IRRIGATION WITH MINING-INFLUENCED WATERS IN MPUMALANGA

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IRRIGATION WITH MINING-INFLUENCED WATERS IN MPUMALANGA

Final Report

to the
Water Research Commission

by

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EXECUTIVE SUMMARY

The coalfields of the Mpumalanga Province, which are crucial to South Africa's electricity production, contain large volumes of mining-influenced waters that require sustainable management. If such waters can be beneficially utilised for irrigation to produce food without the need for significant energy and financial investment to treat and desalinate them, then clear gains will be made in managing the water-energy-food nexus. The agricultural feasibility and limited environmental impact of irrigation with calcium and sulphate-rich mine waters have been clearly demonstrated by the University of Pretoria over many years (since the early 1990s), with support from the WRC and the mining industry. However, much of the research has been of a shorter-term nature, and longer-term monitoring data is invaluable to demonstrate the sustainability of this practice.

In addition to the large volumes of mining-influenced waters, many mines have large tracts of rehabilitated mined land with limited productivity. Irrigation with mining-influenced waters on rehabilitated mined land, therefore, presents an opportunity to increase land productivity and manage these waters, while also serving as a sustainable closure strategy geared towards the Just Energy Transition. Irrigation of rehabilitated land is also important in specific cases where gypsum precipitation is insufficient to reduce the salt load to water bodies; in such cases, irrigation on rehabilitated land that overlies old mine voids provides a greater opportunity to contain any solutes that leach from the profile.

To date, mine water irrigation research has focused on the use of calcium and sulphate-rich circumneutral waters, which is now a proven technology, undergoing long-term verification in field trials and assessments. However, there could be high cost and energy saving benefits if untreated or partially treated acid mine drainage (AMD) could be used on limed soils. The limed soil would act as a neutralisation reactor for acid mine waters, eliminating the need for High-Density Sludge (HDS) liming plants. While some laboratory and greenhouse studies have suggested that this approach is feasible and may yield crops that are safe to consume, further field research was necessary to confirm these findings.

If the use of acid waters per se proved problematic, and liming plants are still needed to neutralise AMD waters for irrigation, significant savings would still be possible if irrigation with neutralised, but unclarified water is possible. This will reduce the capital cost of such plants, as settling ponds would not be required. More importantly, the waste metal hydroxide sludge from the neutralisation plant would not need to be disposed of, as it would be applied to the field with the partially treated mine water. Considerable research on the likely effect of high rates of HDS sludge applications to agricultural soils has been reported on in a previous WRC

and industry-supported project, giving the research team confidence that this may be feasible. However, irrigation with such waters also requires further monitoring of potential impacts on crop yield and quality, as well as on soil quality. Another partially treated source of mine water worthy of consideration is water that emanates from passive treatment plants. These waters may not be suitable for release to river systems, but may be suitable for irrigation.

This research project had five main aims:

- To monitor and model field-scale water and salt balances for four commercial-scale mine water irrigated centre pivots in Mpumalanga (one field of 19 ha on rehabilitated land and three fields covering areas of 20, 30 and 40 hectares on unmined land), to assess the medium to long-term impact and sustainability of mine water irrigation.
- To assess, on a small field plot experimental scale, the use of untreated acid mine drainage (AMD) on limed soil, limed and clarified neutralised AMD, limed and unclarified neutralised AMD still containing metal hydroxide sludge, and effluent from a Biological Sulphate Reduction (BSR) plant, on crop growth and soil properties.
- To assess the food and fodder safety of produce emanating from mine water irrigated crops.
- To update guidelines for locating intermediate to large-scale mine water irrigation schemes in the landscape based on geo-hydrological characteristics, monitoring requirements and thresholds for action, with specific attention to be given to the irrigation of rehabilitated lands.
- To assess the socio-economic feasibility and sustainability of irrigation with mine water. Specifically, opportunities for the development of emerging commercial farmers in this sector were to be considered.

The work completed to address the project aims is presented in five chapters as outlined below:

Chapter 1: Demonstrating the Sustainable Use of Untreated Circumneutral Mine Water for Irrigation on Unmined Land

The commercial-scale mine water irrigation pivot established on unmined land at Mafube Colliery provides a platform for the longer-term quantification, monitoring and modelling of salt and water balances when irrigating with mining-influenced waters. This carefully monitored site has been successfully irrigated with circumneutral, calcium and sulphate-rich mine water for seven consecutive seasons. Medium-term monitoring conducted at the Mafube site demonstrated that untreated calcium and sulphate-rich, circumneutral mine waters can be used productively and sustainably for irrigation with minimal environmental impacts, producing crops that are safe for consumption.

Chapter 2: Irrigation with Mine-Influenced Water on Rehabilitated Land

In this chapter, the use of mine water irrigation on rehabilitated land was explored, and the factors that influence the irrigability of rehabilitated land were investigated. The field assessments indicated that rehabilitated land irrigation could be productive if rehabilitation guidelines are meticulously followed and care is taken to ensure that the area is not just arable, but also free-draining and irrigable. Soil physical conditions and hydrological position in the landscape were identified as crucial factors for the successful irrigation of rehabilitated land. Work completed as part of this chapter was used to develop draft guidelines for the irrigation of rehabilitated land, which are presented in a standalone WRC report (Patoussius et al, 2024).

Chapter 3: Evaluation of Irrigation with Untreated or Partially Treated Acid Mine Drainage

Detailed laboratory and glasshouse studies investigated irrigation with untreated and partially treated AMD. Additionally, a small plot trial site was established at a water reclamation plant to validate the results obtained from the laboratory and glasshouse experiments. The studies assessed crop and soil responses to irrigation with a range of mining-influenced waters. The HDS-treated AMD was considered a control treatment, since fresh water for irrigation was not available, and irrigation with circumneutral, calcium and sulphate-rich water has proven successful in the past. Irrigation with untreated AMD presented some concerns, including reduced productivity and excessive accumulation of trace elements in produce, if soils are not adequately limed. However, it is expected that with appropriate management, crops can be successfully produced using these waters, and concerns, whether real or perceived, regarding the safety of the produce for consumption can be addressed by cultivating industrial or biofuel crops.

Chapter 4: Scale of Opportunity for Mine Water Irrigation in the Upper Olifants Catchment

Desktop assessments were conducted to investigate the potential scale of mine water irrigation schemes in the Upper Olifants Catchment. The analyses suggest that sufficient water is available to support the irrigation of 5 000 to 14 000 ha of land, depending on the selected cropping system. Additionally, the amount of land available in the region should be sufficient to support the establishment of mine water-irrigated cropping systems and to settle emerging farmers on these schemes. A notable limitation of this study was the lack of detailed, up-to-date data on expected water volumes and qualities, which is crucial for making reliable predictions about the sustainability of mine water irrigation schemes.

For mine water irrigation schemes to be sustainable, the volume of water available should not decrease, and its quality should not deteriorate beyond levels suitable for irrigation over time.

Another important consideration is that irrigation with mine waters is a technically challenging undertaking. Therefore, if inexperienced emerging farmers are settled on mine water irrigation schemes, they will require sufficient technical support to help them maintain safe and sustainable use of the mine water.

Chapter 5: Socioeconomic Feasibility of Establishing Mine Water Irrigation Schemes in Mpumalanga

The socioeconomic aspects of irrigation using mine water in Mpumalanga were explored, with a specific focus on the Upper Olifants Catchment. Current land-use, agricultural activity, and socioeconomic profile data were reviewed to gain an understanding of the regional context. The economic feasibility of mine water cropping systems, the potential for incorporating mine water irrigation schemes into social development plans, and the implications for mine closure were also reviewed. The regional analyses indicated that commercial agriculture is an important activity in the catchment, and there is considerable potential for establishing mine water irrigation schemes in existing dryland production areas provided they are suitable for irrigation. Mine water irrigation schemes were found to be economically feasible if a capital contribution is made to such schemes. Incorporating mine water irrigation schemes into social labour plans could significantly contribute to the economic development of mining communities by empowering emerging commercial farmers.

It is concluded that, with appropriate management, irrigation can be a sustainable solution for managing most mining-influenced waters in the Mpumalanga coalfields, offering important socioeconomic benefits, particularly when rehabilitated land is utilised. A considerable investment has been made in establishing the trial sites discussed in this report, and the project team considers them valuable in facilitating the acceptance of irrigation as an option for managing mine waters in the Mpumalanga Coalfields. It would be a lost opportunity to discontinue research at these sites. Therefore, the following recommendations are made for future research:

- Continued monitoring of productivity and environmental impact (crop growth and yield, profitability, food safety, soil quality, surface and groundwater quality) of medium to long-term irrigation with circumneutral waters on unmined land
- Evaluation and revision of the draft guidelines on mine land rehabilitation to irrigable potential and the development of an electronic decision support system to make the mine water irrigation guidelines more user-friendly.
- Establishment and management of small plot and/or glasshouse pot trials to screen food, fodder and industrial crops for their productivity and quality when produced with untreated and partially treated mine-influenced waters.

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ACRONYMS AND ABBREVIATIONS

AMD	Acid mine drainage
ARC	Agricultural Research Council
BDL	Below detection limit
BSR	Biological sulphate reduction
$CaCO_3$	Limestone
$CaSO_4$	Gypsum
$Ca(OH)_2$	Hydrated lime
CCE	$CaCO_3$ (limestone) equivalent
CEC	Cation exchange capacity
CRD	Completely randomised design
DAFF	Department of Agriculture, Forestry and Fisheries
DAP	Days after planting
DCP	Dynamic cone penetrometer
DM	Dry matter
DSS	Decision support system
EC	Electrical conductivity
ECe	Soil saturated paste electrical conductivity
EPA	Environmental Protection Agency
eWRP	eMalahleni Water Reclamation Plant
FAO	Food and Agriculture Organisation
FC	Field capacity
FeS_2	Pyrite
FFU	Fitness-for-use
GypB	Gypsum with brucite
GypFe	Gypsum with iron oxides
GypFeMn	Gypsum with iron oxides and manganese

HDS	High-density sludge
HI	Harvest index
HW	Hazardous waste
IAP	Ion activity product
ICP-AES	Inductively coupled plasma atomic emission spectroscopy
ICP-OES	Inductively coupled plasma optical emission spectrometry
IRR	Internal rate of return
KCl	Potassium chloride
LAI	Leaf Area Index
LAN	Limestone ammonium nitrate
LaRSSA	Land Rehabilitation Society of Southern Africa
LF	Leaching fraction
LSD	Least significant difference
MDL	Method detection limit
MPRDA	Mineral and Petroleum Resources Development Act
MWCB	Mine Water Coordinating Body
NPV	Net present value
RCBD	Randomized complete block design
RO	Reverse osmosis
SABI	South African Institute of Irrigation
IRRIGWQ	Irrigation Water Quality Guidelines
SLA	Specific leaf area
SPAD	Chlorophyll content meter
SSA	Specific surface area
SSP	Single superphosphate
SSV	Soil screening value
SWB	Soil-water balance
TDM	Total dry mass

TDS	Total dissolved solids
TWQR	Target Water Quality Range
UP	University of Pretoria
VWC	Volumetric water content
WRC	Water Research Commission

INTRODUCTION

With the mining industry in South Africa producing large volumes of mining-influenced water and the agricultural industry requiring significant water inputs to improve and optimize crop yields, irrigation with mining-influenced water presents a noteworthy opportunity. As a result of Mpumalanga's high but erratic rainfall, Annandale et al. (2021) have shown that this region is highly dependent on irrigation to consistently produce crops economically. The agricultural feasibility and limited environmental impact of irrigation with calcium and sulphate-rich mine waters has been clearly illustrated with work done by the University of Pretoria over many years (since the early nineties), with support from the WRC and the mining industry (Jovanovic,et al., 1998, Tanner et al., 1999, Annandale et al. 1999 (b), Annandale et al., 2001, Annandale et al.,2006, Idowu et al. 2010, van der Laan et al., 2014; Annandale et al. 2019). Irrigation with such waters causes gypsum to precipitate in the soil profile, thereby markedly reducing solute migration to water sources. Gypsum is typically used as a soil amendment and is not considered harmful to crops.

The availability of large volumes of mining-influenced waters and extensive tracts of unfarmed land, often owned by mines or privately, in close proximity to these water sources, creates an opportunity to utilize these poor-quality waters for irrigation. The application and reuse of mining-influenced waters will not only reduce water treatment costs and conserve electricity, but also minimize the environmental impact associated with the release of these mine waters into surface water sources. In addition, a significant contribution will be made towards ensuring food security, and perhaps most importantly, much-needed employment will be created, which is especially crucial after mine closure, when economies need to diversify away from mining. It is clear that irrigation with mine water is closely linked to the much-discussed Water-Energy-Food Nexus (Mpandeli et al., 2018). It is due to the production of energy that the coal was mined and the waters polluted in the first place – conventional mine water treatment processes will use more energy, which leads to the need for more mining, whereas irrigation with these waters will reduce energy usage and provide food. Vermeulen et al. (2008) estimated that 20 000 ha could eventually be irrigated with coal mine water in the Mpumalanga region.

Mine water irrigation research has typically focused on using circumneutral, calcium- and sulphate-rich waters, which present an opportunity to precipitate gypsum in the irrigated soil profile. There could be significant cost benefits to using untreated AMD for irrigation on limed soils, rather than relying on expensive High-Density Sludge (HDS) liming plants. If this is successful, the limed soil could, in effect, serve as a neutralization reactor for acidic mine waters. However, this had to be researched, as the crop's response to acidic waters was unknown, and the effect of such irrigation on the soil was also unknown. Whether or not crops that can be produced in such an environment would be safe to consume also had to be ascertained. There were also questions about the effect of such waters on irrigation infrastructure.

If this approach proves problematic, and it becomes apparent that liming plants are needed to neutralize AMD waters for irrigation, significant savings would still be possible if the water is neutralized, but unclarified water could still be used. This will reduce the capital cost of such plants, as settling ponds will not be required. More importantly, the waste metal hydroxide sludge from the neutralization plant will not need to be disposed of, as it will be applied to the field with the water. Research on the potential effect of heavy sludge applications suggests that this approach could be feasible (Sukati, 2020). However, irrigation with such waters also requires further monitoring of potential impacts on crop yield and quality, as well as on soil quality. Another partially treated source of mine water worthy of consideration is water that emanates from passive treatment plants. These waters may not be suitable for release to streams but may be suitable for irrigation.

This research project had five main aims:

- To monitor and model field-scale water and salt balances for four commercial-scale mine water irrigated centre pivots in Mpumalanga (one field of 19 ha on rehabilitated land and three fields covering areas of 20, 30 and 40 hectares on unmined land), in order to assess the medium to long-term impact and sustainability of mine water irrigation.
- To assess, on a small field plot experimental scale, the use of untreated acid mine drainage (AMD) on limed soil, limed and clarified neutralized AMD, limed and unclarified neutralized AMD still containing metal hydroxide sludge, and effluent from a Biological Sulphate Reduction (BSR) plant, on crop growth and soil properties.
- To assess food and fodder safety of produce emanating from mine water irrigated crops.
- To update guidelines for locating intermediate to large-scale mine water irrigation schemes in the landscape based on geo-hydrological characteristics, monitoring requirements and thresholds for action. Specific attention was given to the irrigation of rehabilitated lands.

- To assess the socio-economic feasibility and sustainability of irrigation with mine water. Specifically, opportunities for the development of emerging commercial farmers in this sector were considered.

The work completed to address the project aims is presented in four chapters. The first aim is addressed in Chapter 1, which follows.

CHAPTER 1: DEMONSTRATING THE SUSTAINABLE USE OF UNTREATED CIRCUMNEUTRAL MINE WATER FOR IRRIGATION ON UNMINED LAND

Mine water irrigation is a promising technology that could provide farmers with a much-needed additional source of irrigation water and serve as a cost-effective strategy for managing mine water (Du Plessis, 1983). According to Grobelaar et al. (2001), the coal mines in Mpumalanga, South Africa (both operational and defunct), will collectively discharge an estimated 360 ML/d of mine water, with 170 ML/d flowing into the Olifants River catchment. These estimates were based on the extent of the different mines and the mining methods used. The high volume of water decanting into the Olifants River catchment alone can maintain more than 6 000 ha of irrigated crop production (Annandale et al., 2006).

Coal mines produce different types of water, mainly due to the geology of the mined area and the materials that the water encounters, as well as the method used to extract the coal (Jarvis and Younger, 2001; Equeenuddin et al., 2010; Amy et al., 2023). Care must be taken when deciding whether a particular water can be used for irrigation, as different crops have different tolerances for parameters such as salinity (Maas and Hoffman, 1977). Additionally, some mine waters are highly saline, and their continuous use could lead to the salinization of soils (Bauder and Brock, 2010) as well as the deterioration of nearby surface and subsurface water sources (McCarthy, 2011, van Rensburg et al., 2011). Calcium- and sulphate-ion-dominated (calcium- and sulphate-rich), non-acidic waters are preferred, as they present the opportunity to precipitate gypsum in the soil profile (du Plessis, 1983). Gypsum precipitation can remove up to 40% of salts from the soil solution, thereby reducing the salt load that enters nearby water bodies through leaching and surface runoff (Annandale et al., 2023).

Past studies have demonstrated that calcium and sulphate-rich circumneutral mine waters can successfully be used to irrigate field crops (Annandale et al., 2002). However, this practice was only demonstrated over a relatively short period. As a result, many regulators and practitioners remain concerned about the productivity and environmental impact of large-scale, long-term irrigation with these mine waters. An ideal site was established at Mafube Colliery to demonstrate commercial-scale medium- to long-term irrigation with calcium and sulphate-rich circumneutral mine water. This chapter presents the findings from the medium-term monitoring conducted at the site.

1.1 Trial overview

The Mafube demonstration site was established in 2017 with WRC and industry funding (Heuer et al., 2021). Continued maintenance and monitoring of the site are vital for facilitating informed, evidence-based decision-making. Irrigation with poor-quality water can often be performed successfully in the short term, but once salinity levels or specific constituents of concern have built up in the profile to unacceptable levels, such irrigation schemes may fail. Therefore, sustainable irrigation with mine water must be demonstrated, and this site is ideal for this purpose. Three consecutive maize cropping seasons, from season 5 to 7, were monitored as part of this project. Three unmined sites, each with an irrigated and dryland area, were monitored to demonstrate the advantage of having mine water available to increase production over that of dryland agriculture. The research team refers to these irrigation sites as the Beestepan Road Pivot (31 ha), Beestepan Central Pivot (38 ha) and Unmined Pivot (19 ha) and are presented in Figure 1-1.

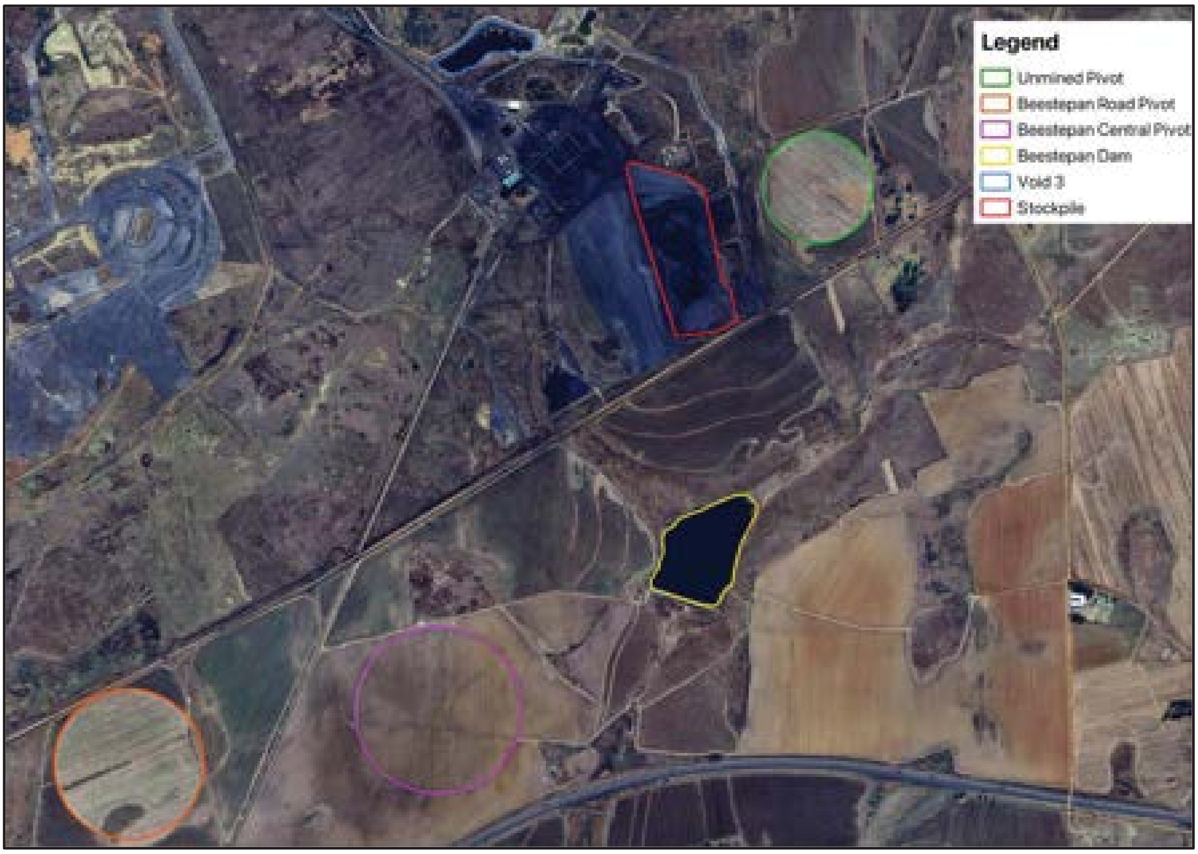

Figure 1-1: Google Earth image of the study site with the three pivots

The main focus of the monitoring was to determine if the successful and economical production of crops that are safe to consume is possible with mine water irrigation and to assess the medium-term effects such irrigation has on the soil and environment. The Beestepan Road Pivot and Beestepan Central Pivots, collectively referred to as the Beestepan Pivots, are within 4 km of the Unmined Pivot.

