-slope) and moving down to the natural stream. Figure 4.5 indicates the transects and each quadrant on them:

Figure 4.7: Map overview of the rehabilitated area (the white lines indicate the transects numbered 1 to 5 from North to South and the red blocks indicate the quadrants numbered from 1 to 5 from the East to the West).

4.11.1 Mean transect data

The average of the various pasture species and composition of each transect are provided in Table 4.28. The results show germination of all the different seeds that were introduced. Only species that have grown to reproductive maturity are included.

Table 4.31: Mean grass species (amount ± SD) found over all five transects.

Species	Average amount
Cynodon dactylon	4.40 ± 2.97
Pennisetum clandestinum	2.80 ± 3.11
Eragrostis curvula	15.60 ± 2.30
Eragrostis tef	4.00 ± 1.58
Digitaria eriantha	22.60 ± 3.29
Sorghum bicolor	4.20 ± 3.11
Weeds	1.80 ± 1.30

4.11.2 Mean quadrant data

Table 4.32: Mean of each species (amount ± SD) found between the different quadrants on the five transects.

Species	Quadrant 1	Quadrant 2	Quadrant 3	Quadrant 4	Quadrant 5
Cynodon dactylon	1.33 ± 0.58	3.67 ± 4.04	1.25 ± 0.50	2.00 ± 1.83	1.20 ± 1.30
Pennisetum clandestinum	1.00 ± 1.00	5.00 ± 8.66	2.25 ± 2.63	0.50 ± 0.58	0.40 ± 0.55
Eragrostis curvula	4.00 ± 2.00	3.67 ± 1.53	5.00 ± 3.92	6.25 ± 1.71	7.80 ± 4.60
Eragrostis tef	2.00 ± 2.65	5.33 ± 1.15	7.25 ± 4.65	7.25 ± 2.99	3.40 ± 1.14
Digitaria eriantha	7.00 ± 2.65	11.67 ± 9.02	6.75 ± 2.22	15.75 ± 3.40	8.40 ± 2.61
Sorghum bicolor	1.33 ± 1.15	1.33 ± 1.53	0.75 ± 0.96	1.25 ± 1.26	1.40 ± 0.55
Weeds	1.67 ± 1.15	1.00 ± 1.73	1.00 ± 0.82	2.00 ± 1.63	2.40 ± 1.14

4.12 Weather data of the area

During the rehabilitation of the site between 2010 and 2016 South Africa had a few years of severe drought with higher than normal temperatures. The following weather data was compiled by and received from the South African Weather Service. The data was extracted on 6 November 2017.

Table 4.33: Average maximum temperatures (℃) measured in Emalahleni (weather station 0515320 8) between – 2010 and 2016.

Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
2010	24.8 ±2.21	26.2 ±2.14	25.7 ±2.17	21.4 ±3.80	20.8 ±2.78	18.1 ±3.13	17.9 ±2.49	21.7 ±3.37	25.9 ±2.75	27.1 ±3.17	25.3 ±3.66	25.4 ±2.99
2011	23.9 ±2.50	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	28.7 ±3.57	27.9 ±3.52	27.9 ±3.40
2012	28.3 ±2.64	29.8 ±1.41	28.5 ±2.91	24.6 ±2.13	24.7 ±2.79	19.9 ±2.88	20.9 ±1.97	22.5 ±5.21	22.4 ±4.58	24.4 ±3.74	25.7 ±3.96	26.3 ±2.84
2013	27.3 ±3.36	29.3 ±2.38	27.0 ±2.78	23.4 ±3.84	22.6 ±1.53	21.3 ±2.27	20.3 ±2.35	20.6 ±3.31	26.1 ±4.90	26.0 ±4.13	28.3 ±2.73	28.6 ±3.60
2014	31.2 ±2.37	30.5 ±2.00	26.9 ±3.05	26.1 ±1.98	26.2 ±2.39	23.4 ±2.47	22.3 ±2.81	24.4 ±3.02	29.6 ±3.31	29.4 ±3.93	29.0 ±1.36	N/A
2015	N/A	28.3 ±N/A	27.2 ±1.86	24.0 ±2.59	24.6 ±1.93	18.8 ±2.36	19.6 ±2.45	24.5 ±3.25	25.2 ±4.81	28.7 ±3.08	28.0 ±4.18	29.3 ±2.79
2016	27.8 ±3.09	29.5 ±2.81	26.8 ±3.51	25.6 ±3.00	20.9 ±1.77	19.4 ±3.12	18.9 ±2.29	23.3 ±3.08	22.6 ±7.51	27.6 ±4.36	26.0 ±3.27	27.5 ±3.03