The main difference between the Beestepan Pivots and the Unmined Pivot is the irrigation water source and the duration they have been irrigated with mining-influenced waters. The Unmined Pivot receives untreated circumneutral irrigation water from one of the mine voids, Void 3, while the Beestepan Central and Road Pivots extract water from a nearby dam (Beestepan Dam, outlined in yellow in Figure 1-1). The Beestepan Dam is affected by mining activities and the two fields have been irrigated with mining-influenced water from this dam for at least 15 years.

White maize (cultivar PHB 32B07BR) is planted yearly at all three sites in September/October and harvested around April/May. The cultivar choice and fertilizer application remained consistent throughout the monitoring period. This was to ensure that any observed changes in crop productivity and food safety could solely be attributed to the irrigation water used.

1.2 Site layout and monitoring methodology

Measurements were taken throughout the monitoring period at all three sites. Crop measurements, including height, leaf area index (LAI) and growth stage, were measured every 10 to 14 days. Soil samples were taken before planting and after harvesting to compare possible changes in the chemical properties of the soil. Rainfall and irrigation were closely monitored for the major impact these have on crop growth, yield and the effect of the mining-influenced irrigation water on the soil and water environment.

Most of the sampling and measurements were made by the research team; the mine assisted with water monitoring. More detailed measurements were made at the Unmined Pivot than at the two Beestepan pivots, for a more in-depth analysis of the effects of irrigation with the void mine water. Figure 1-2 represents a layout of the Unmined Pivot. In each season, three soil profile water content and salinity monitoring stations were set up in this field, two inside the pivot area and 1 in the dryland area. These were paired with one inside and one outside the pivot, with one pair in a well-drained area and the other in an area prone to waterlogging. There are also four boreholes (BH) upstream and downstream of the Unmined Pivot. These are denoted BH1 (upstream, deep ±30 m), BH2 (upstream, shallow ±10 m), BH3 (downstream, deep ±30 m) and BH4 (downstream, shallow ±10 m).

Two piezometers were installed at a depth of approximately 3 m, an upstream piezometer (PZm_{US}) north of the pivot and a downstream piezometer (PZm_{DS}) south of the pivot, as indicated in Figure 1-2. Water samples were collected with a bailer every two weeks from the piezometers, if a perched water table was present, and the water level was measured using an electronic dip meter. Consultants to the mine analyse the water quality of the boreholes and Beestepan Dam every quarter, and the irrigation water quality every two weeks

Figure 1-2: Unmined Pivot layout and monitoring sites

The Unmined Pivot was initially located near boreholes BH3 and BH4 (orange outline in Figure 1-2). However, this area was prone to ponding after rainfall and this was exacerbated by irrigation. During high rainfall events, the ponding restricted any access to that part of the pivot so cultivation and planting could not be undertaken. Even when cultivation and planting were successful, the ponding would create waterlogged conditions, impacting crop growth and development. It was, therefore, resolved to move the pivot northeast to the position outlined in green in Figure 1-2. This change was implemented at the end of the 2021-2022 season.

As seen in Figure 1-2, an automatic weather station is situated close to BH2. Any change in weather conditions is accurately monitored by the weather station. This station consists of a data logger (CR 300) with an automatic tipping bucket rain gauge (TE525MM-L), a pyranometer (LI-200R M5), an anemometer (Model 03101), and a temperature and relative humidity probe (HMP60) with a radiation shield (Model 41303), all supplied by Campbell Scientific Africa. The weather station setup is presented in Figure 1-3. A manual rain gauge was also installed close to the weather station, and measurements were taken either by the UP team every two weeks or by the farmer.

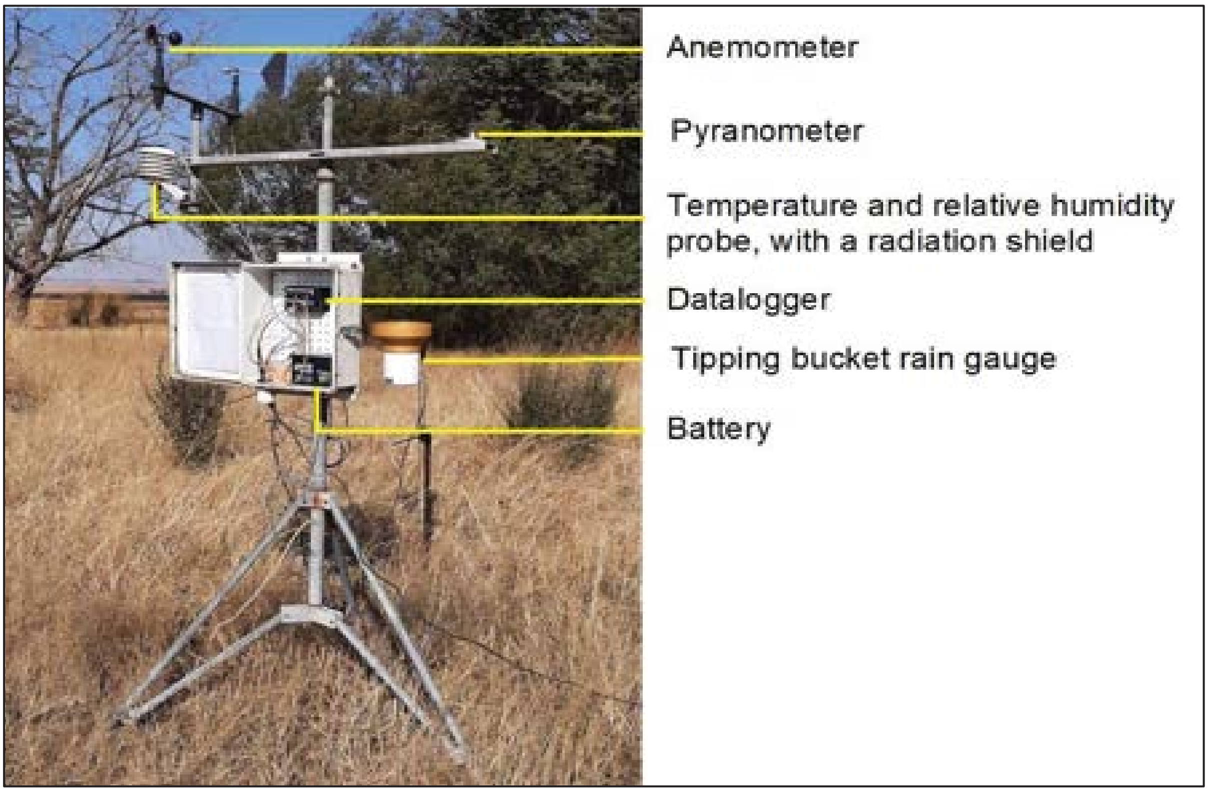

Figure 1-3: Weather station set-up.

Figure 1-4 shows the setup of the soil monitoring stations. Initially, there were four soil monitoring stations: two under the pivot (P1 and P2 in Figure 1-2) and two in the dryland (D1 and D2 in Figure 1-2). The dryland area where the second station was located is also a wetland, so the farmer decided to stop planting there at the end of the 2021/22 season. Since the stations are used to record the conditions experienced by the plants, it was decided that this particular soil monitoring station (D1) would be excluded from the monitoring.

Soil monitoring stations consisted of a battery-powered CR300 data logger connected to three CS 655 soil water, temperature and salinity monitoring probes, both manufactured by Campbell Scientific Inc., Logan, Utah, USA. Soil probes were installed at 30 cm, 60 cm and 90 cm (as indicated in Figure 1-4). An automatic TE525 (Texas Electronics) tipping bucket rain gauge, which monitors irrigation and rainfall under the pivot area and rainfall in the dryland area, also formed part of the monitoring stations. The CS 655 soil probes monitored the soil's bulk electrical conductivity (EC), volumetric water content (VWC) and soil temperature at each depth. These measurements were recorded throughout the season, and the data was retrieved from the logger every two weeks.

This setup enabled continuous measurement of EC, temperature and soil water content while mine water was used for irrigation. Soil samples were also taken after each cropping season to track the changes and impact of mine water irrigation on the soil. The monitoring stations were placed in approximately the same locations as in previous seasons to track changes over time. The monitoring stations were placed as far as possible from the road and kept out of sight to minimize the risk of theft. The stations were also clearly marked from both sides of the field to increase visibility for staff working on the farm. This reduces the risk of machinery damaging the stations.

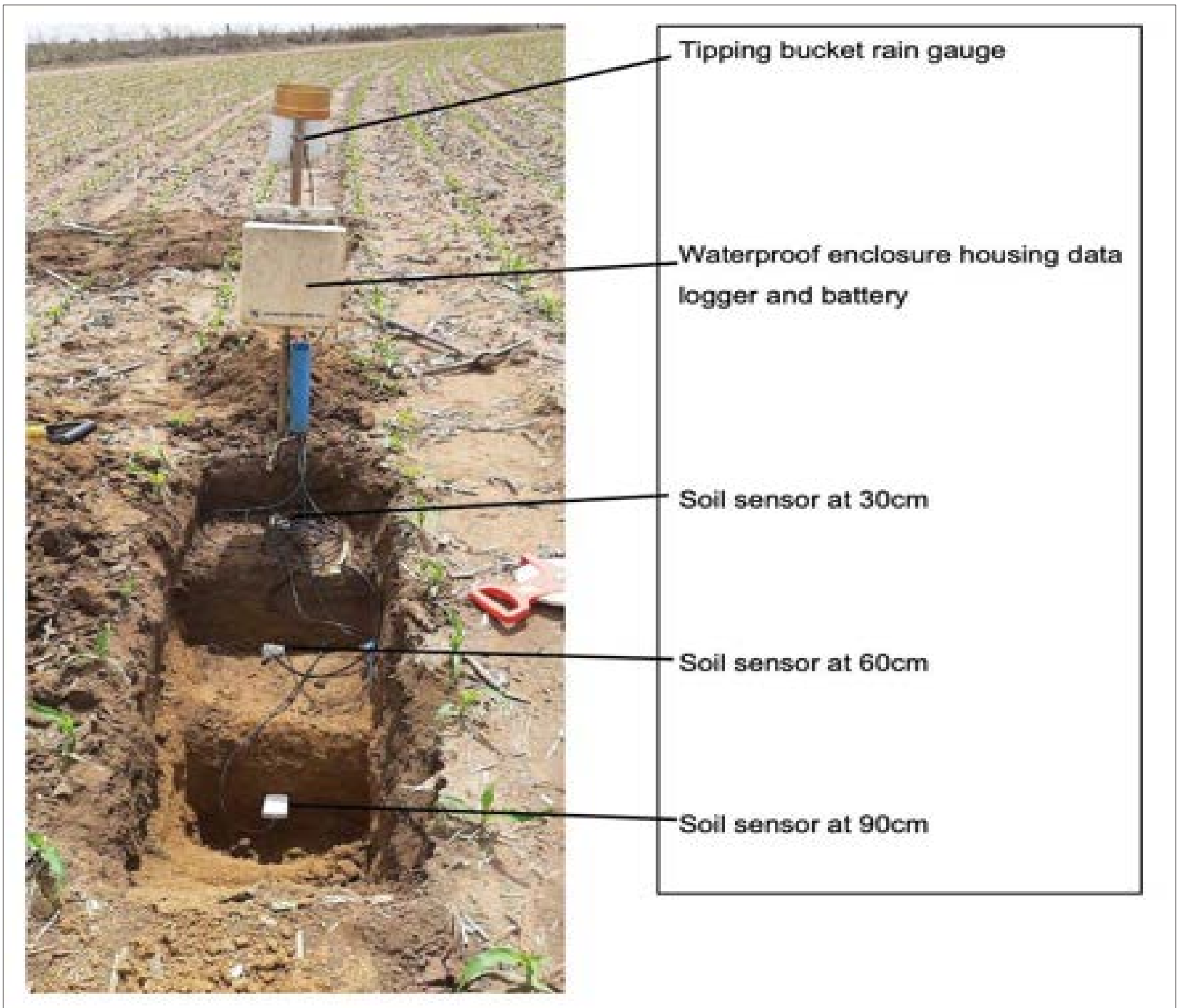

Figure 1-4: Soil monitoring setup at the Unmined Pivot.

1.3 Irrigation water quality

A summary of the average irrigation water quality used at the Unmined Pivot since the trial was established in 2016 is presented in Table 1-1. It should be noted that water from other voids and other collieries is occasionally discharged into the pivot's water source, Void 3, which can cause variations in the water quality. Figure 1-5 shows a time series of the irrigation water pH prior to irrigation and following the commencement of irrigation, which is marked by the red dashed vertical line. The graph shows notable variability in pH throughout the monitoring period, with pH ranging from 6.8 to 8.8. However, the irrigation water remained largely circumneutral to slightly alkaline throughout the monitoring period.

The EC has been variable, with a general increase since irrigation commenced. However, this trend was disrupted by a sharp decline at the end of 2020. Another notable change was observed towards the end of 2022 when EC rapidly increased. The fluctuations in EC are likely due to a combination of dilution effects by rainfall and/or mixing of Void 3 water with water from other voids. Similar trends have been observed with the concentrations of certain elements. Calcium and magnesium showed a generally increasing trend, with dips in concentration occurring towards the end of 2020 (Figure 1-7), similar to the trend in EC in the same period. Sodium, chloride and potassium remained relatively consistent with slight changes occurring occasionally.

Water samples taken by the UP team were also analysed to confirm the accuracy of the water quality data received from the laboratory used by the mine's consultant. Figure 1-8 shows that the water quality reported by the mine correlates well with that measured by UP, providing confidence that the received data is reflective of in-field conditions.

Table 1-1: Average irrigation water quality used at the Unmined Pivot.

Parameter	Units	Dec'16-Dec'17	Dec'17-Dec'18	Dec'18-Dec'19	Dec'19-Dec'20	Dec'20-May'21	Jun'21-Jul'22	Aug '22-Dec '23	Dec '23-Jul '24
pH		7.69	8.02	8.15	8.06	7.90	8.10	7.95	7.71
EC	mS/m	148	207	258	263	154	183	335	286
TDS	mg/L	2131	2065	1887	2876	2929	1836	1932	1963
Ca		129	224	333	278	129	336	307	313
Mg		100	154	207	234	77	276	200	179
Na		58	62	58	56	42	64	69	88
K		25	30	23	27	17	23	25	42
Alkalinity as $CaCO_3$		191	249	191	127	176	189	168	176
Cl		24	20	21	26	14	15	19	21
SO_4^{2-}		718	1090	1589	1121	599	949	1601	1523
F		0.63	0.41	0.68	0.43	0.54	0.51	0.70	0.33
Nitrate as N		3.40	3.49	0.39	0.83	0.41	0.68	1.21	2.04
Al		0.068	0.018	0.252	0.175	0.056	0.119	0.105	0.076
Fe		0.030	0.094	0.004	0.091	0.052	0.098	0.119	0.065
Mn		1.17	2.32	0.05	0.22	0.53	0.37	0.46	0.481
Zn		0.027	0.013	0.004	0.067	0.057	0.023	0.068	0.034
Total Hardness as $CaCO_3$		944	1191	416	970	1044	1423	1575	1482
Suspended Solids		65	9.6	40	55	53	41	27	21

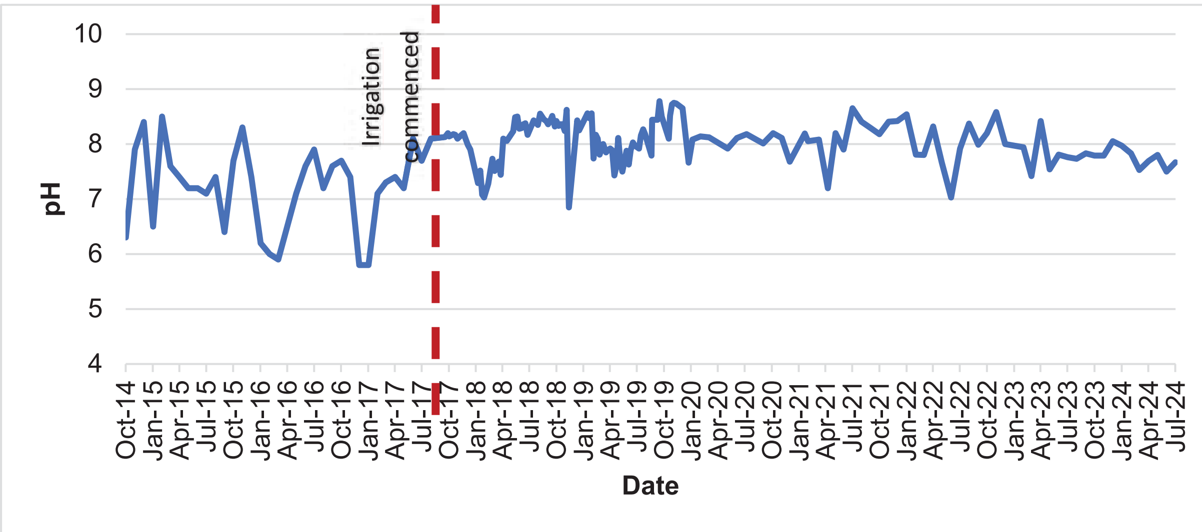

Figure 1-5: Void 3 water pH values.

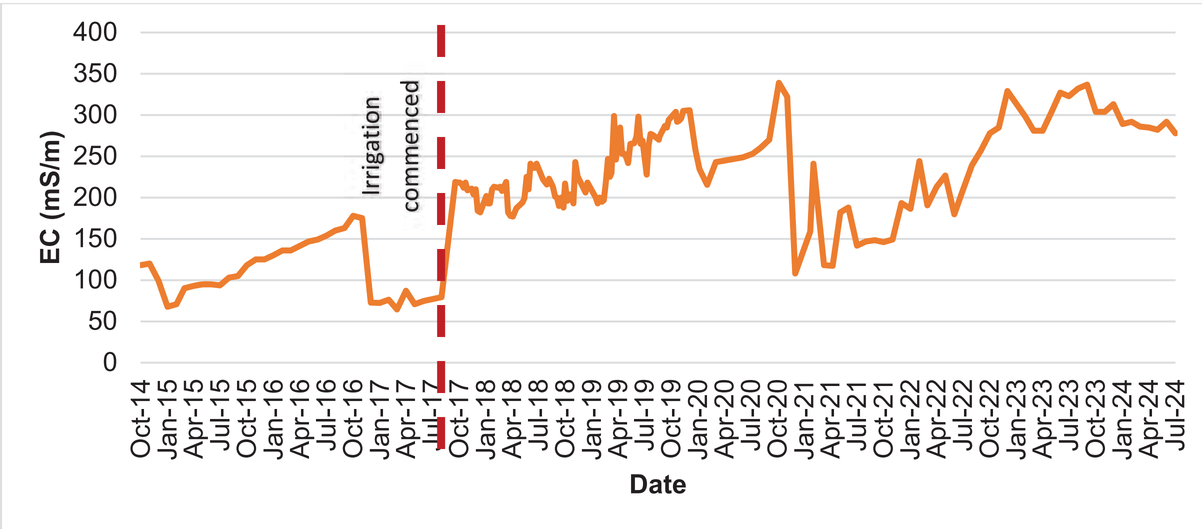

Figure 1-6: Void 3 water electrical conductivity (EC) values.

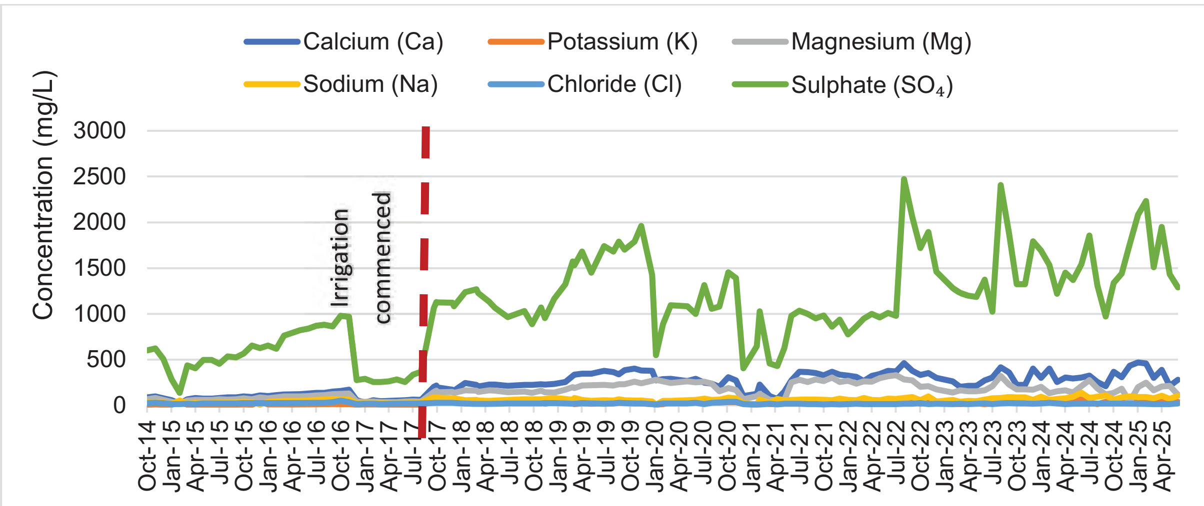

Figure 1-7: Fluctuations in Void 3 water quality over time

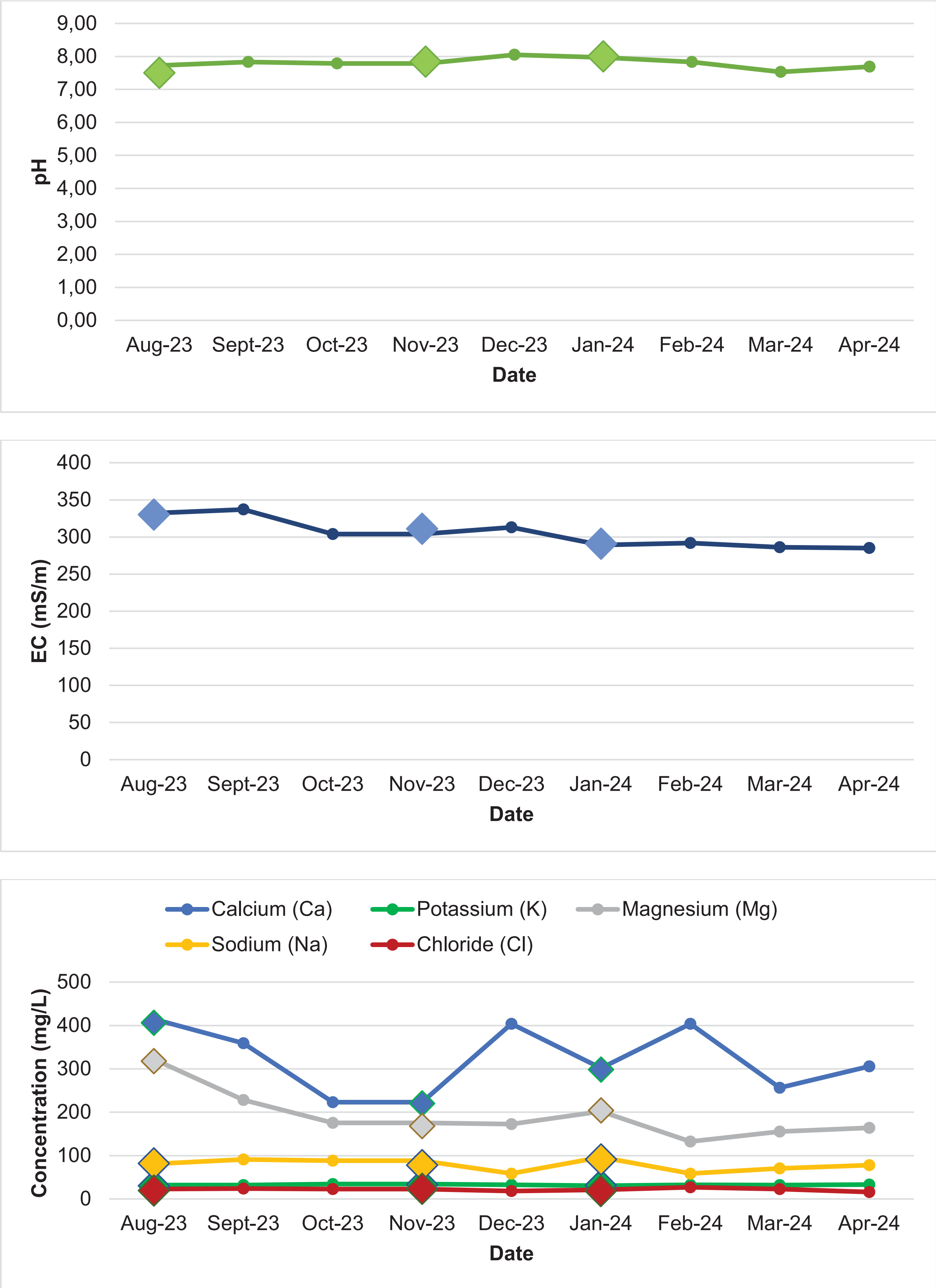

Figure 1-8: Water quality measured by the mine (lines) and that measured by UP (diamonds)

1.4 Crop growth, productivity and chemical composition

1.4.1 Crop growth and yield

The growth of crops provides a clear indication of the soil's potential and the effect of irrigation with mine water. An increase in yield over that achieved through dryland agriculture remains one of the basic aims of the project. Another important opportunity with mine water irrigation in the Highveld is crop production during the dry season. Unfortunately, it has not been possible to demonstrate this very well in this trial so far, as the commercial farmer partnering with us is not geared towards winter crop production. The tables and figures in this section present the growth and yields of the maize at the Unmined and Beestepan Dam pivots.

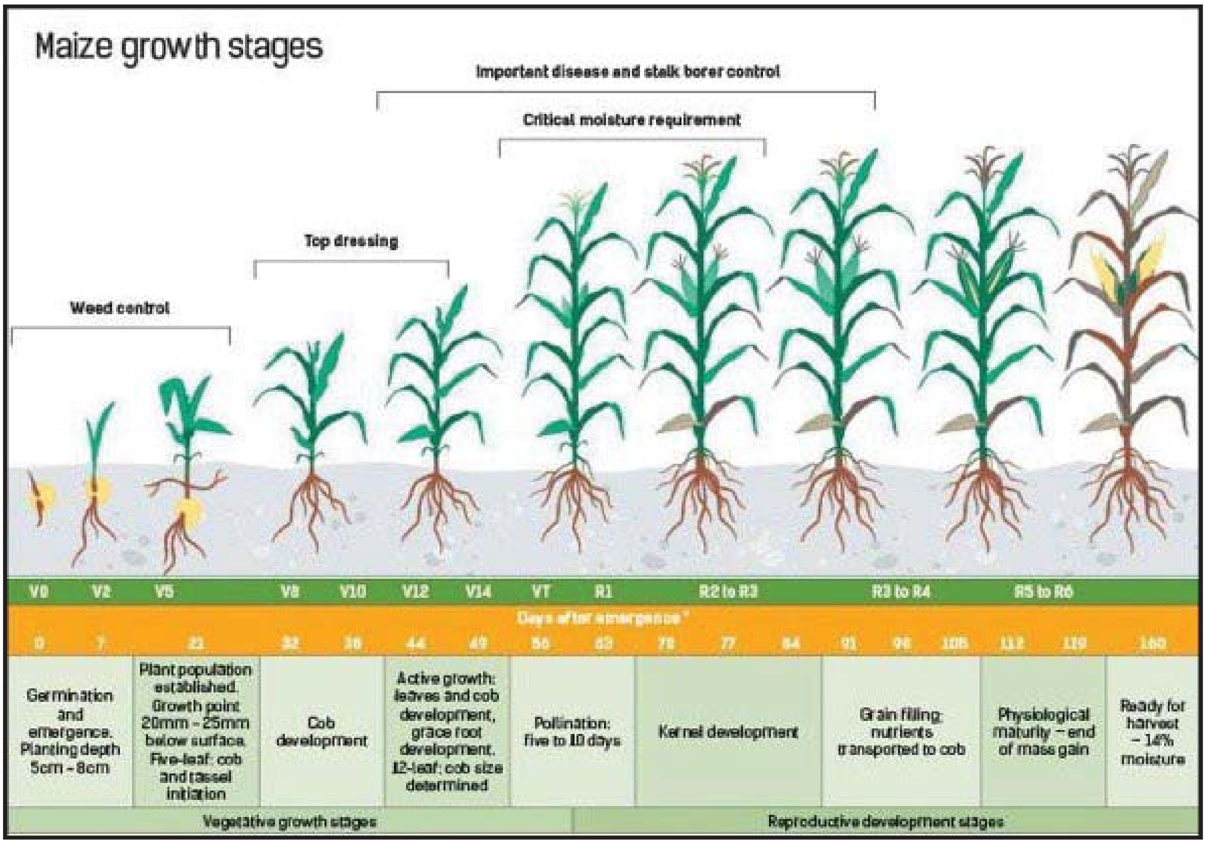

Figure 1-9: Phenological growth stages of maize (He et al. 2010)

Phenological stages, as depicted in Figure 1-9, are an indicator of crop development and are important for irrigation and fertilizer application scheduling. Table 1-2 presents phenological stages and the dates on which these were observed, together with crop heights, for all three monitored maize fields. There was no substantial difference in crop height between the three pivots, and the crops had similar growth patterns. This was expected as the irrigation water sources are of similar quality, with the main difference being that Beestepan Dam water has higher concentrations of selected trace elements.

Table 1-2: Average plant height for all 3 unmined pivots

Date (Weeks after planting)		**Pivot Name**					
		Unmined Pivot		**Beestepan Central Pivot**		**Beestepan Road Pivot**	
		Height (cm)	**Growth Stage**	**Height (cm)**	**Growth Stage**	**Height (cm)**	**Growth Stage**
03-Oct-23	**0**	Planting	NA	Planting	NA	Planting	NA
11-Oct-23	**1**	7	V2	5	V2	7	V2
19-Oct-23	**3**	11	V3-V4	10	V3-V4	13	V3-V4
30-Oct-23	**5**	23	V4-V5	22	V4-V5	29	V4-V5
06-Nov-23	**7**	44	V5-V6	40	V5-V6	51	V5-V6
20-Nov-23	**10**	89	V7-V8	96	V7-V8	102	V7-V8
30-Nov-23	**12**	140	V8-V9	133	V8-V9	151	V8-V9
12-Dec-23	**14**	233	VT-R1	185	VT-R1	217	VT-R1
22-Dec-23	**15**	254	R1-R2	243	R1-R2	271	R1-R2
03-Jan-24	**17**	266	R2-R3	261	R2-R3	284	R2-R3
11-Jan-24	**18**	278	R3-R4	280	R3-R4	293	R3-R4
22-Jan-24	**20**	289	R3-R4	287	R3-R4	305	R3-R4
08-Feb-24	**22**	300	R4-R5	304	R4-R5	320	R4-R5
21-Feb-24	**24**	297	R5-R6	300	R5-R6	323	R5-R6
05-Mar-24	**26**	301	R5-R6	296	R5-R6	315	R5-R6
20-Mar-24	**28**	291	R5-R6	288	R5-R6	300	R5-R6

A time series of crop growth in the Unmined Pivot is presented in Figure 1-10. Crop height was fairly consistent at the Unmined Pivot throughout the monitoring period, with crops reaching a maximum height of roughly 3 m in most seasons. This suggests that irrigation with the mine water had little to no effect on crop growth over the monitoring period.

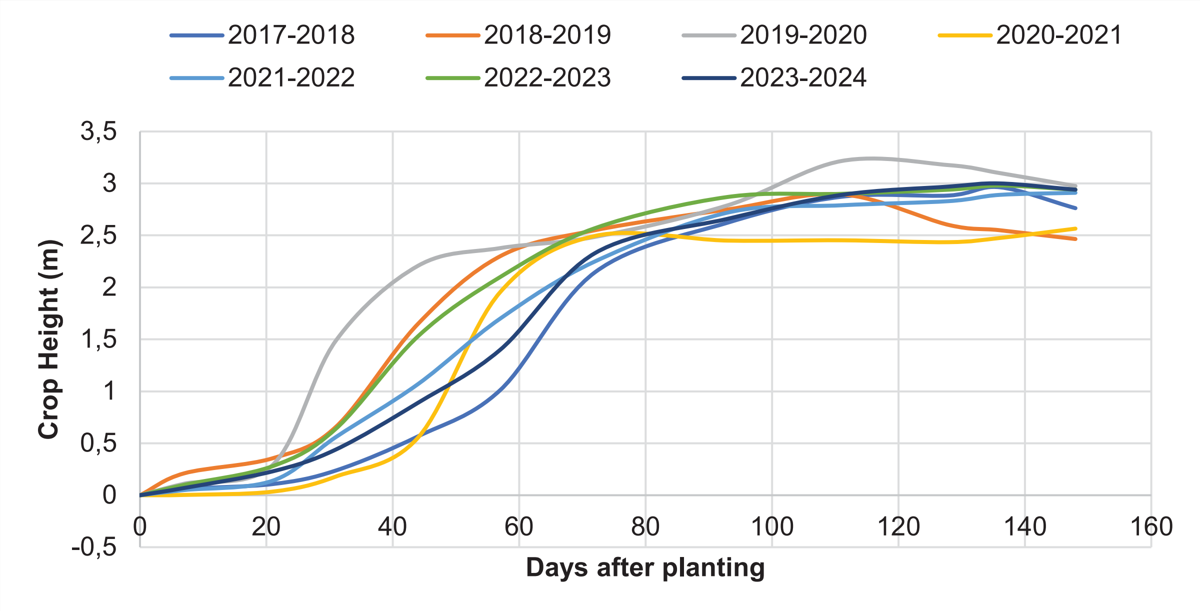

Figure 1-10: Crop height in the Unmined Pivot over seven seasons.

Table 1-3 shows seasonal grain and dry matter yields recorded since irrigation commenced. Irrigated maize productivity and yield were fairly consistent and exceeded that of the dryland maize throughout the monitoring period. This indicates that irrigation with circumneutral calcium- and sulphate-rich mine waters was more productive than dryland production, highlighting the value of supplemental irrigation in regions with high but erratic rainfall.

Table 1-3: Grain and dry matter yields of maize produced at the Unmined Pivot over seven seasons

Season	Grain Yield (t/ha)		Total Dry Matter (t/ha)		Harvest Index (%)	
	Irrigated	Dryland	Irrigated	Dryland	Irrigated	Dryland
2017/18	14	5	30	11	46	45
2018/19	12	6	25	17	48	35
2019/20	14	5	38	28	37	18
2020/21	12	8	27	22	44	36
2021/22	14	9	36	26	39	35
2022/23	12	8	28	21	43	38
2023/24	13	8	31	22	42	36

Leaf area index (LAI) is directly related to crop growth and water use, making it a useful indicator of the effect of mine water on crop performance. A healthy, large canopy that stays green for as long as possible maximizes the interception of solar radiation and facilitates the gas exchange necessary for photosynthesis. These processes are essential for biomass production and grain yield. LAI data was collected every season and is presented in (Figure 1-11). As shown in the figure, LAI was fairly consistent throughout the monitoring period, indicating that irrigation with the mine waters did not interfere with crop growth. The rapid increase in LAI in the first few weeks indicates the exponential vegetative growth stage, and the onset of the plateau marks the beginning of the reproductive stage, during which no further vegetative growth occurs in this determinate crop.

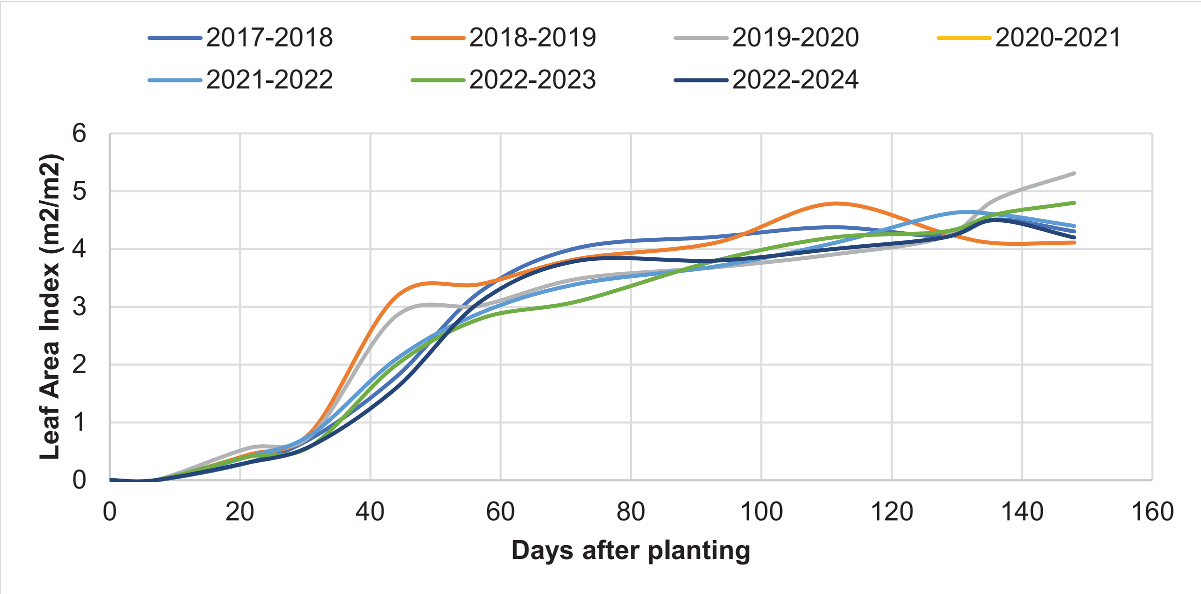

Figure 1-11: Leaf area indices from the Unmined Pivot

1.4.2 Plant composition

Plant analyses were conducted at the end of every season to evaluate the effect of mine water irrigation on the inorganic chemical composition of crops. Chemical analyses of the grain and stover of maize produced at the Unmined Pivot are presented in Table 1-4 and Table 1-5. The concentrations of most elements remained relatively stable over the monitoring period. There were no substantial differences in elemental concentrations between the dryland and mine water irrigated maize throughout the monitoring period, which indicates that irrigation with the mine water had minimal effect on the uptake of nutrients and selected trace elements.