During March and July in 2010, the averages are omitted due to unreliable and missing daily data. In 2011 the data for February to September is missing and the data for January are deemed unreliable due to missing daily data. In 2013 the average maximum temperatures for January and May considered to be unreliable due to missing daily data. In 2014 the average maximum temperatures for July, November and December contains missing daily data. In 2015 the average maximum temperatures for January and February is considered unreliable due to missing daily data. In 2016 the average maximum temperatures for September also includes missing daily data.

Table 4.34: Average (Ave./day) and total (Tot.) monthly rainfall (mm) measured in Emalahleni (weather station 0515320 8) between 2010 and 2016.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
2010 (Tot.) (mm)	114.8	52.4	67.2	114.0	38.8	0.0	0.2	0.0	0.0	63.4	48.0	259.0
2010 Ave./day (mm)	7.7 ±5.34	5.8 ±6.78	6.7 ±14.61	8.1 ±10.27	6.5 ±6.71	N/A	0.2 ±N/A	N/A	N/A	6.3 ±7.15	4.4 ±6.88	15.2 ±17.95
2011 (Tot.) (mm)	172.2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	31.4	31.0	121.6
2011 Ave./day (mm)	14.4 ±15.55	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	5.2 ±5.56	2.8 ±3.48	6.1 ±9.56
2012 (Tot.) (mm)	92.6	39.8	66.6	10.8	0.0	0.8	0.0	0.6	84.8	94.8	92.4	98.6
2012 Ave./day (mm)	5.1 ±8.81	3.3 ±5.89	6.7 ±8.80	1.8 ±2.11	N/A	0.4 ±2.28	N/A	0.6 ±N/A	12.1 ±22.04	10.5 ±13.08	9.2 ±10.12	5.2 ±7.58
2013 (Tot.) (mm)	75.4	29.4	101.0	79.8	6.4	0.0	0.0	3.2	6	107.6	180.8	115.6
2013 Ave./day (mm)	6.3 ±6.50	3.3 ±3.66	10.1 ±15.58	10.0 ±9.97	1.3 ±2.09	N/A	N/A	1.1 ±1.33	2.0 ±2.16	9.8 ±8.83	10.6 ±17.57	5.5 ±6.55
2014 (Tot.) (mm)	90.6	113.0	221.4	22.8	0.4	9.4	0.0	0.4	1.2	71.0	160.2	197.8
2014 Ave./day (mm)	6.0 ±7.49	9.4 ±14.11	10.5 ±16.85	2.3 ±2.77	0.2 ±0.00	4.7 ±6.36	N/A	0.4 ±N/A	0.4 ±0.20	7.1 ±8.08	7.6 ±8.07	9.4 ±12.11
2015 (Tot.) (mm)	65	21.8	30.6	29.4	0.0	0.8	1.0	0.4	46.2	34.2	54.2	135.2
2015 Ave./day (mm)	4.3 ±3.96	2.0 ±1.66	2.6 ±3.89	2.9 ±4.02	N/A	0.8 ±N/A	0.3 ±0.23	0.4 ±N/A	9.2 ±10.14	3.8 ±3.43	6.8 ±6.18	9.0 ±10.33
2016 (Tot.) (mm)	85.4	40.8	170.2	5.8	29.0	12.0	3.0	0.6	6.4	84.0	224.6	81.8
2016 Ave./day (mm)	5.0 ±4.57	2.7 ±3.63	17.0 ±15.24	1.5 ±2.43	14.5 ±15.13	2.0 ±3.24	0.8 ±0.85	0.6 ±N/A	3.2 ±3.96	12.0 ±6.39	14.0 ±14.69	5.5 ±8.56

In 2010 the total and averages for January, September and December are considered unreliable due to missing daily values. In 2011 only the total and averages of December are reliable due to missing daily values. In 2012 the total and average of September are unreliable due to missing daily values. In 2013 the totals and averages of January, March, May and August are unreliable due to missing daily values. In 2014 the total and average of October are unreliable for the same reason. In 2015 the totals and averages of February, June and August are unreliable due to missing daily values. In 2016 the total and average of September are also deemed unreliable for this reason.