Table 1-4: Elemental concentrations of the grain of maize produced at the Unmined Pivot[1]

Element	Dryland							Irrigated						
	2017/ 2018	2018/ 2019	2019/ 2020	2020/ 2021	2021/ 2022	2022/ 2023	2023/ 2024	2017/ 2018	2018/ 2019	2019/ 2020	2020/ 2021	2021/ 2022	2022/ 2023	2023/ 2024
K (mg/kg)	18	15	13	21	28	23	28	17	22	18	24	27	25	27
Mg (mg/kg)	9	10	9	10	15	13	12	10	10	10	11	14	13	14
Ca (mg/kg)	0.4	0.6	0.7	0.7	0.8	0.8	0.4	0.3	0.6	0.9	0.5	0.42	0.6	0.6
Na (mg/kg)	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
S (mg/kg)	9.5	8.2	8.9	8.3	8.8	8.3	9.1	9.9	8.3	9.1	8.8	7.4	8.1	8.7
P (mg/kg)	32	24	28	34	31	29	30	31	27	30	30	27	29	30
B (mg/kg)	BDL	0.1	BDL	BDL	BDL	BDL	0.1	BDL	BDL	BDL	0.1	BDL	BDL	0.1
Fe (mg/kg)	0.1	0.1	0.2	0.5	0.3	0.3	0.5	0.1	0.1	0.2	0.7	0.3	0.2	0.4
Mn (mg/kg)	BDL	BDL	BDL	0.1	0.3	0.1	0.1	BDL	0.1	0.1	0.1	0.3	0.1	0.1
Al (mg/kg)	BDL	BDL	BDL	0.1	BDL	BDL	BDL	BDL	BDL	BDL	0.1	BDL	BDL	BDL
Cu (mg/kg)	BDL	BDL	BDL	BDL	BDL	BDL	0.5	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Zn (mg/kg)	17	10	20	14	20	13	18	22	11	16	17	17	20	10
Hg (mg/kg)	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Cd (mg/kg)	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Cr (mg/kg)	BDL	BDL	BDL	0.011	0.01	0.01	BDL	BDL	BDL	BDL	0.038	0.01	0.01	BDL
Pb (mg/kg)	0.05	0.08	BDL	0.06	BDL	0.05	BDL	0.09	0.06	0.08	0.06	BDL	BDL	BDL
As (mg/kg)	0.1	0.07	0.05	0.04	BDL	BDL	BDL	0.13	0.1	0.08	0.11	BDL	BDL	BDL

[1] BDL = Below the detection limit of 0.001 mg/kg

Table 1-5: Elemental concentrations of leaves and stem of maize produced at the Unmined Pivot[2]

Element	Dryland							Irrigated						
	2017/ 2018	2018/ 2019	2019/ 2020	2020/ 2021	2021/ 2022	2022/ 2023	2023/ 2024	2017/ 2018	2018/ 2019	2019/ 2020	2020/ 2021	2021/ 2022	2022/ 2023	2023/ 2024
K (mg/kg)	12250	11632	11775	7635	6533	7341	11028	13065	13495	13998	8814	2723	9841	12821
Mg (mg/kg)	3318	3189	3417	1527	2048	1835	2400	3580	3402	3505	1210	2301	2533	4100
Ca (mg/kg)	4048	4115	4115	2376	4026	3504	4000	4215	4030	4050	1997	4671	3681	6400
Na (mg/kg)	47	50	50	33	31	27	55	49	48	49	57	17	44	42
S (mg/kg)	763	667	1042	798	827	725	1100	1323	1198	835	563	838	800	1300
P (mg/kg)	665	603	900	781	758	708	400	1115	933	636	363	856	721	300
B (mg/kg)	5	5	5	4	5	4	4	7	7	8	6	6	7	6
Fe (mg/kg)	11	12	12	4	19	14	12	7	9	9	5	17	12	10
Mn (mg/kg)	22	24	24	35	57	47	41	29	30	27	37	78	39	67
Al (mg/kg)	270	281	289	174	283	261	271	220	211	225	170	231	247	278
Cu (mg/kg)	1	1	2	6	14	8	7	1	3	1	4	7	6	7
Zn (mg/kg)	20	18	21	14	10	7	31	24	16	21	13	17	15	33
Hg (mg/kg)	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.01	BDL
Cd (mg/kg)	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.01	BDL
Cr (mg/kg)	0.001	BDL	BDL	0.01	0.01	0.01	BDL	BDL	BDL	BDL	BDL	0.01	0.01	BDL
Pb (mg/kg)	0.006	0.006	0.002	BDL	BDL	BDL	BDL	0.006	0.001	0.001	0.002	BDL	BDL	BDL

[2] BDL = Below the detection limit of 0.001 mg/kg

1.5 Crop consumption safety

At the end of each growing season, plants and grain samples were analysed and compared to current local and international guidelines for grain and fodder safety. Mine waters typically contain numerous trace elements; however, arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb) and mercury (Hg) have been identified as the most important elements of concern to monitor. Table 1-6 presents concentrations of the five elements of concern considered in the local and international food and fodder guidelines for maize grain from the Unmined Pivot. The grain elemental concentrations were always below the accepted local and international thresholds throughout the monitoring period, indicating that they were safe for human and animal consumption.

Table 1-6: Comparison of grain element concentrations with accepted food and fodder safety thresholds for the past seven seasons [3]

Element			As	Cd	Zn	Pb	Hg
Local and international thresholds	China	ppm or mg/kg	0.5	0.1	-	0.2	0.02
	SA/EU/USA		-	0.1	-	0.2	-
	Ireland		-	0.1	-	0.1	-
	SA Feed safety		2	1	150	10	0.1
Average concentrations in white maize	Method Detection limits		**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
	2017/ 2018		0.13	BDL	22	0.09	BDL
	2018/ 2019		0.10	BDL	11	0.06	BDL
	2019/ 2020		0.08	BDL	16	0.08	BDL
	2020/ 2021		0.11	BDL	17	0.06	BDL
	2021/ 2022		BDL	BDL	17	BDL	BDL
	2022/ 2023		BDL	BDL	20	BDL	BDL
	2023/ 2024		BDL	BDL	10	BDL	BDL

[3] BDL =Below the detection limit and cells highlighted in green indicate that measured concentrations are below accepted thresholds

1.6 Economic analysis

This section delves into the financial aspects of crop production over the past seven seasons of growing maize at the Unmined Pivot. The main costs incurred by the farmer were for fertilizer and pesticides, as the water and pumping costs were covered by the mine (Mafube Colliery). The fertilizer and pesticide programs have remained unchanged for the past seven seasons of irrigation. Although the inputs have not changed, the costs involved have increased gradually over the years due to inflation. The maize price has also been steadily increasing, allowing some farmers to still make a profit despite the rising input costs.

Since the primary goal of commercial farming is to generate a profit, it is essential to review the end of every season and assess its profitability. The input costs and earnings have been calculated and summarized in Table 1-7, together with the profit or loss determination. The input costs were determined using mainly industry data sourced online, and our farming partner confirmed that the costs presented in the table were in line with the figures in his balance sheet.

Table 1-7 shows that the irrigated yields were constantly higher than those produced under dryland conditions and this can be attributed to the additional available water which allowed for higher plant populations and reduced water stress. However, higher plant populations also lead to higher input costs as more seed, fertilizer and pesticides are required. Since the price of maize was the same regardless of how it was grown, the yield under irrigation needed to be significantly higher than that under dryland conditions for a profit to be realized and for the additional fuel and labour costs involved to be justified.

Dryland production incurred a net loss in the first three seasons of the study (highlighted in red) and only began showing a profit (highlighted in green) in the fourth season. Irrigated production, however, showed a profit from the very first season. When comparing the profit under dryland or irrigated conditions, it can be seen that irrigated production yielded typically two to three times the profit made with dryland production. It should be noted that the cost of irrigation, estimated at R5000 per ha, is not included in this table. However, even if the profit reported was reduced by this amount, the mine water irrigation production system would still have always been profitable, highlighting the risk reduction value of supplemental irrigation with suitable mine water in the Highveld of Mpumalanga.

Table 1-7: Summarized costing report for the Unmined Pivot for the past seven seasons[4]

Season	Yield (t/ha)		Cost per ha		Maize price per ton	Earnings per ha		Profit / Loss per ha	
	Irrigated	Dryland	Irrigated	Dryland		Irrigated	Dryland	Irrigated	Dryland
2017/2018	13.5	4.5	R18 000	R16 000	R2 103	R28 390	R9 460	R10 390	R6 540
2018/2019	11.6	5.5	R18 770	R16 800	R2 910	R33 760	R16 010	R14 990	R790
2019/2020	14.3	4.9	R19 700	R17 700	R2 450	R35 040	R12 010	R15 340	R5 690
2020/2021	12.2	8.4	R20 600	R18 580	R3 508	R42 800	R29 470	R22 200	R10 890
2021/2022	14.2	8.7	R22 000	R19 510	R4 079	R57 920	R35 490	R35 920	R15 980
2022/2023	12.4	8.1	R24 200	R21 461	R3 501	R43 412	R28 358	R19 212	R6 897
2023/2024	12.6	8.5	R32 000	R26 000	R4 935	R62 181	R41 948	R30 181	R15 948

[4] Cells highlighted in green indicate a profit gain and cells highlighted in red indicate a loss in profit.

1.7 Water and salt balances

1.7.1 Irrigation and rainfall

In areas with high but erratic rainfall, such as the Mpumalanga Highveld, supplemental irrigation is important to minimize yield losses during extended dry periods. Figure 1-12 shows the total amount of irrigation applied and rainfall received at the Unmined Pivot over the seven seasons of monitoring. As indicated in the figure, supplemental irrigation was required to meet crop requirements despite the substantial rainfall. Irrigation was low in the 2020-2021 season, partly due to challenges with low water pressure. There was, however, sufficient rain during this period to meet the crop requirements.

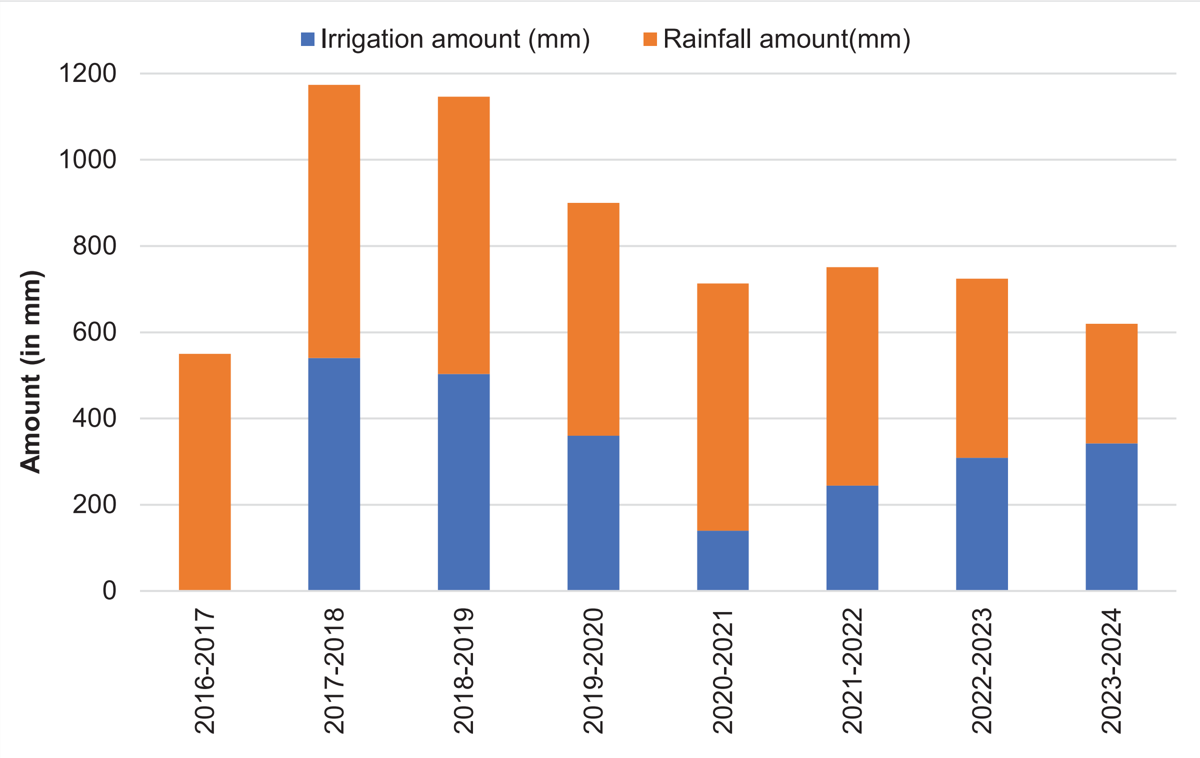

Figure 1-12: Irrigation and rainfall for seven seasons at the Unmined Pivot

Figure 1-13 shows the monthly rainfall and irrigation at the Unmined Pivot for the 2023-2024 maize season, which provides a more detailed illustration of the contribution made by irrigation. Throughout the season rainfall was insufficient to meet crop demand, and mine water irrigation was able to bridge the deficit. This highlights the value of having access to this water source for irrigation, even in wet seasons, to bridge any periods in which a deficit is experienced.

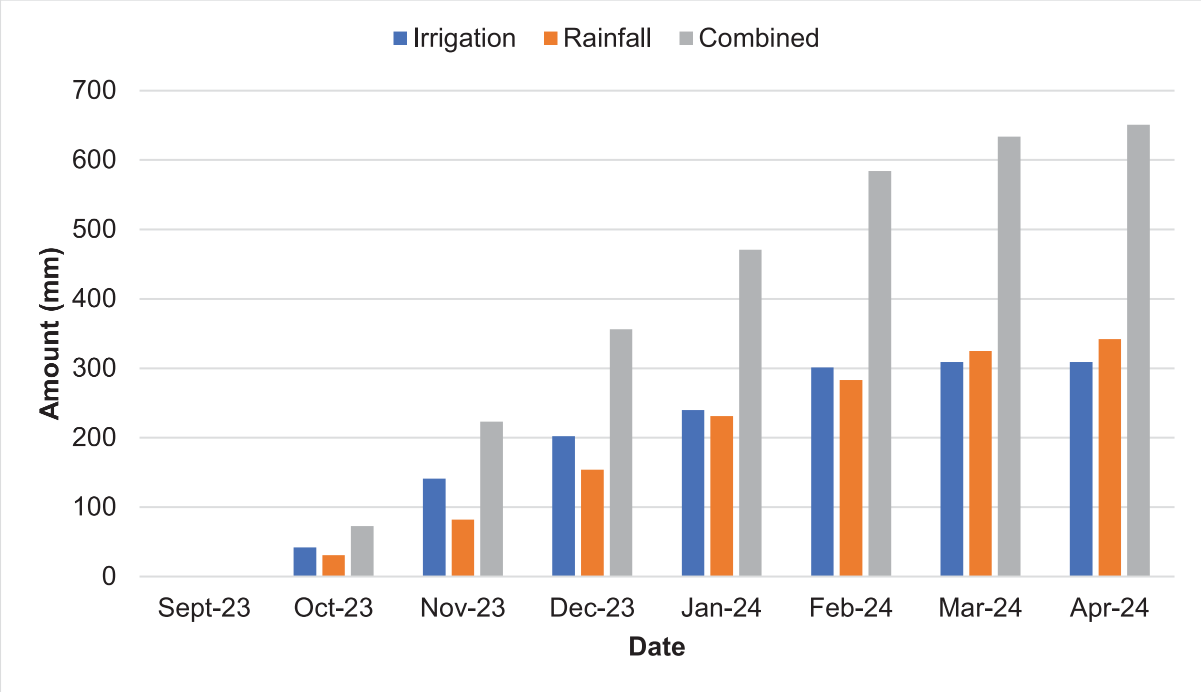

Figure 1-13: Rainfall and irrigation for the 2023/2024 season at the Unmined Pivot

Irrigation with untreated, circumneutral mine water from Void 3 has supplied a substantial amount of solutes to the Unmined field since the inception of this study (in excess of 47 t/ha). Since the water is rich in calcium and sulphate, it was expected that gypsum would precipitate. Gypsum precipitation is expected to maintain root zone salinity at moderate levels and reduce the leaching of soluble salts to the surrounding water environment. However, the leaching fraction has been too high to facilitate gypsum precipitation, with only supplemental irrigation applied in summer. The addition of a winter crop is expected to facilitate some gypsum precipitation due to increase irrigation and less rainfall. Table 1-8 shows the amount of salts supplied through irrigation. As indicated in the table, the higher the irrigation water supply, the higher the salt loading.

Table 1-8: Solutes applied to 19 ha pivot field through irrigation since 2017

Season	Constituent	Irrigation amount (mm)	Concentration (mg/L)	loading rates kg/ha
2017-18	Ca	304	209	636
	K		29	89
	Mg		155	472
	Na		68	206
	Cl		23	70
	SO_4^{2-}		1174	3568
2018-19	Ca	503	269	1354
	K		45	226
	Mg		166	833
	Na		74	373
	Cl		23	118
	SO_4^{2-}		1301	6544
2018 winter	Ca	236	227	536
	K		33	78
	Mg		154	363
	Na		60	140
	Cl		19	46
	SO_4^{2-}		1027	2423
2019-20	Ca	360	382	1377
	K		51	184
	Mg		22	77
	Na		244	877
	Cl		55	198
	SO4		1805	6499
2020-21	Ca	140	220	308
	K		25	34
	Mg		158	221
	Na		59	82
	Cl		21	29
	SO_4^{2-}		1137	1592

Season	Constituent	Irrigation amount (mm)	Concentration (mg/L)	loading rates kg/ha
2021-22	Ca	244	204	498
	K		21	51
	Mg		122	298
	Na		51	124
	Cl		24	59
	SO_4^{2-}		1233	3008
2022-23	Ca	309	247	763
	K		25	77
	Mg		144	444
	Na		62	191
	Cl		19	58
	SO_4^{2-}		1343	4149
2023-24	Ca	342	321	1099
	K		33	112
	Mg		192	656
	Na		79	270
	Cl		22	75
	SO_4^{2-}		1625	5558
Total	Ca	2438		6571
	K			851
	Mg			3365
	Na			2264
	Cl			652
	SO_4^{2-}			33341

1.7.2 Soil water content and bulk salinity

It is essential to monitor changes in soil water conditions, as this enables a better understanding of water movement and, consequently, solute movement in the soil profile. The main factors that control water movement in soil are the physical properties, such as texture. Soil texture influences the water holding capacity and hydraulic conductivity. Figure 1-14 to 1-17 present soil water content and bulk salinity data for the 2023-2024 maize season for two (P2 and D2, see Figure 1.2) of the four soil monitoring stations installed at the Unmined Pivot.

Soil water content was generally higher in the pivot area and showed a more linear trend throughout the season, with soil water contents maintained at 0.15 to 0.3 m^3/m^3 (Figure 1-14). In the dryland area, the water content was maintained at 0.12 to 0.2 m^3/m^3 in the first half of the season and showed a decreasing trend in the second half of the season despite an overall increase in rainfall during this period (Figure 1-15). Overall, the irrigated area had a higher volumetric water content than the dryland area, as expected, hence the higher crop yields obtained in the irrigated field.

The volumetric water content (VWC) increased with depth in the irrigated area. This is reflective of the water movement in the soil profile, where the water received from rainfall and irrigation drains to the deeper soil layers, and the top 30 cm of the soil experiences greater water losses through evapotranspiration.

The opposite was observed in the dryland field where soil water content was lowest in the deeper soil layer (>60 cm) and highest in the top 30 cm. Additionally, the water content in the 30 to 60 cm layer of the dryland area remained stable during the first half of the season and decreased gradually in the second half of the season. The patterns of soil water content observed in the dryland field indicate that the water received through rainfall does not drain into the deeper soil layers (>60 cm) and most of it is likely stored in the 30 to 60 cm layer.