For the area of Emalahleni that receives a historical average precipitation of 693mm annually, we see according to the data provided by the South African Weather services that in 2010 a total of 278.8mm, 121.6mm in 2011, 497mm in 2012, 519.2mm in 2013, 817.2mm in 2014, 395.8mm in 2015 and 737.2mm in 2016 of precipitation was recorded. Even though the data contains a large number of missing values, the reported values are very low for 2010, 2011, 2012 and 2014 due to drought.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

When considering the rehabilitation procedures implemented by RC1, it becomes clear that their main focus was on the EC of the growth medium. Clearly the pollutants that were present in the soil were considered to be of secondary importance. The first rehabilitation company stated in a report that the primary problem is the salinity, which is caused by the pollutants and that the pollutants did not constitute a severe problem in and of itself. Further investigations showed that this was not the case and, therefore, RC1 underestimated the degree and extent of the pollution on the site.

Throughout the reports issued by RC1, it is evident that their efforts were mainly focused on the EC. This is clear because of the fact that that the EC forms the main focus of the monitoring and hand over criteria that were formulated by RC1. The results of their growth medium analysis are not seen in any of these reports because they focussed more on the physical aspects of the rehabilitation than on the soil chemical aspects. The only chemical analysis reported by RC1 were performed in order to determine the levels of the EC, pH, NO_3, NH_4 and SO_4 in the soil and water. However, these results were not made available in the issued reports.

RC1 stated in their completion report that all sources of contaminants were removed. Later analyses clearly demonstrated that this was not the case. It is clear from the soil analysis performed in 2010 that the source of contaminants was not removed, due to the high nitrate levels seen after the site had been rehabilitated by RC1. Some soil amelioration was attempted on the site by RC1, but this proved to be inadequate.

RC1 constructed various drainage trenches; however, these were not placed in the optimal location. The only apparent reason for this is a lack of understanding of the underlying geology. The monitoring done by RC1 was inadequate, since they deemed the site as being successfully rehabilitated before it returned to its denuded state without any human intervention.

One of the reports drafted by RC1 contained a figure that was used in order to explain the subsurface geology on the site. When inspecting this figure closely, several misconceptions are observed. In actuality, the subsurface laterite does not slope in the same direction as the slope on the surface (to the south) but the underground geology slopes to the opposite side (as is seen in Figure 5.1). The drainage trenches were constructed by RC1 in such a way that it would only stop the shallow seepage from the plant, old soak-away and prills silo (which can be seen as the source of the pollutants). This strategy did not prove to be successful because the contaminants leached deep into the soil over a very long period. When conducting the first rehabilitation, RC1 attempted to stop the water on the surface and shallow seepage from moving over the denuded area by means of the drainage trenches and contour berms. However, shallow seepage from the plant, prills and soak-away did not carry substantial concentrations of the pollutants. The contour berms constructed by RC1 were constructed with the soil on the site. The soil contained a high salt concentration. This soil is also dispersive, in other words, there is a substantial probability that the berms were flushed away by the first rain (Bell & Maud, 1994).

The intensive focus on a physical rehabilitation procedure (mainly the leaching of contaminants and the removal of all water from entering the denuded area), coupled with the neglect of the ignored chemical imbalances conspired to ensure that the first rehabilitation of the site proved to be unsuccessful. As a specific example of the problems caused in this regard, consider the bicarbonate (HCO_3) concentration in the soil. The level of HCO_3 was never taken into account by RC1. As a result, the soils lacking buffering capacity were not taken into consideration. The low bicarbonate was the cause of the low pH values, which, in turn, caused a problem as is discussed below (Van Rensburg & Maboeta, 2004).

No nutrients are mentioned in the reports of RC1, and no fertilizers were applied on the site in order to create a favourable chemical environment for vegetation establishment and growth. Micro-elements weren't taken into account and with the low pH levels, this may cause problems with vegetation establishment due to the toxicity of these micro-elements for plants (Sparks, 2003). Furthermore, neither the CEC nor base saturation was studied by RC1. A further oversight was that the exchangeable cation percentages in the soil were not taken into account. This proved to be a significant problem for vegetation establishment.

The second rehabilitation attempt was substantially aided by a better understanding of the underlying geology. This rehabilitation approach showed results that were more successful because the drainage channels were placed in the optimal area for the removal of the contaminants from the soil. After the first rehabilitation attempt, these were still entering the denuded area. With the improved soil chemical rehabilitation procedures implemented, the result proved more successful. This positive change was affected by creating a viable growth medium for vegetation establishment and growth.

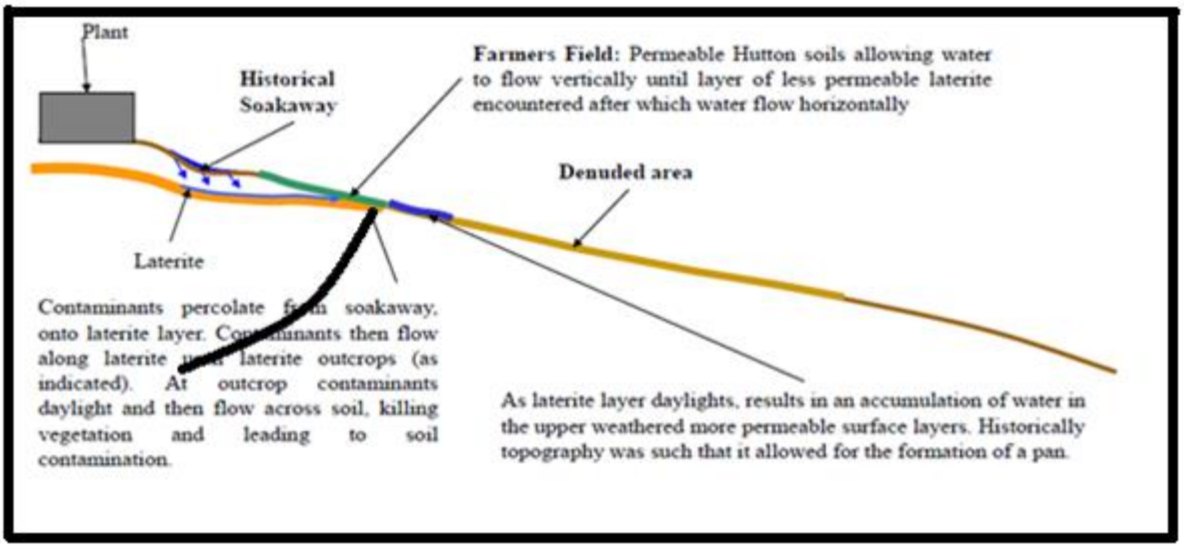

Figure 5.1: New understanding of the underlying geology with the sub-surface laterite indicated by the black line.

Revegetation of the denuded area:

After the successful revegetation of the site in October 2015, a vegetation survey was conducted, in May 2016, in order to determine the success of the rehabilitation. The findings were that all the plant species introduced to the site was not only present, but has reached maturity and was in a reproductive state. With the drought of 2016 in mind, the vegetation cover seen on the site in such a short period of time was impressive.

Soil quality is reflected from the physical, chemical and biological properties of the soil. The second rehabilitation approach ensured that each of these properties were addressed in order to better the soil quality on the site (Brady & Weil, 2008).

The soil prior to rehabilitation showed substantial areas, completely denuded of all vegetation. This was especially noticeable after large amounts of rain that caused contaminants to enter these areas. The soil was an abiotic medium with characteristics like poor or no structure and with erosion problems all over the surface. The little vegetation found on some spots of the site during this time was clearly struggling for survival and could be described as sparse. Figure 5.2 displays images captured before and after the rehabilitation procedure were implemented.