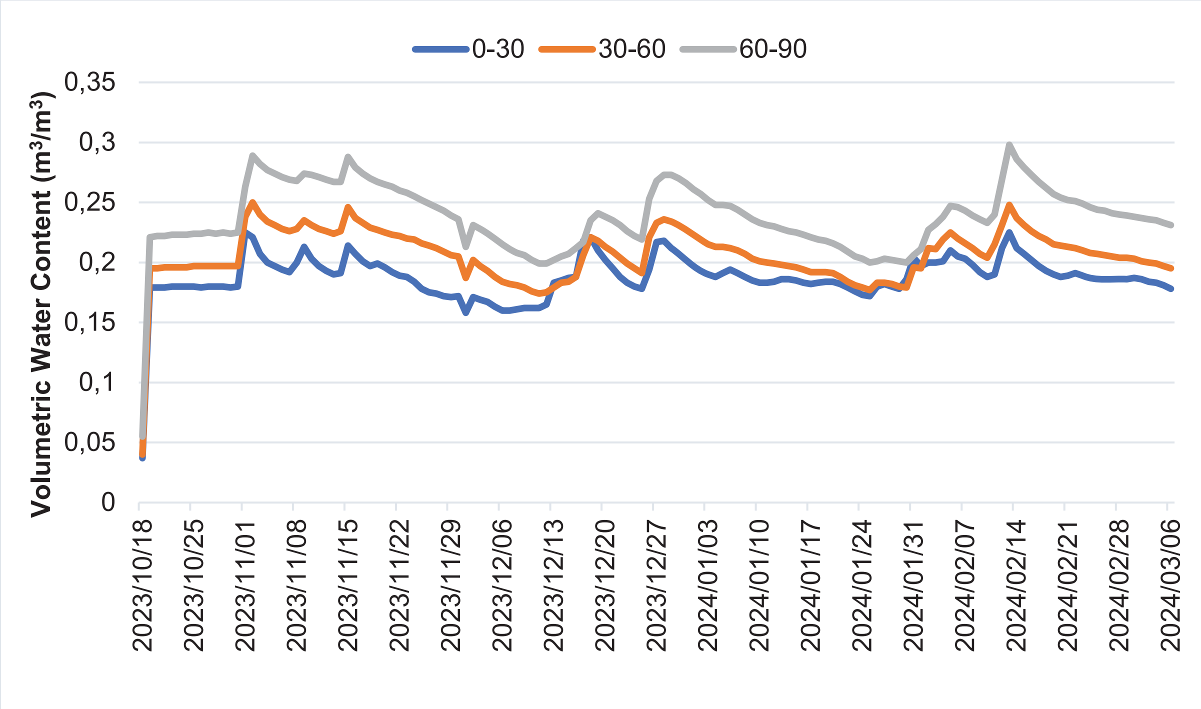

Figure 1-14: Seasonal volumetric water contents (VWC) from three depths in the irrigated field

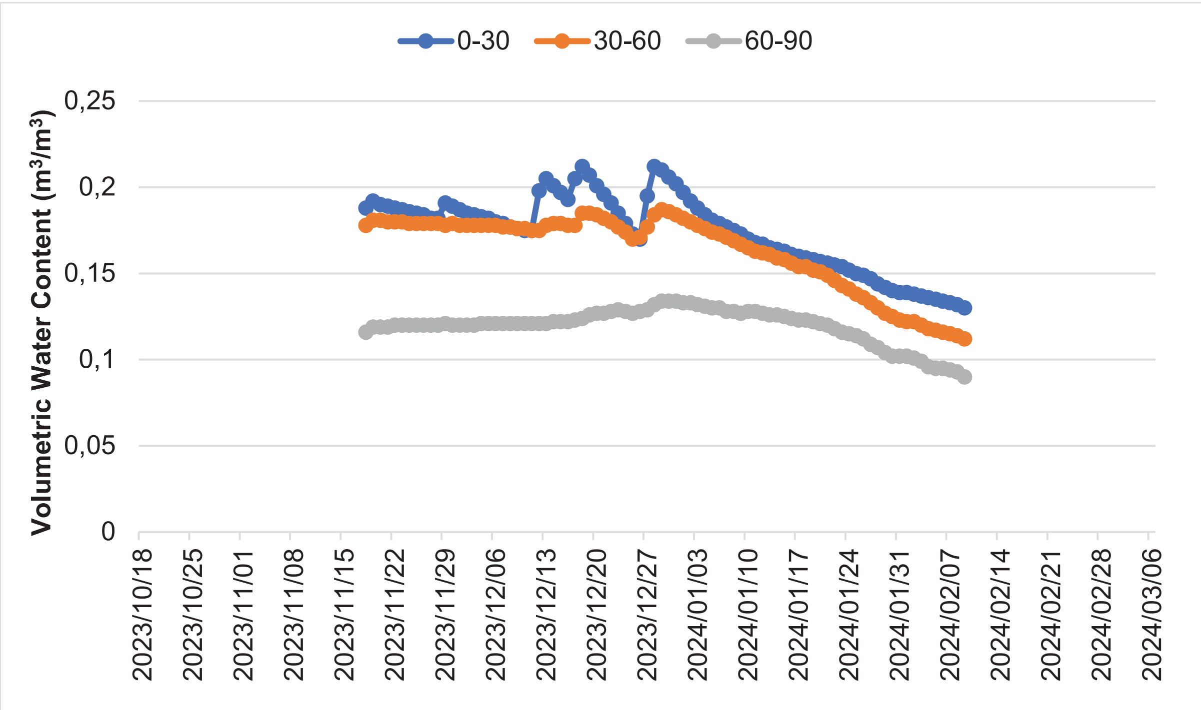

Figure 1-15: Seasonal volumetric water contents (VWC) from three depths from the dryland field

In the irrigated area, bulk EC was low at the beginning of the season and increased rapidly as irrigation was applied (Figure 1-16). However, there was an overall decreasing trend in bulk EC in the irrigated area from a maximum of 414 mS/m at the beginning of the season to a minimum of 151 mS/m at the end of the season, in the top 30 cm of the soil profile. The decreasing trend is likely due to dilution as rainfall increased. EC was typically higher in the 30-60 cm layer at the start of the season; however, as the season progressed, the EC of the top 30 cm increased above that of the 30-60 cm layer. This suggests that solute movement from the top 30 cm to the 30-60 cm layer was high at the start of the season and decreased as salts became more concentrated at the top 30 cm as the season progressed. However, changes in EC occurred in a similar pattern in all layers and reflect the effect of irrigation and rainfall.

In the dryland area, bulk EC showed a decreasing trend from a maximum of 169 mS/m to a minimum of 74 mS/m in the top 30 cm Figure 1-17. EC was substantially higher in the top 30 cm throughout the season and the EC of the 60-90 cm layer remained fairly stable for most of the season, suggesting that there was little movement of solutes from the top layer of the soils to the deeper layer. This is consistent with the observations from the volumetric water content data, which indicates limited movement of water from the top layers to the deeper layers of soil. Overall bulk EC was substantially higher in the irrigated field than in the dryland field. However, this did not affect the yield of the crops irrigated with mine water.

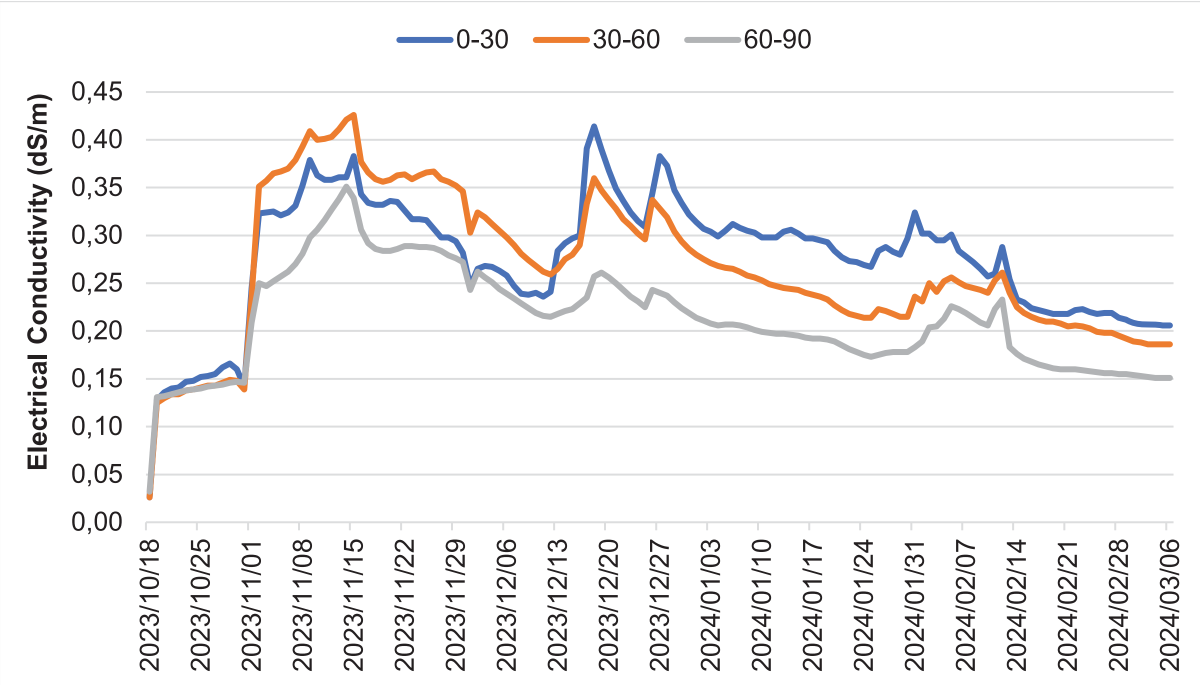

Figure 1-16: Seasonal bulk electrical conductivity (EC) from three depths in the irrigated field

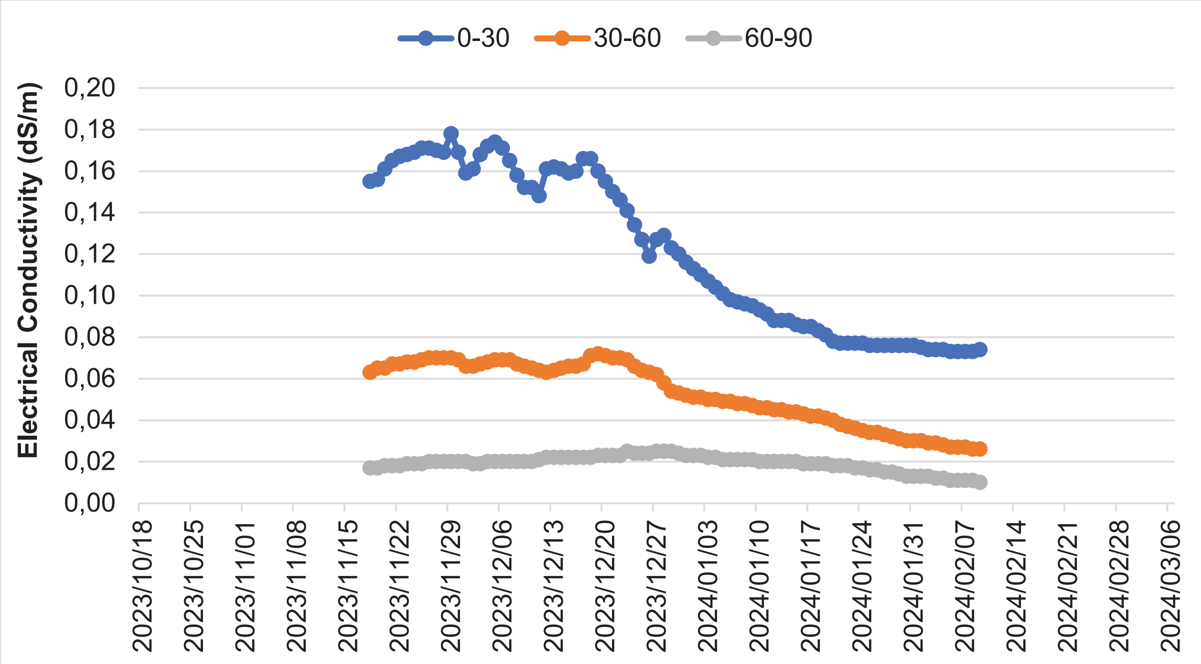

Figure 1-17: Seasonal bulk electrical conductivity (EC) from three depths from dryland field

1.8 Effect of mine water irrigation on soil chemical properties

Soil samples were collected for analysis at the end of every season to determine pH, electrical conductivity (EC_e), and the concentration of selected elements using a Mehlich-3 extraction. Figure 1-18 shows the sampling locations. There were changes made in the sampling locations due to the pivot being moved and the number of samples collected was decreased from a total of 21 to a total of 19.

Figure 1-19 and Figure 1-20 show the pH and EC_e levels in the dryland and irrigated portions of the Unmined Pivot. There has been an overall decrease in soil pH in the irrigated area and an increase in the pH of the dryland soils. The decrease in the pH of the irrigated soils was unexpected since the irrigation water was circumneutral to alkaline and contained high levels of alkalinity (Table 1-1). This decrease in pH is likely due to the irrigated field receiving more nitrogen fertilizer. EC_e in the irrigated area showed an increasing trend and was higher than that of the dryland area, which is expected. Nonetheless, the EC_e remained below the threshold for maize, which is 170 (mS/m).

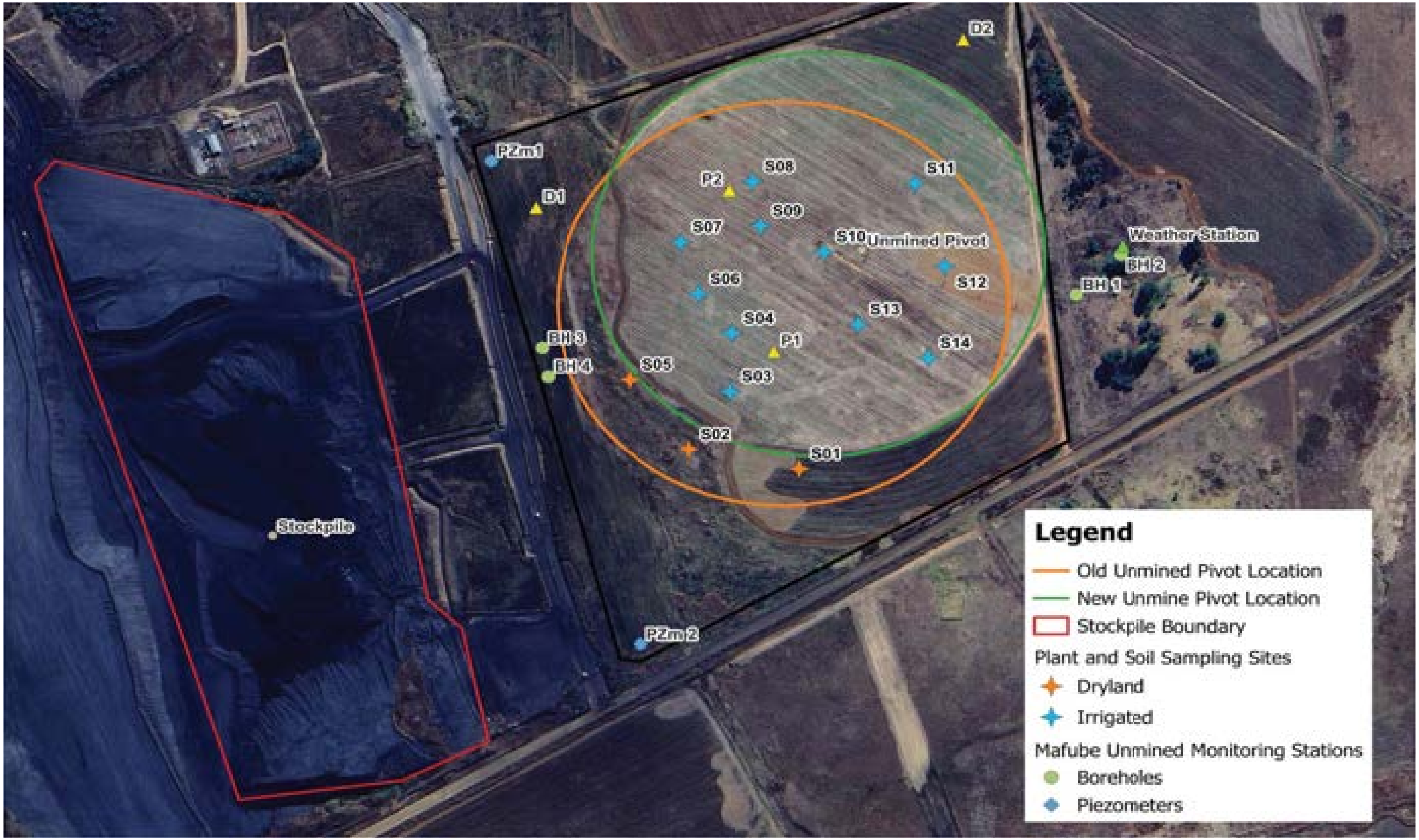

Figure 1-18: Google Earth image of the Unmined Pivot showing the different soil sampling locations

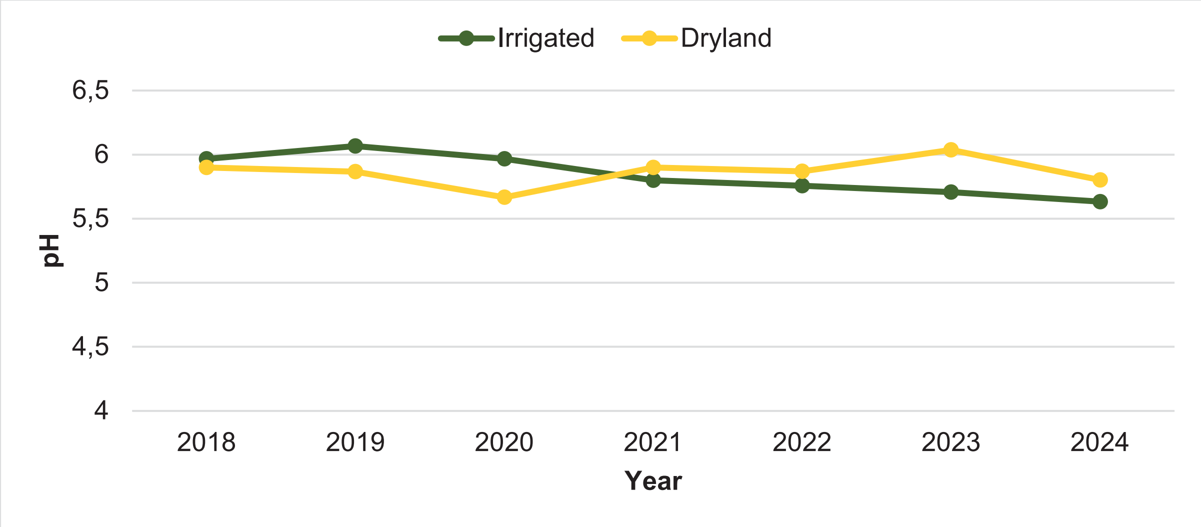

Figure 1-19: pH levels in the top 30 cm of soil in the dryland and irrigated portions of the Unmined Pivot.

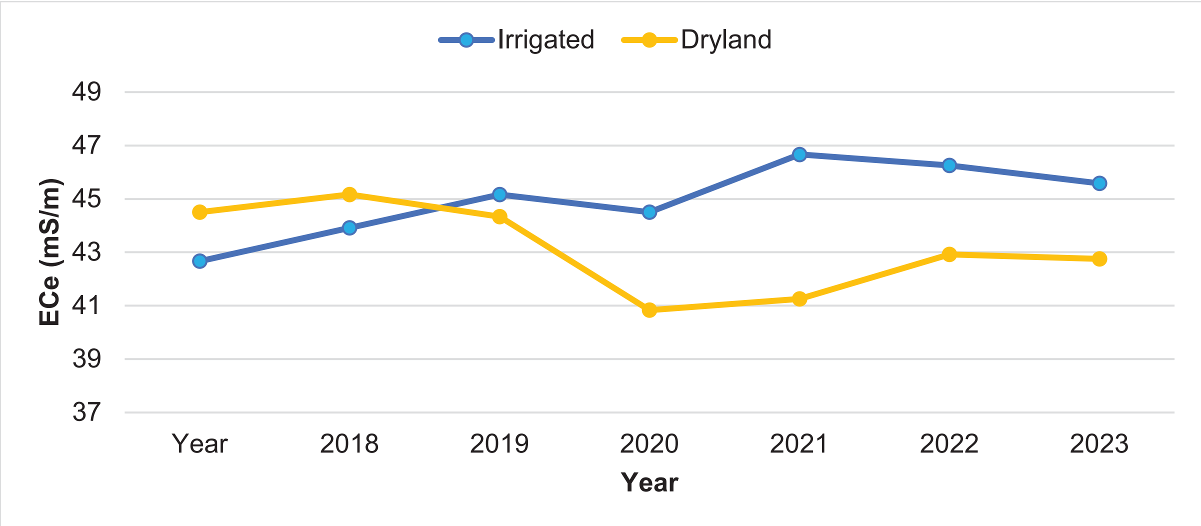

Figure 1-20: ECe levels in the top 30 cm of soil in the dryland and irrigated portions of the Unmined Pivot

Table 1-9 shows the concentrations of selected constituents: Na, Ca, Mg, K and SO_4. The table shows slight changes over the monitoring period. However, there was no substantial accumulation of constituents in the irrigated field. A similar trend was observed between the irrigated and dryland fields. There was also no substantial depletion of these elements in the irrigated field relative to the dryland field. This suggests that mine water irrigation had minimal impact on selected soil chemical properties. This may be partly due to the rainfall facilitating leaching.

Table 1-9: Average element concentrations from multiple soil sampling sites from the irrigated and dryland fields

Element	Field	2018	2019	2020	2021	2022	2023	2024
		ppm or mg/kg						
Na	Irrigated	19	19	24	25	23	29	21
	Dryland	21	24	25	20	31	24	22
K	Irrigated	65	66	72	108	73	82	84
	Dryland	81	81	84	104	93	106	91
Ca	Irrigated	621	617	630	700	646	520	612
	Dryland	592	606	610	669	624	512	581
Mg	Irrigated	172	176	189	217	197	204	220
	Dryland	181	192	193	194	209	187	201
SO_4^{2-}	Irrigated	200	202	220	207	226	211	224
	Dryland	194	207	205	179	211	204	183

1.9 Off-site environmental impacts

Figure 1-21 shows the locations of the piezometers and boreholes used to monitor groundwater impacts of irrigation. The piezometers and boreholes enabled the research team to sample both shallow and deep waters, with the understanding that potential impacts are likely to initially become apparent in the shallower waters.