Figure 5.2: Photographs taken before the implementation of the rehabilitation procedure (on the left) and 1 month after seeding (on the right).

One month after seeding the area the site changed significantly. Broad leaf weeds were present throughout the site, however, the intended species were also present in large numbers. Weed control was implemented, but this step will have to be repeated at a later time. In Figure 5.3 the transformation is seen from a site denuded from all vegetation to a vegetated landscape.

Figure 5.3: Photos taken 3 months after seeding on the previously denuded area.

After 3 months the vegetation cover showed a significant increase in planted pasture species in spite of the drought that caused lower than average rainfall in the region and higher than average daily temperatures.

5.2 Initial recommendations for area 2 in 2010

Because the acidification had already stopped in this area in 2010 (because of residual HCO_3 present, slightly higher average pH and low average EC value) the area could have been ameliorated and rehabilitated. The amelioration and rehabilitation procedures entailed ripping the area to a depth of 500mm, against the natural gradient, and applying 20 tons of dolomitic lime per ha. This was done prior to the rainy season and after the first large amount of rain. At that time, it was recommended that the area should receive 30 tons of well-cured organic material per ha, 300kg of super phosphate and no K. Following this step, the area was seeded with 25kg per ha of an indigenous seed mixture.

5.3 Initial recommendations for area 1 in 2010

The group 1 samples (taken in the denuded area at two sampling points, namely ¼ denuded and ¾ denuded) indicated that it would not be wise to implement any of the procedures that were used on area 2 (a combination of the plant, prills and soak-away) on the denuded area. Investigations into this area indicated that these steps would likely not be cost-effective or successful because of the ongoing pollution and acidification in this area observed at that time. The pollutants in the soil must was required to be removed first and the alkalization process of the soil needed to be accelerated. This was done by the construction of drainage channels that were dug into the denuded area at a depth of 1 - 2m and starting 5 - 10m up slope from where the denuded area is found. Thirty tons of dolomitic lime per ha was then ripped into the growth medium at a depth of 500mm in the areas between the channels. This area did not receive any further attention before the end of the rainy season. Water samples were taken in order to determine whether or not the drains were succeeding to remove the pollutants. Additionally, soil sampling was done to determine the changes in quality of the growth medium.

5.4 General recommendations

It is good practice to keep monitoring the site in future in order to determine the long-term success of the rehabilitation. From their reports, RC1 believed the site to be successfully rehabilitated, but shortly thereafter problems common to many rehabilitation problems started to reoccur. The rehabilitation will only truly by successful when it is not only stable, but can be considered to be a functional ecosystem (Thompson & Thompson, 2004).

The drainage system has not been removed to date and the liner of the collection pond was damaged by some severe wind storms. It is recommended that it should be repaired. The reason for not removing these structures at this time is to use the water in the collection pond for analysis if any problems occur in the future. This should simplify further monitoring.

The site has been barren for more than 10 years and during the time of the rehabilitation and even after reseeding the previously denuded area weeds appeared. Weed treatment may be required in the future, however, it is recommended that this be determined based on the monitoring of the site.

Because this is a rehabilitated pasture and cannot yet be seen as a natural pasture, more fertilizer applications and other soil amelioration may be needed in future. Again, the need for this will be determined by monitoring and sampling the site in future.

5.5. Concluding remarks

In line with the objectives of this study, the first rehabilitation attempt implemented by RC1 was critically evaluated. This provided information regarding, and insight into, the problems that made it possible to learn from previous mistakes and compile a more efficient rehabilitation procedure. A different and more effective rehabilitation procedure was implemented on the site. This rehabilitation procedure proved to be successful. The rehabilitation of the site is now complete and the site is considered to be successfully rehabilitated to a state where it can be utilized as grazing. However, until the coal mine on which the site is situated obtains a closure certificate, the mining company will still be responsible for the site from a legal point of view. The EMC will not have any liability after monitoring is complete and the site is self-sufficient from an ecological perspective.

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