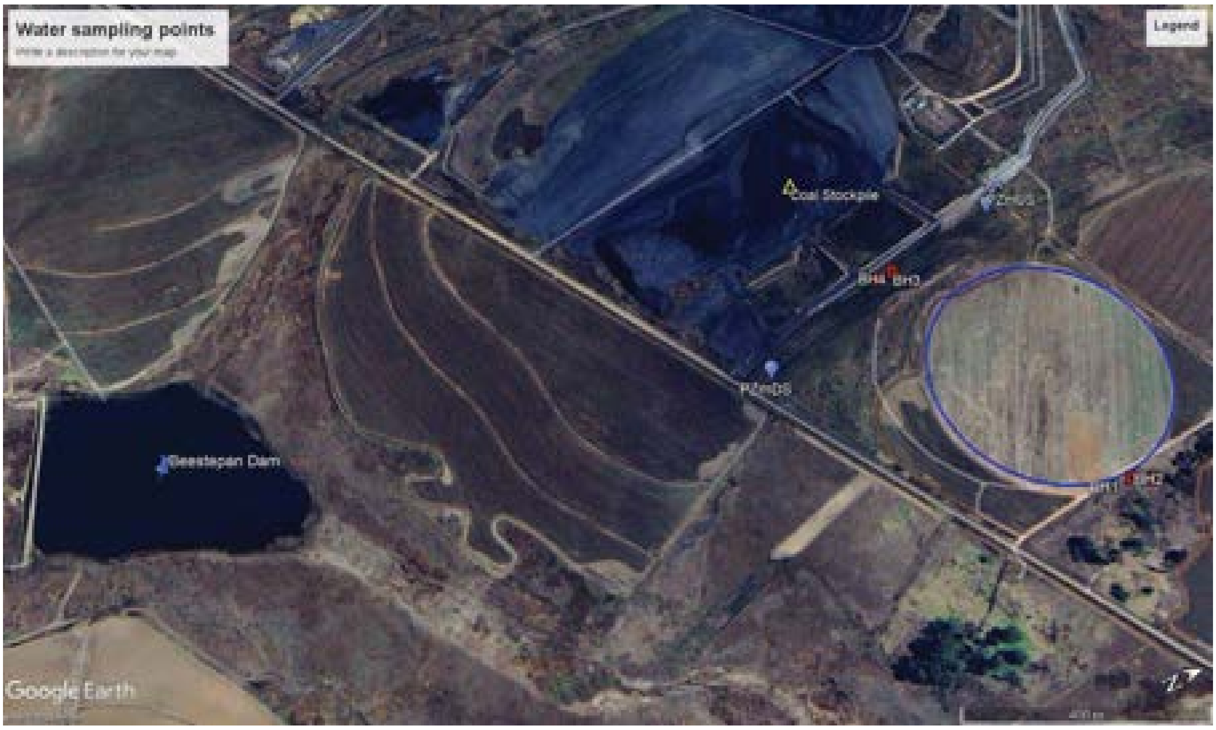

Figure 1-21: Water monitoring stations at the Unmined Pivot

1.9.1 Groundwater

1.9.1.1 Piezometer monitoring

Water levels were measured every two weeks at the two piezometers, as has been the case since 2017, and the values are presented in Figure 1-22 and Figure 1-23. These figures show typical groundwater response curves in the irrigated field. The water table depth below the surface is greatest during the winter months due to low or no rainfall received during these periods, and lowest during the summer months in this humid summer rainfall region.

Water samples were taken regularly from the two piezometers, analysed in the laboratory, and their water qualities are presented in Table 1-10. Even though the concentrations of the various elements were generally similar, they were often higher in the downstream piezometer (PZm_{DS}). This is probably due to surface runoff from the coal stockpile directly next to Unmined Pivot (see Figure 1-21). Runoff water from the stockpile, combined with the low-lying nature of the area where this piezometer has been installed, results in almost constant waterlogging conditions throughout the summer months, which has a visible effect on the water quality at PZm_{DS}. There were slight differences in selected constituent levels between Season 6 (2022-2023) and Season 7 (2023-2024). However, these changes are not substantial, indicating minimal impact.

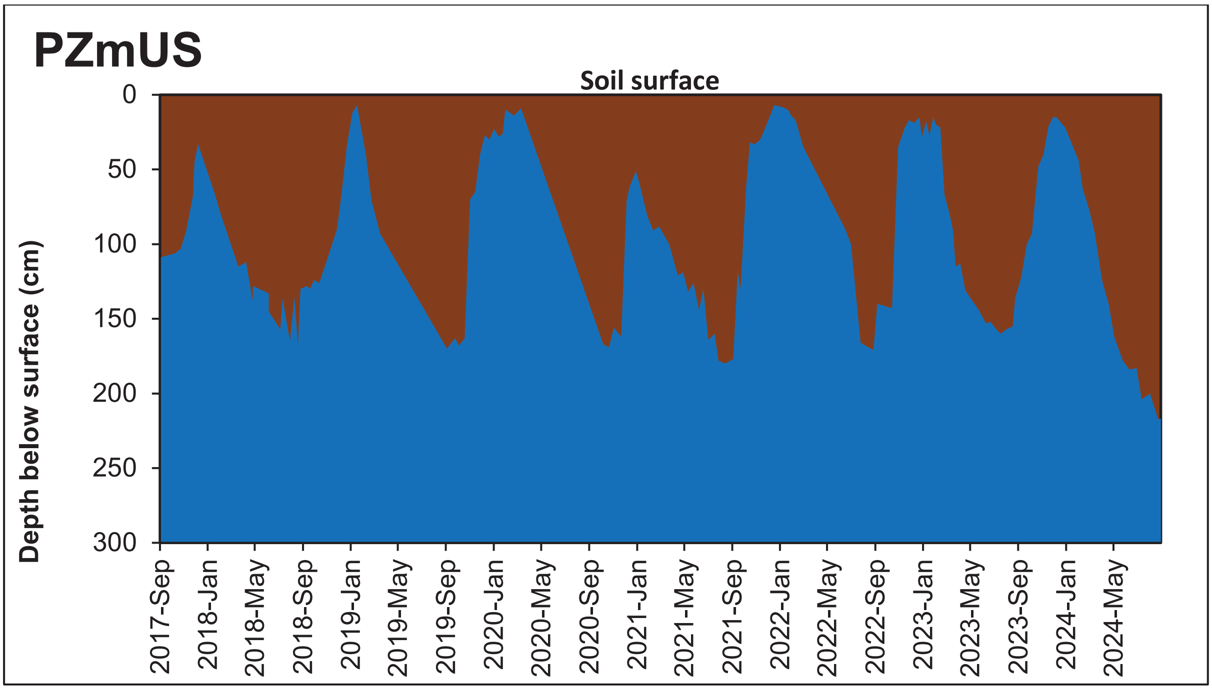

Figure 1-22: Water levels (blue) measured at the upstream piezometer starting in September 2017

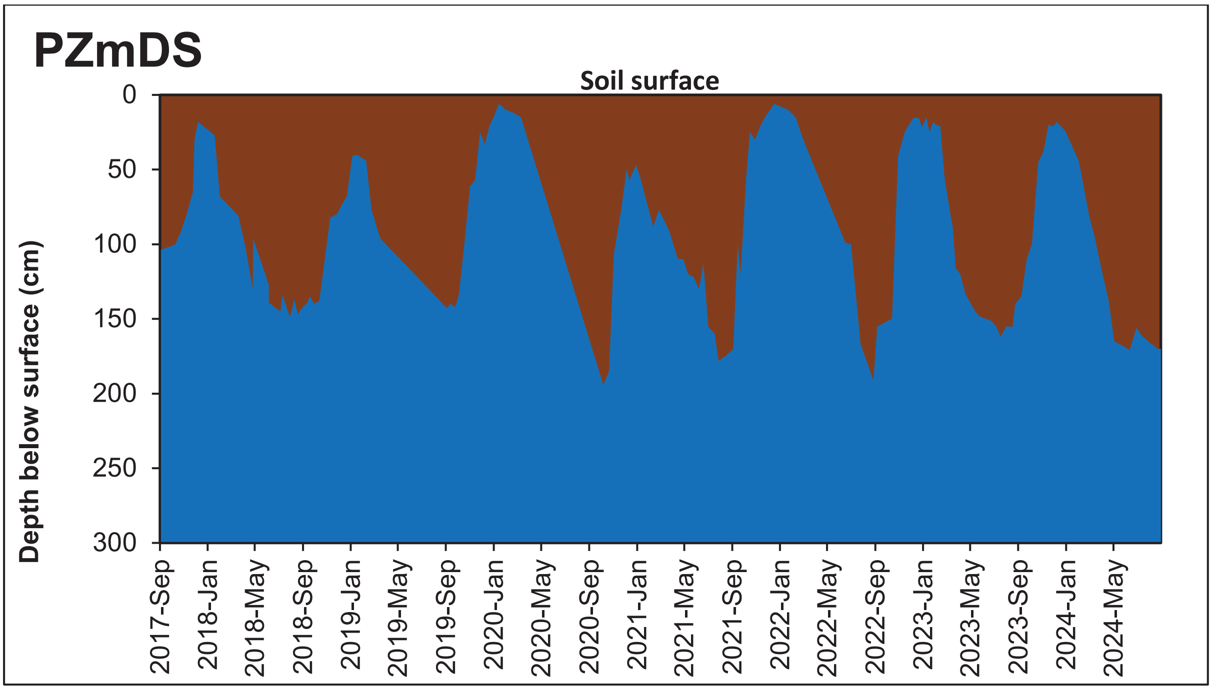

Figure 1-23: Water levels (blue) measured at the downstream piezometer starting in September 2017

Table 1-10: Summary of the average piezometer water quality for the 2022-2023 and 2023-2024 seasons

Parameter	Units	Piezometer			
		Upstream		Downstream	
		2022-2023	2023-2024	2022-2023	2023-2024
pH		7.5	7.2	6.2	6.8
EC	**(mS/m)**	88	97	104	112

1.9.1.2 Borehole monitoring

The groundwater environment was studied by analysing borehole water samples from and around the Unmined Pivot area. Boreholes 1 (BH 1) and 2 (BH2) are located on the well-drained eastern side of Unmined Pivot, and boreholes 3 (BH3) and 4 (BH4) are on the poorly-drained western side next to the stockpile. Boreholes 2 and 4 are shallow (10 m), while boreholes 1 and 3 are deeper (30 m).

A summary of the average borehole water quality is presented in Table 1-11. The average water pH in the boreholes was mostly circumneutral across all boreholes, with clear differences in element concentrations evident. This illustrates the benefit of multiple sampling points. BH4 seems to record the highest concentrations because it is shallow and sits in a wetland area where soluble elements are easily leached on rainy days.

Table 1-11: Summary of the four onsite boreholes at Mafube from 2016-2023

Parameter	**Units**	**Borehole1 (Deep upstream East)**	**Borehole2 (Shallow upstream East)**	**Borehole3 (Deep downstream West)**	**Borehole4 (Shallow downstream West)**
pH		6.0	5.7	6.7	7.0
EC	**(mS/m)**	12.1	7.8	93.7	333.6
Suspended Solids	**mg/L**	90.7	20.9	27.0	49.3
TDS		88.6	54.0	591.4	2134.7
Ca		5.4	2.7	32.4	73.8
Mg		4.2	1.9	18.3	72.1
Na		7.5	5.2	118.8	516.8
K		4.6	2.8	6.2	11.7
Cl		13.2	6.9	206.2	822.7
SO_4^{2-}		4.6	3.9	62.7	391.9
Total P		0.7	0.6	0.4	0.3
Total N		2.6	3.6	7.0	16.1
Al		0.1	0.2	0.2	0.2
Fe		0.1	0.1	0.2	0.2
Mn		0.4	0.0	0.0	1.5
Zn		0.0	0.0	0.0	0.1

Figure 1-24 presents SO_4 concentrations since the commencement of irrigation in 2017. The two downstream boreholes (BH3 and BH4) have shown marked increases in salinity at various stages. Although sulphate is the major contributor to salinity in the irrigation water, high concentrations of sodium and chloride are also present in these boreholes. Given that the concentrations of these elements in the irrigation water were very low and unlikely to have such a drastic effect on the groundwater, these solutes likely originate from another source. It is hypothesized that additional sodium and chloride was introduced into the groundwater by seepage from the nearby coal stockpile.

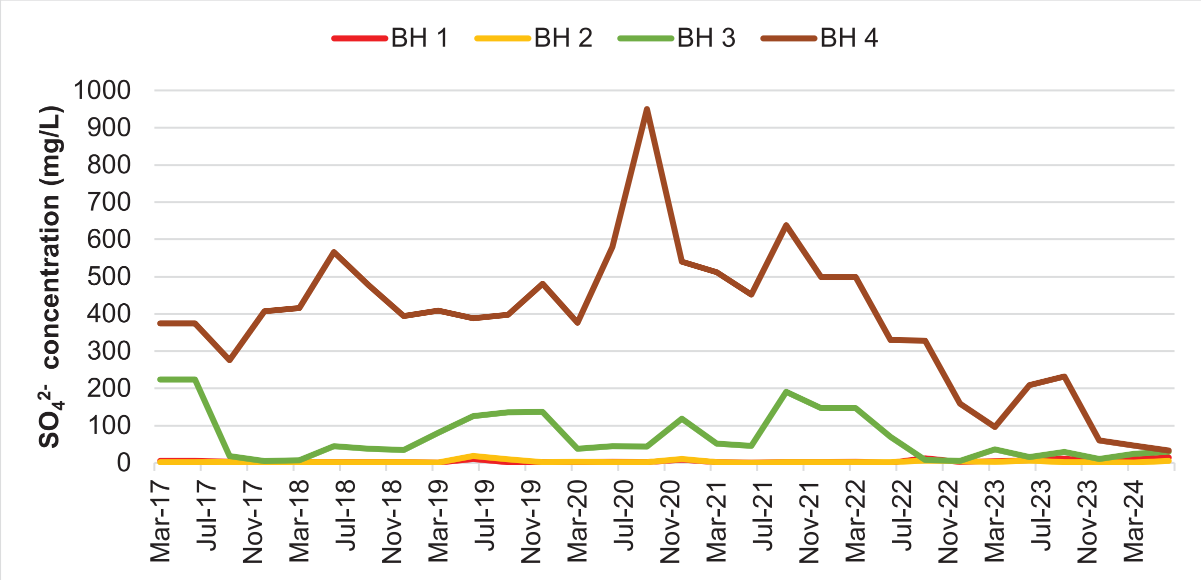

Figure 1-24: SO_4 concentrations from the boreholes at the Unmined Pivot

1.9.2 Surface water environment

Beestepan Dam was initially identified as a monitoring point to assess the potential downstream surface water impacts of irrigation with mine waters. A trigger value of a 20% increase above the average sulphate concentration between 2014 and 2017, before irrigation commenced, was set to stop irrigation if such exceedances could be attributed to irrigation. However, it was later realized that the dam is also downstream from one of the mine's coal stockpiles and a pollution control dam, making it difficult to attribute any changes in water quality solely to irrigation. Despite this concern, the threshold for sulphate concentration (642 mg/L) has not been consistently exceeded. The main indicators for water quality at Beestepan Dam are summarized in Table 1-12 and shown in more detail in Figure 1-25 and Figure 1-26.

Table 1-12: Average water quality at Beestepan Dam

Parameter		Oct'14 to May'17	Jun'17 to May'18	Jun'18 to May'19	Jun'19 to May'20	Jun'20 to May'21	Jun'21 to May'22	Jun'22 to May'23	Jun'23 to Jul'24
pH		7.1	8.1	7.9	7.7	7.8	7.6	7.1	6.9
EC (mS/m)		115	72.0	93.6	105.9	111.6	112.9	70.6	127.2
Na	mg/L	52	30.6	41.7	46.0	43.7	53.1	27.8	36.7
SO_4^{2-}	mg/L	535	291.3	376.6	402.6	447.4	502.9	208.4	594.4

From Figure 1-25, it can be seen that the pH has remained mostly circumneutral, becoming slightly alkaline at times. EC shows seasonal variation, increasing during the dry winter months and decreasing in the rainy summer when dilution occurs.

Figure 1-26 shows that the SO_4^{2-} concentrations have largely remained below the set threshold. Exceedances observed in 2022 and 2024 are suspected to be the result of seepage from the stockpile and/or spillage from the pollution control dam. The concentrations of the other ions remained fairly stable throughout the study period. However, there were slight increases in these ions that correspond to the increase in sulphate, which led to exceedances in 2022 and 2024. This supports the hypothesis that exceedances may be a result of seepage from the coal stockpile and/or spillages from the pollution control dam.

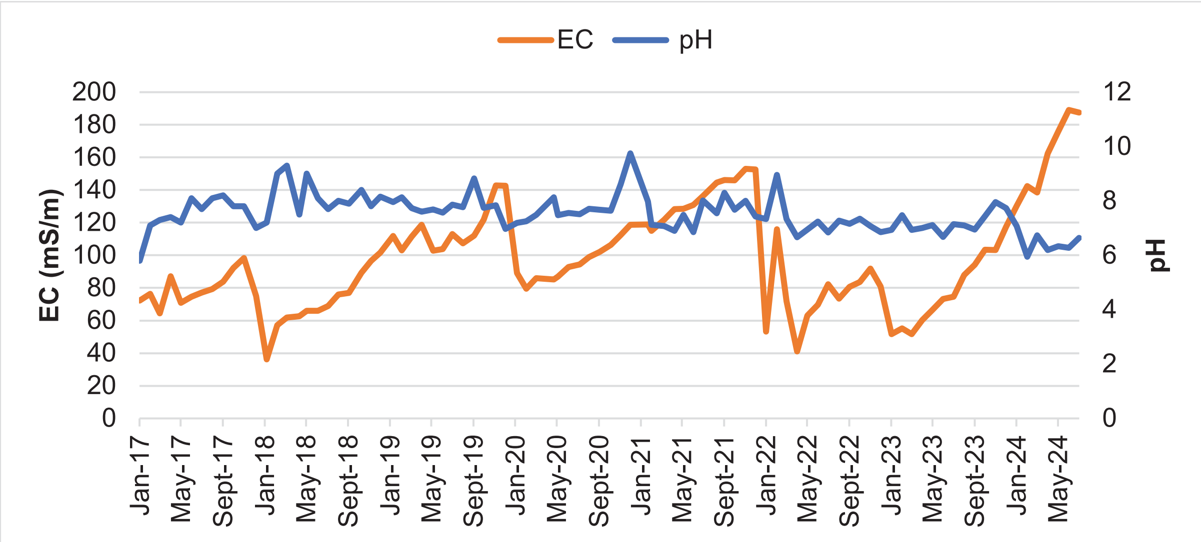

Figure 1-25: Beestepan Dam water pH and EC since 2016

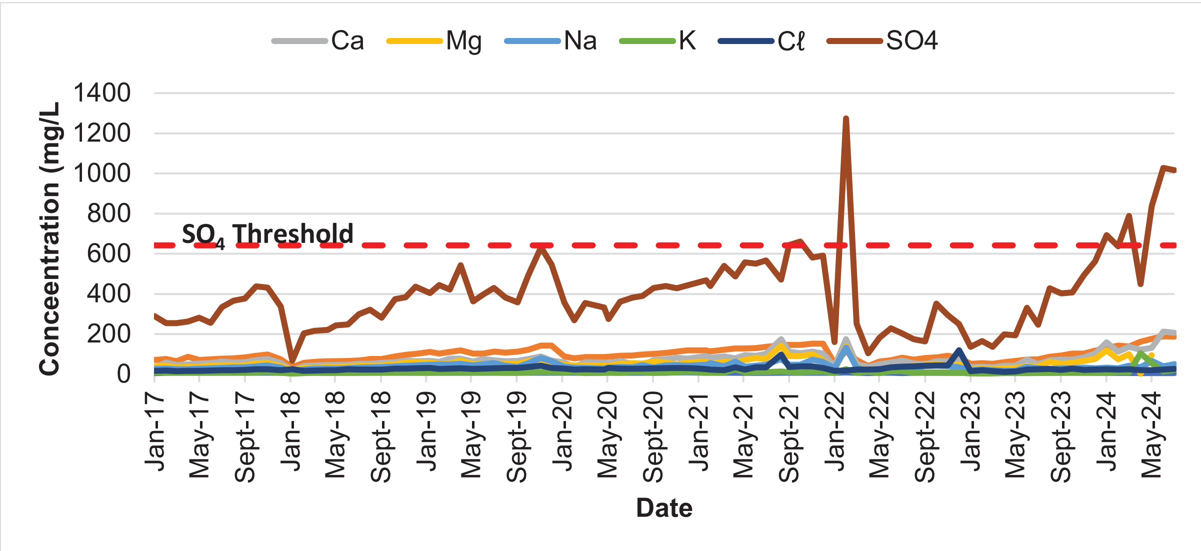

Figure 1-26: Concentrations of major anions and cations in Beestepan Dam since 2017, with SO_4^{2-} threshold indicated

1.10 Conclusion

Successful irrigation with untreated, circumneutral calcium and sulphate-rich mine water will greatly benefit farmers, mining companies, and surrounding communities by providing an additional source of irrigation water, creating an alternative and cost-effective mine water management strategy, and generating new job opportunities. Past studies have produced positive results, but only in the short term; therefore, longer-term studies like this are invaluable.

For mine water irrigation to be successful, it must be managed effectively, and close monitoring is crucial. It is essential to note that not all mine waters are suitable for crop irrigation. This trial has demonstrated that commercial-scale irrigation with untreated calcium and sulphate-rich circumneutral mine water is sustainable with minimal environmental impacts. The yields produced in the mine water-irrigated field were consistently much higher than those produced in the dryland area, making it more profitable. The crops produced were safe for consumption, with concentrations of elements of potential concern well below local and international food and fodder safety thresholds.

The Mafube Unmined Pivot is a valuable site for generating the long-term data required to make informed decisions about the use of mine waters for irrigation under specific conditions. Additionally, government and industry are aware of this demonstration site and view it as a case study proof of concept, making it an ideal location for regulators and potential irrigators to visit to see for themselves first hand.

With the success achieved at the unmined site over the years, the question arose of whether similar success could be obtained on rehabilitated land. Successful irrigation on rehabilitated land has important socioeconomic and environmental benefits. The conditions required to successfully produce agronomic crops on rehabilitated land, using mine water, are investigated in the next chapter.

CHAPTER 2: IRRIGATION WITH MINE-INFLUENCED WATER ON REHABILITATED LAND

Mpumalanga accounts for almost half of South Africa's high-potential arable land (Simpson et al., 2019). While coal mining generates a high income, by its very nature, it is not a sustainable practice. However, the legacy of mining is more permanent; therefore, land rehabilitation must be carried out properly at the end of the mine's life cycle. As such, the standards for the Land Rehabilitation Guidelines for South Africa (LaRSSA, 2018) were developed to ensure that rehabilitation is conducted to a standard that allows for the productive use of the land post-mining. If the level of rehabilitation is inadequate, issues such as land degradation may arise, resulting in a permanent decline in land productivity. The problem of land degradation is generally variable and differs from site to site; usually, this variation can also be observed within the same field.

Proper land rehabilitation has long been recognized as an integral part of closure planning in South Africa, as evidenced by guidelines for rehabilitation published in 1981 and 1983. The need for good rehabilitation was codified in the Minerals Act of 1991. This means that mining companies must make financial provisions for the rehabilitation of the land on which they mine and carry it out correctly to receive a closure certificate. The pre-mining land capabilities of mining areas are determined before mining commences, and targets are then set for the land capabilities of the same areas post mining. Thus, it becomes essential that rehabilitation is conducted to a level that enables these targets to be met.

The primary aim of mine land rehabilitation is to protect the environment and closely replicate pre-mining conditions. This is important because many of the coal deposits in Mpumalanga lie beneath high-potential agricultural lands, and so inadequate land rehabilitation makes coal mining in the region an even bigger threat to food production in the country than it already is. The rehabilitation process presents numerous challenges. Careful attention should be paid to minimize compaction, as this can greatly impact vertical water movement and the extent of the rooting zone. It is essential to produce a post-mining land surface that is resistant to erosion and has free drainage. Compaction can cause the formation of impermeable layers in the soil, which reduces water infiltration and limits drainage of the profile. This can lead to waterlogging and ponding in the field, especially in concave surface areas.

High-quality rehabilitated land presents a significant opportunity for irrigation using water affected by mining. The unmined land study has already demonstrated that field crops can be grown successfully on a commercial scale using untreated circumneutral void water. It has been demonstrated that this practice can yield crops that are safe for human and animal consumption, with yields that enable higher profits than those currently produced under dry land conditions. This success has been achieved while causing minimal, if any, measurable harm to the environment. This raises the question of whether this success can be replicated on rehabilitated land.

One of the notable benefits of using mining-influenced water on rehabilitated land is that all the excess water will accumulate in the pit below the field and will hence not end up in the groundwater or nearby surface waters. Although a substantial fraction of the salts applied through irrigation with calcium– and sulphate-rich mine water is expected to precipitate as gypsum in the soil profile, some salts will remain in solution and leach through the profile. It is, therefore, beneficial to determine the conditions under which rehabilitated land can be successfully used to produce agronomic crops with mine water.

This component of the study aimed to address four main objectives. Firstly, to understand how physical and chemical changes in soil properties caused by the land rehabilitation process affect crop performance. Secondly, to study the effects of irrigating rehabilitated lands using mining-influenced water. Thirdly, to examine how the physical properties of rehabilitated lands affect the irrigability of that field, and finally, to develop guidelines for the irrigability of rehabilitated lands.

2.1 Site history

The rehabilitated site, selected for this trial in 2016, is located in Mpumalanga Province, approximately 2 km NE of Mafube Colliery, 4 km N of the N4 highway, with a longitude of 29°45'59.85"E and latitude of 25°47'30.43" S. The main advantages of this site were its depth of topsoil, proximity to the mine water irrigation water source (Void 3), and easy access for the research team, thereby creating a safer working environment than is generally found on an active mine. Although only limited information was available regarding the timeline of the rehabilitation process at the site, satellite images from Google Earth indicated that mining was completed by 2016 and rehabilitation was completed in 2017. The original rehabilitation was to arable potential.

After selecting a suitable site to erect a centre-pivot irrigation system, Mafube Colliery proceeded to procure and commission the system's assembly. South32 collaborated with this endeavour by donating an old centre pivot that was not in use at one of their mines. Unfortunately, this pivot was not disassembled correctly, with many bolts and stays being removed with a cutting torch, causing considerable damage. The costs to refurbish this pivot were enormous, with the farmer responsible for this field estimating that it would have been easier and cheaper to install a new pivot. There were also delays in establishing the central foundation for this pivot and supplying electricity and water to the site. From the outset of this project, there were problems with insufficient water pressure to the pivot. Figure 4.5 shows the unassembled pivot in 2017 at the rehabilitation site.

After the assembly of the pivot, the area received heavy rainfall, which resulted in surface ponding of water in several depressions that had developed in the Rehabilitated Field. Figure 2-1 shows a Google Earth image of the pivot area in January 2019, where heavy water ponding is clearly visible in the north-western part of the pivot. High variability in soil colour is also visible, with the red/brown patches in the centre of the pivot indicating soil that had been recently added to the site.

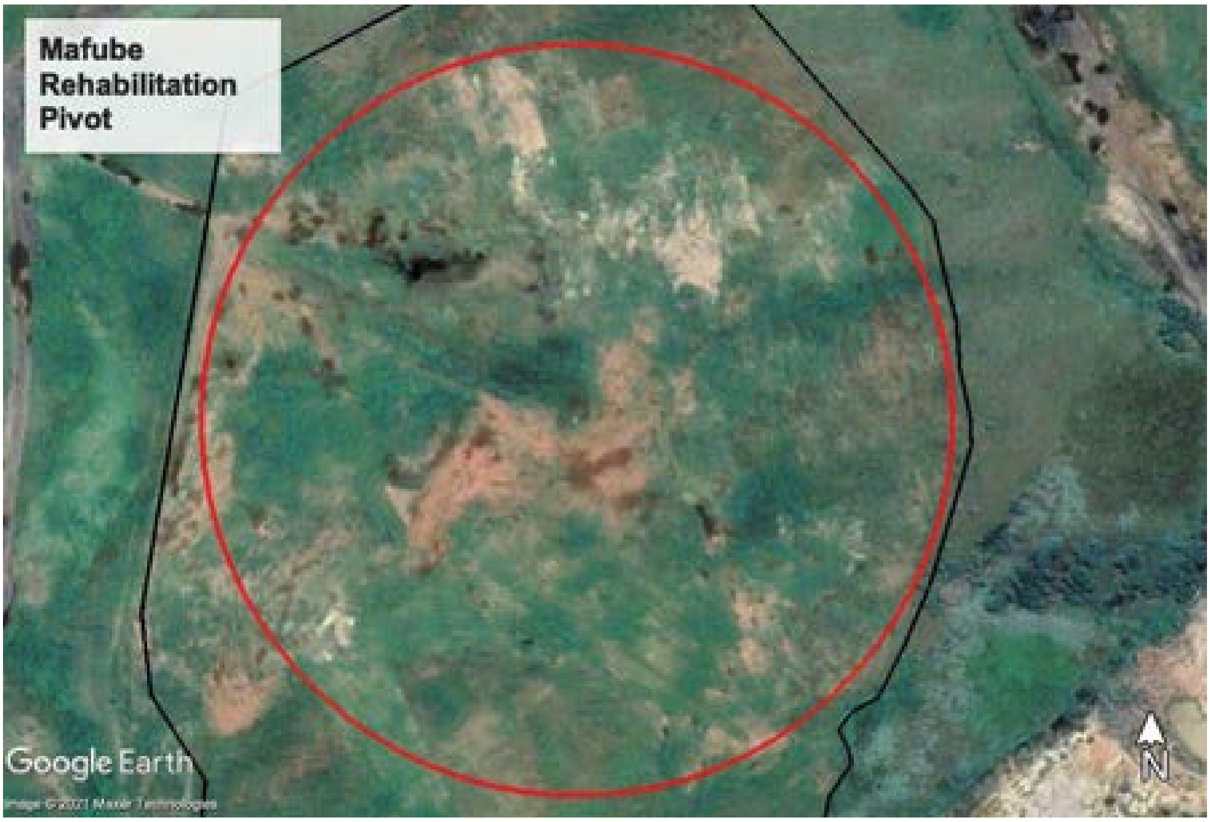

Figure 2-1: Google Earth image from January 2019 with heavy water ponding visible in the north-western part of the pivot.

The subsidence and settlement that occurred as a result of the heavy rainfall necessitated additional remediation work. Suitable stockpiled soil around Mafube was selected with which to fill the depressions. In 2019, large volumes of this soil were trucked in to fill hollows, and reshaping was done with a bulldozer and grader to create a free-draining surface. Figure 2-2 and Figure 2-3 show Google Earth images of the rehabilitated site from May and July 2019. Heaps of soil that were trucked in to fill the depression that caused the ponding are visible in Figure 2-2. This soil shown in Figure 2-2 was levelled, as can be seen in Figure 2-3. Unfortunately, the additional soil trucked in was not of the same quality as the stockpiled soil originally selected for this task. This resulted in marked soil variability throughout the site.

Figure 2-2: Google Earth image from May 2019 showing heaps of soil trucked in to fill additional depressions.

Figure 2-3: Google Earth image from July 2019 showing the levelled heaps of soil.

Large trucks were used to transport soil during the rainy season, leading to severe compaction in some rehabilitated areas. Initial efforts to remedy this compaction were undertaken using equipment that was unable to rip deep enough, resulting in soil disturbance and loosening of only the top 150 to 300 mm of the profile. A bulldozer with a better ripping configuration was subsequently hired, which was able to rip in excess of 400 mm. Only half of the pivot area was ripped using this bulldozer due to the start of the next rainy season.

Apart from muddy conditions, the land surface was too uneven for the pivot to make a complete circle safely, and the commercial farmer could not plant, as this would likely have resulted in equipment damage. The unevenness of the field affected the pivot's ability to run and delayed its commissioning. Subsequent soil cultivation and preparation for crop production reduced the unevenness to a state where planting and pivot maintenance were possible. Figure 2-4 shows the Google Earth image of the Rehabilitation Pivot taken in November 2020.

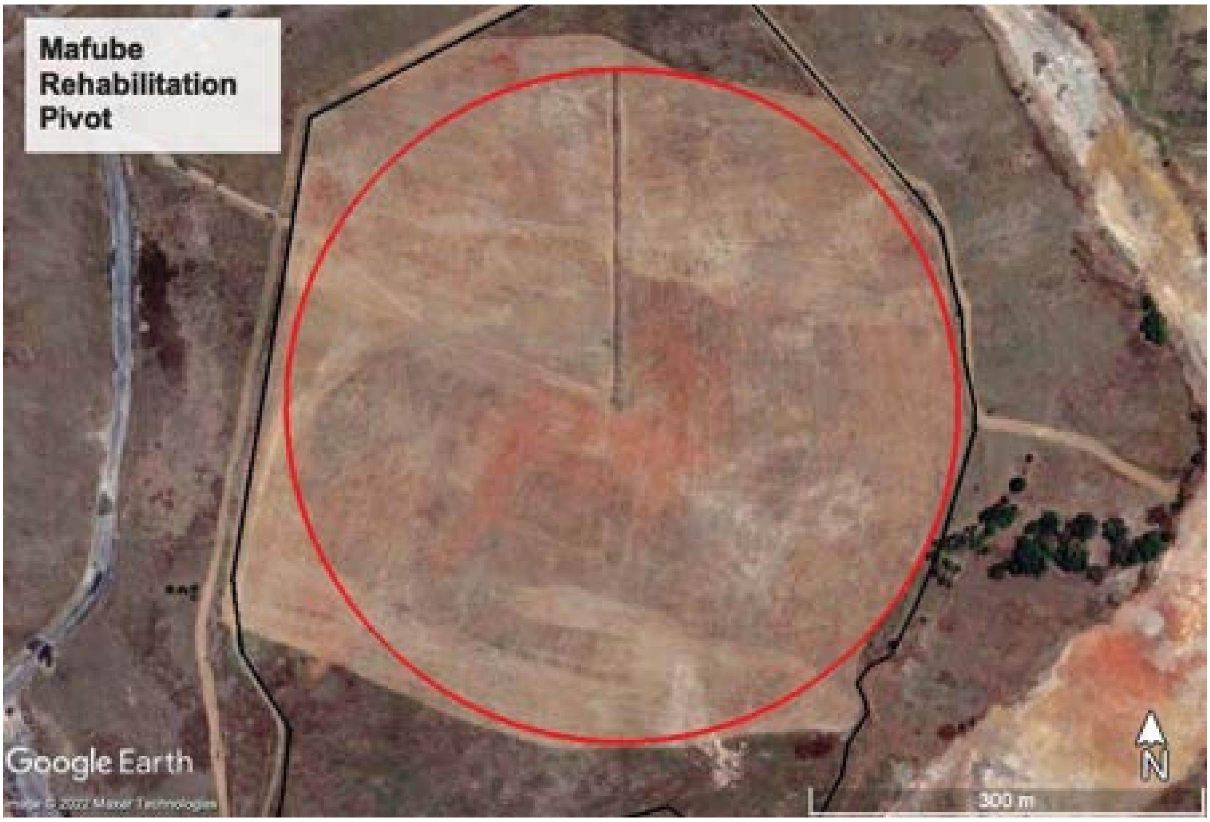

Figure 2-4: Google Earth image from the Rehabilitation Field, November 2020.

2.2 Baseline soil properties and vegetation cover

Before it was possible to grow crops commercially at the Rehabilitated Pivot, weed growth was considerable over the whole area in the summer, with variability in growth clearly visible. Major variations in bulk density, root growth, compaction, and soil chemistry were expected across the pivot area due to the variety of soil types introduced during the rehabilitation process and the severe compaction generated by the heavy equipment used to bring in the soil. It was therefore decided to evaluate in detail the effects of variations in soil chemical and physical characteristics on weed growth, as a surrogate for effects on crop growth that could only be measurable after successful cropping of this field.

2.2.1 Sampling and analyses

Soil sampling and measurements were done before any soil preparation started at the Rehabilitated Field. Soil physical conditions, chemical constituents, and vegetation yield (predominantly weeds) were measured and analysed.

Thirty-two sampling locations were selected over the Rehabilitated Field. At each location, the following readings or samples were taken:

- 4 soil samples were taken over the 0-300 mm layer; one from the centre of each of three 0.75 m x 0.75 m plant sampling squares, and a fourth sample from the centre of the sampling point (see detail Figure 2-5). These samples were mixed to generate 1 sample per site
- Soil samples from 300-600 mm and 600-900 mm depth intervals, one from the centre of each sampling point
- Three penetrometer measurements in each square, nine in total at each sample location
- Weed dry matter yield (0.75m x 0.75m) 3 samples per location
- Clod samples (for bulk density)

Figure 2-6 indicates the sampling points at the rehabilitated pivot, and Figure 2-5 illustrates where plant and soil samples and penetrometer readings were taken within each sampling location. Details of the sampling methods, sample preparation and analyses undertaken follow.

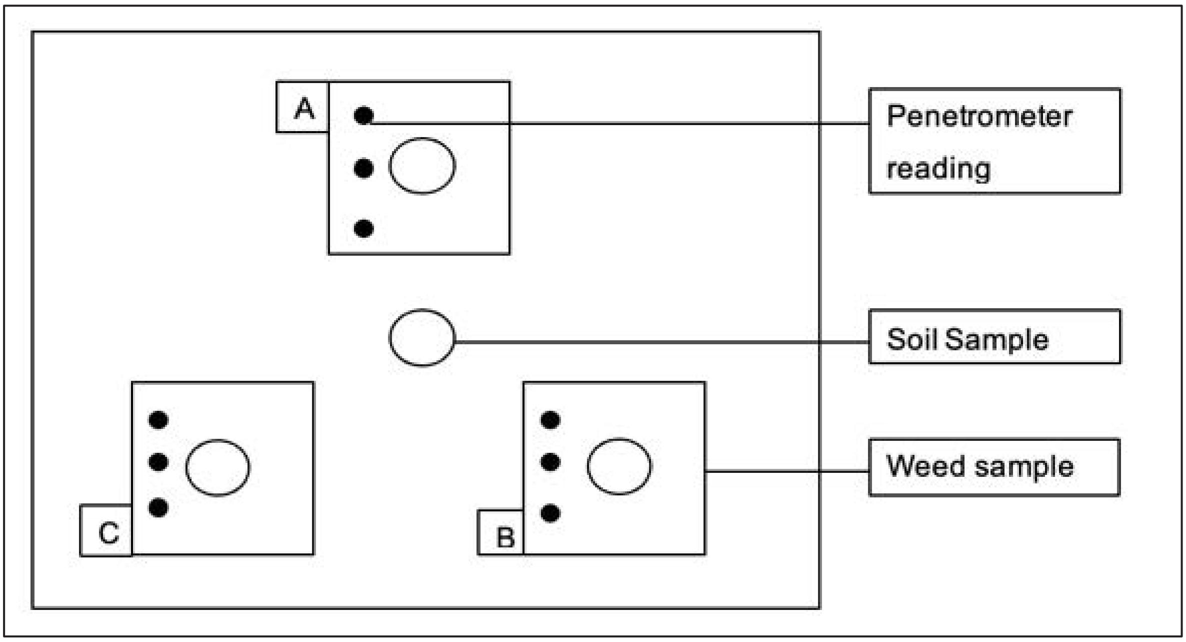

Figure 2-5: Typical distribution of monitoring points within a sampling location at the rehabilitation pivot

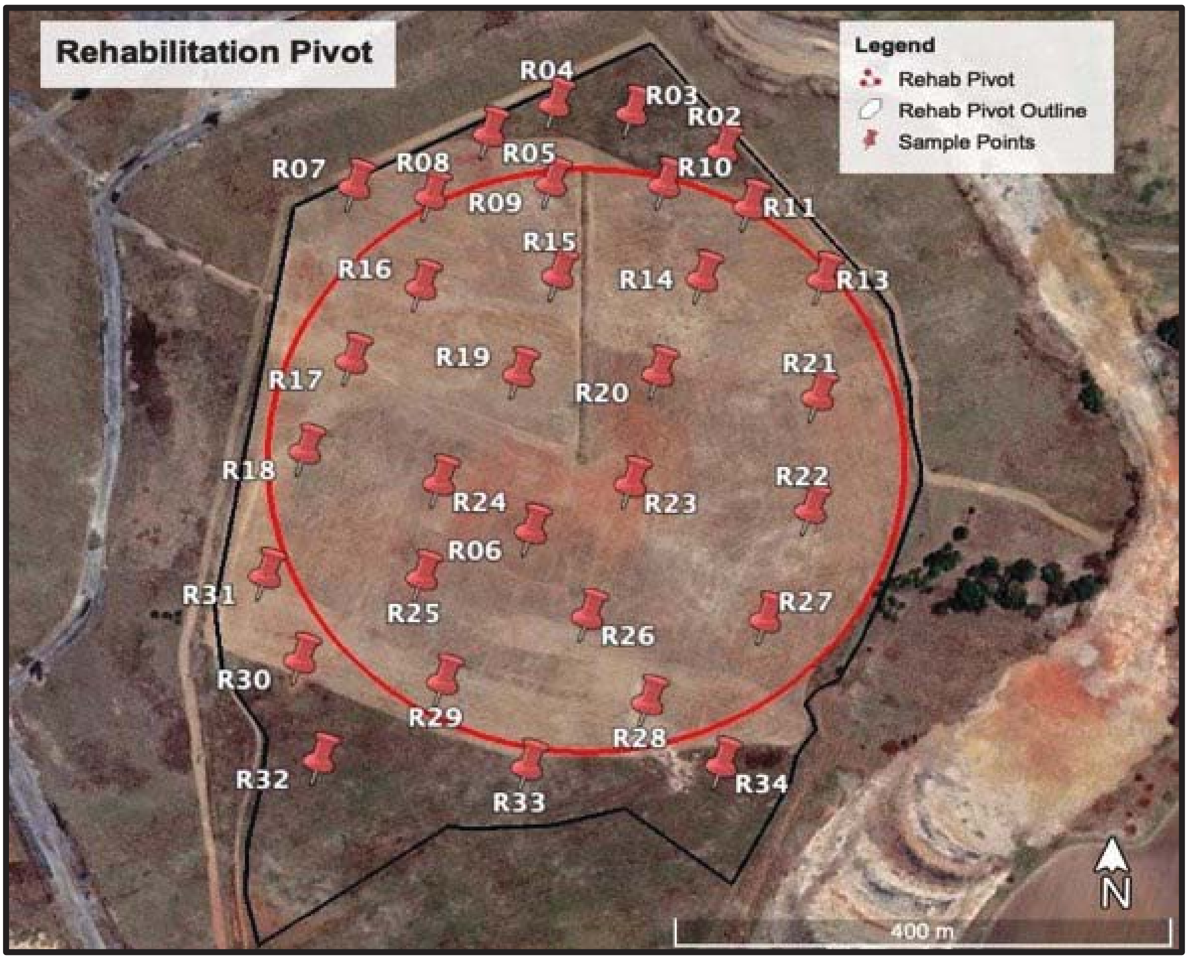

Figure 2-6: Sampling points at the rehabilitated field

2.2.2 Vegetation cover

The rehabilitated area was covered in weeds. Due to difficulties commissioning pivots, which led to the failure to establish crops, it was decided to use weed growth as an indicator of the relationship between soil chemical and physical characteristics and plant growth.

A total of 96 weed samples, three from each of 32 locations, were collected across the rehabilitated field, both inside and outside the irrigation area. Within each sample location, three steel squares (0.75 m x 0.75 m) were placed around the sample point. Square A was located 1m to the north, Square B, 1m southeast, and Square C, 1m southwest of the centre point. All plant material inside the square was cut directly above the soil surface and collected.

Figure 2-7 demonstrates plant material sampling. The composition of the weeds collected was 90% Cosmos (*Cosmos bipinnatus)*, and occasionally Johnson grass (*Sorghum halepense)*.

Samples were taken in April 2021 when most of the weeds were fully grown and mature. Samples were initially dried at 65 °C for 24 to 27 hours. Weighed material was returned to the oven every 4 hours until a constant mass was achieved. Masses of the samples were converted from grams per square meter (g/m²) to tons per hectare (t/ha). High variability was expected between samples and within samples, and this proved to be the case.

Figure 2-7: Steel square (0.75 m x 0.75 m) within which all plant material was sampled

Table 2-1 presents the mass of each 0.75 x 0.75 m sample, and the average mass of all three samples for each sampling location. There was notable variability in the average mass between sample locations, as well as high variability between the three samples at each location. Samples in Table 2-1 are sorted from highest to lowest average in t/ha.

Table 2-1: Weed mass of samples collected at the rehabilitated pivot in April 2021

Sample location	A	B	C	Average
	t/ha	t/ha	t/ha	t/ha
R20	6.5	8.3	7.3	7.4
R08	9.0	5.7	6.0	6.9
R22	6.1	5.6	8.1	6.6
R07	9.5	4.5	3.9	6.0
R16	4.0	7.8	4.8	5.5
R25	4.8	5.0	6.7	5.5
R11	8.3	4.1	3.9	5.5
R04	5.5	5.5	5.3	5.4
R05	6.0	6.4	3.6	5.3
R10	4.0	7.9	4.2	5.3
R19	4.9	4.2	6.2	5.1
R21	6.7	4.7	3.8	5.1
R06	4.3	4.6	5.9	4.9
R33	4.6	4.4	5.1	4.7
R03	5.8	5.1	3.2	4.7
R14	3.1	4.9	5.6	4.5
R30	5.3	4.6	3.6	4.5
R13	5.2	4.9	3.2	4.4
R09	3.0	4.0	6.1	4.4
R29	6.1	3.9	2.9	4.3
R27	3.7	4.3	4.7	4.2
R02	6.2	3.0	3.4	4.2
R28	4.0	4.5	3.4	3.9
R15	3.2	4.7	2.2	3.3
R32	3.5	3.3	3.2	3.3
R31	3.8	1.7	4.4	3.3
R23	4.9	1.7	3.1	3.2
R34	2.4	3.1	2.9	2.8
R26	3.5	1.9	2.7	2.7
R24	3.8	2.1	1.6	2.5
R18	2.3	1.3	1.2	1.6
R17	1.3	1.3	1.4	1.3

2.2.3 Soil Chemical Properties

Soil samples were taken for chemical analysis of the rehabilitated area. As shown in Figure 2-8, four soil samples were taken at each sample point at a depth of 0-300 mm. The four samples were mixed, and a composite sample was taken to represent the sampling location. High variability was expected.

Because these were the first soil samples taken after supplementary rehabilitation, and before the commencement of irrigation in this project, they provided a baseline from which changes over time with mine water irrigation could be detected. Analyses include pH (H_2O), organic carbon (Walkley-Black), as well as macro- and micronutrients using a Mehlich-3 extraction.

The short-term objective in this section was to determine if weed growth could be related to soil fertility. Figure 2-8 shows soil sampling, which was done directly after the weeds had been sampled. Sample R34 was contaminated during lab analyses and discarded.

Figure 2-8: Soil sampling in the rehabilitated field

Table 2-2 presents a summary of chemical analyses together with average total above ground dry matter of weeds (TDM) in t/ha. The table is sorted according to yield from highest to lowest.

Table 2-2: Summarized chemical analyses of the rehabilitated field, together with above ground dry matter yields of weeds at several sampling locations

Sample	pH (H_2O)	%C	P	K	Ca	SO4	Fe	TDM
			mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	t/ha
R20	6.1	0.5	10	101	369	28	37	7.4
R08	5.8	0.5	11	55	188	19	90	6.9
R22	6.1	0.5	5	55	519	34	71	6.6
R07	6.7	1.2	53	129	1218	22	78	6.0
R25	6.4	0.6	16	62	616	22	57	5.5
R11	6.4	0.6	6	96	579	24	55	5.5
R04	5.5	0.5	15	65	331	35	99	5.4
R05	6.2	0.5	6	96	576	32	51	5.3
R10	6.9	0.7	9	103	870	21	63	5.3
R19	6.4	0.7	7	147	819	23	78	5.1
R21	6.0	0.5	7	64	468	32	84	5.1
R06	6.4	0.4	5	38	497	22	41	4.9
R16	5.6	0.4	6	34	290	66	49	4.8
R03	6.4	0.5	5	77	579	30	59	4.7
R14	6.3	0.5	4	76	515	25	61	4.5
R30	5.5	0.5	15	65	331	35	99	4.5
R13	6.1	0.4	11	70	384	28	59	4.4
R09	7.1	0.6	4	128	745	21	94	4.4
R29	6.3	0.6	12	90	552	21	48	4.3
R27	6.4	0.5	5	77	579	30	59	4.2
R02	6.3	0.5	7	95	464	20	52	4.2
R28	6.4	0.6	7	78	631	24	68	3.9
R15	6.3	0.7	5	100	570	28	66	3.3
R31	6.1	0.4	3	32	396	35	93	3.3
R23	5.4	0.5	12	31	311	90	35	3.2
R26	6.5	0.6	14	152	849	26	63	2.7
R24	6.2	0.5	6	83	457	36	72	2.5
R18	6.6	0.5	2	47	481	49	58	1.6
R17	6.0	0.4	8	51	411	53	42	1.3
Average	6.2	0.5	9	79	538	32	65	4.6

Variability across the rehabilitated field, shown in Table 2-2, was high. For rehabilitated soil, the high variability was expected, but is uncommon for arable agricultural soil that is undisturbed by mining. This was also undoubtedly the result of different soil types being trucked in during the rehabilitation and levelling process.

Table 2-3 presents chemical analyses of soils from a pivot on unmined land adjacent to Mafube. Variability of these samples is much lower than that for the rehabilitated land.

Table 2-3: Summarized chemical analyses of the unmined land

Sample	pH	% C	P	K	Ca
			mg/kg	mg/kg	mg/kg
S01	5.5	0.9	105	96	529
S03	6.4	0.9	86	186	772
S13	6.2	1.0	74	88	775
S08	6.6	0.9	97	212	722
S11	5.9	1.1	63	138	735
S04	6.5	0.9	82	160	805
S02	5.6	0.9	104	90	523
S17	6.1	0.8	83	93	764
S20	6.6	1.3	48	248	1288
S21	6.1	1.0	71	130	870
S18	5.9	1.3	59	171	1061
S15	6.4	1.0	73	103	564
Average	6.1	1	79	143	784

The overall fertility of the rehabilitated field was much lower than that of the unmined and regularly cropped pivot. While pH from the rehabilitated land differed little from that of the unmined land, there are large differences in respect to organic carbon, P, K and Ca.

Comparing Table 2-2 and Table 2-3 shows there are clear differences between undisturbed (unmined) and rehabilitated mine land.

2.2.4 Soil physical properties

2.2.4.1 Compaction

The Dynamic Cone Penetrometer (DCP) is frequently used to provide a quick and simple indication of soil compaction (De Moraes et al., 2014). The DCP was designed in South Africa by Kleyen, and its original purpose was for pavement applications as an indicator of soil resistance (Mogotsi & Van der Merwe, 2017).

The Dynamic Cone Penetrometer consists of two shafts (16 mm diameter) coupled near the midpoint as shown in Figure 2-9a. The lower shaft contains a pointed tip that is driven into the soil. A sliding hammer on the upper shaft is dropped onto the anvil between the shafts, which drives the pointed tip into the soil. After each blow, the distance that the shaft penetrates into the soil is measured. These distances are used to determine soil strength.

The 8 kg free-falling hammer can be seen in Figure 2-9b. The hammer is lifted to the top of the upper shaft and allowed to fall 575 mm. Conducting the DCP test involves raising and dropping the hammer to drive the shaft into the soil. After each blow, the shaft penetrates the soil deeper and the distance is measured and recorded.

Within each sample location, nine penetrometer measurements were made, three within each square (as seen in Figure 2-5). Two of the sampling points, R28 and R30, were unreachable during penetrometer sampling due to high snake activity in those specific areas. Sample locations R3 and R4 were also not measured due to the penetrometer breaking and soil preparation commencing for the winter crop.

Penetrometer readings are summarized in Table 2-4, and presented as the number of blows required to reach certain depths.

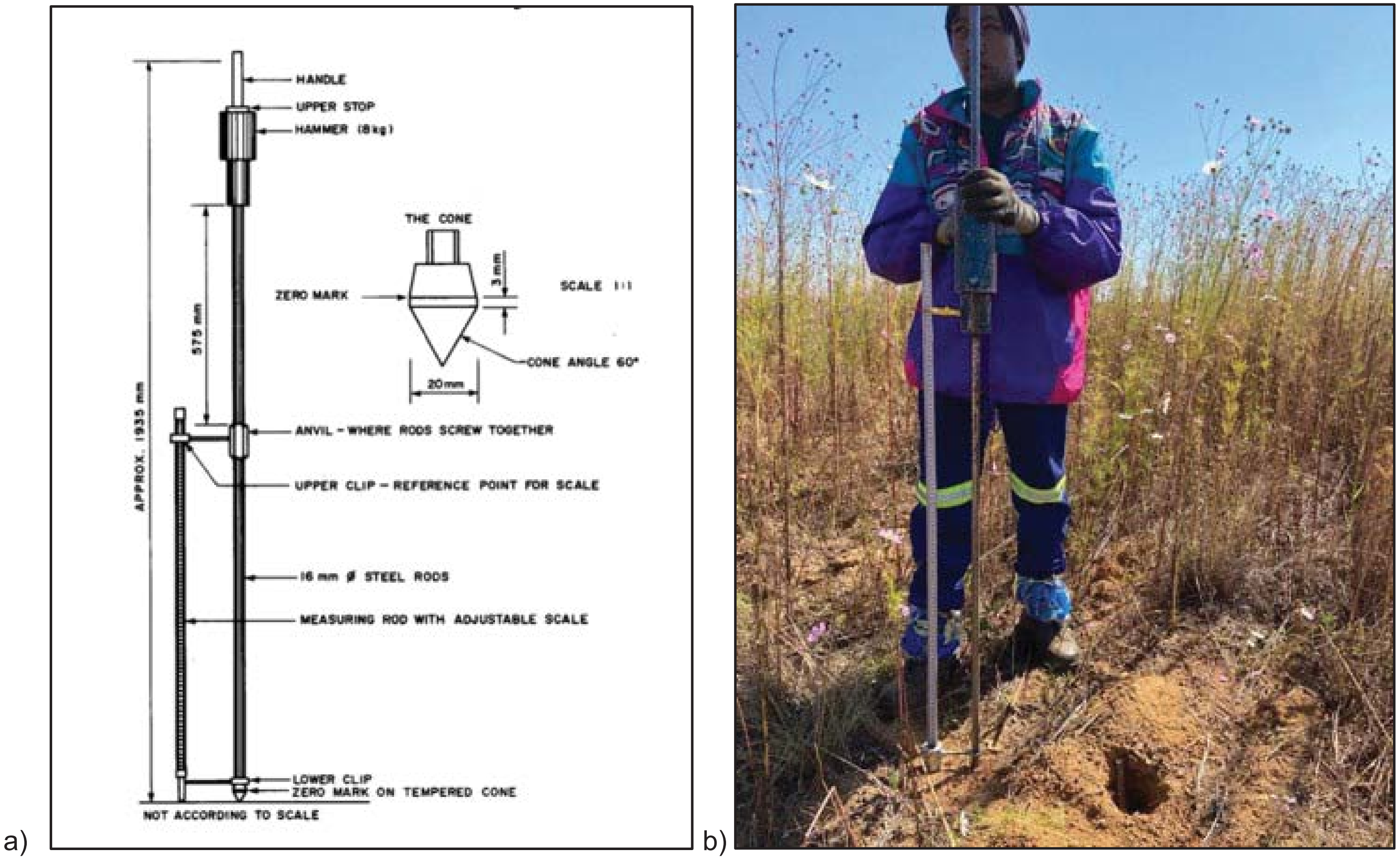

Figure 2-9: a) Schematic illustration of a Dynamic Cone Penetrometer5 and b) photograph of the penetrometer being used infield

[5] Image sourced from Paige-Green & Du Plessis, 2009

Table 2-4: Penetrometer readings (number of blows to specific depths) in relation to weed yield

Sample	Yield (t/ha)	Number of blows 0-100 mm	Number of blows 100-200 mm	Number of blows 200-300 mm	Number of blows 300-400 mm
R 20	7.4	1	7	11	18
R 08	6.9	1	4	8	6
R 22	6.6	3	7	13	20
R 07	6	1	5	11	14
R 11	5.5	1	2	6	10
R 16	5.5	1	1	6	10
R 25	5.5	1	3	*	***
R 05	5.3	1	3	5	4
R 10	5.3	2	5	13	***
R 19	5.1	1	3	14	32
R 21	5.1	1	2	5	8
R 06	4.9	1	6	8	6
R 33	4.7	2	*	*	***
R 14	4.5	1	5	9	11
R 30	4.5	-	-	-	-
R 09	4.4	3	8	9	10
R 13	4.4	3	8	10	12
R 29	4.3	1	5	8	*
R 02	4.2	3	4	6	6
R 27	4.2	1	3	12	16
R 28	3.9	-	-	-	-
R 15	3.3	1	5	11	*
R 31	3.3	2	*	*	***
R 32	3.3	1	3	9	7
R 23	3.2	2	6	*	**
R 34	2.8	2	4	7	18
R 26	2.7	1	3	6	16
R 24	2.5	2	*	*	*
R 18	1.6	**	**	**	**
R 17	1.3	2	**	**	***

*One penetrometer measurement per site reached refusal at this depth

** Two penetrometer measurements per site reached refusal at this depth

*** All three penetrometer measurements per site reached refusal at this depth

Table 2-5 represents sampling locations with clear restricting layers present and the depth of the layer. Six sample locations with no layer present are also included in the table as the data in Table 2-5 was used to predict the irrigable potential for different sampling sites in the rehabilitated area.

Table 2-5: Sampling sites showing clear indications of restricting layers (depth) and sites showing no indications of restricting layers present

Sample Site	Clear restricting layer present	Depth (cm)
R 02	No	-
R 05	No	-
R 06	No	-
R 09	No	-
R 18	No	-
R 29	No	-
R 20	Yes	30
R 13	Yes	30
R 19	Yes	30
R 27	Yes	25
R 16	Yes	60
R 25	Yes	30
R 15	Yes	20
R 17	Yes	15

2.2.4.2 Bulk Density

Bulk density measurements are routinely used to investigate different soil properties, most commonly to measure soil compaction. There are different methods for measuring soil bulk density. The clod method was used in this study due to limited time for sampling before soil preparation commenced. Soil was overturned with a normal garden fork at a depth of 0-250 mm. Clods were collected from the overturned soil at each sampling location and the wax method was used (Le Roux et al., 2019). Original clod sizes were around 500 g, but these were split into smaller clods for ease of analysis. This is the reason for the small clod sizes typically used in the wax method.

The volume is determined by coating a clod of known dry mass (oven dried at 65 °C for three days) with a water-repellent substance (wax) and by weighing it first in air, then again while immersed in a liquid of known density, in this case water. Bulk density can be calculated by dividing the mass of the clod with the volume of the clod.

Some of the samples were too poorly structured for the wax method to work. These clods simply fell apart when handled. This was the case for samples R3, R4, R10 and R32. Table 2-6 presents the bulk density obtained from the wax clod method.

Table 2-6: Bulk density at the measured locations sorted from highest to lowest yield

R Sample	Clod (g)	Clod Volume (cm3)	Density (g/cm3)	Yield (t/ha)
20	21.3	10.6	2.0	7.4
8	12.6	6.4	2.0	6.9
22	18.5	9.5	1.9	6.6
7	11.2	5.5	2.0	6
11	20.6	10.1	2.0	5.5
21	15.8	7.8	2.0	5.5
5	8.5	4.3	2.0	5.3
19	12.8	5.6	2.3	5.1
6	26.2	12.9	2.0	4.9
16	32.6	17.4	1.9	4.8
14	13.9	7	2.0	4.5
9	15.7	7.3	2.2	4.4
29	40.8	23.4	1.7	4.3
27	25.1	12.7	2.0	4.2
28	18.3	9.2	2.0	3.9
15	26.6	13	2.0	3.3
31	14.7	6.7	2.2	3.3
23	11.1	6.7	1.7	3.2
26	18.8	10.6	1.8	2.7
24	17	8	2.1	2.5
18	14.2	6.7	2.1	1.6
17	21.5	10	2.2	1.3

High variability was expected over the area but was not observed, with all samples exhibiting high levels of compaction. The high bulk density indicates overall compaction over the rehabilitated field.

2.2.4.3 Relationship between vegetation cover and soil chemical properties

Table 2-7 shows yield in relation to pH above 6.5 and below 6. Five of the samples have a pH above 6.5 and five are below pH 6. There was no indication that yield is related to soil pH. Potassium concentration decreased with the decreasing pH, but phosphorus did not seem to be related to pH.

Data from Table 2-7 indicates that weed yield did not decrease with soil pH values below 6. Chemical analysis showed very low P and K concentrations at R18, and one of these factors may be responsible for the low yield in this case.

Yields were higher with organic carbon at or above 0.7% than with organic carbon at 0.4% (Table 2-7). There was a correlation between organic carbon and potassium but no apparent correlation between phosphorus and organic carbon. Organic matter in soil is extremely difficult to increase permanently, and a "quick fix" is not possible. Once topsoil, which has a high carbon content, is mixed with spoil or other subsurface layers of soil that contain very little carbon, organic carbon will be diluted drastically. Research in temperate climates indicates that it may take up to 100 years to reinstate the organic carbon status of topsoil once it is lost.

Table 2-7: Yield of weeds for samples with soil pH above 6.5 and below 6.

Sample	pH	TDM	P	K
		t/ha	mg/kg	mg/kg
Above 6.5				
R09	7.1	4.4	4	128
R10	6.9	5.3	9	103
R07	6.7	6.0	53	129
R18	6.6	1.6	2	47
R26	6.5	2.7	14	152
Average	6.8	4.0	16	112
Below 6				
R 08	5.8	6.9	11	55
R16	5.6	4.8	6	34
R 04	5.5	5.4	15	65
R 30	5.5	4.5	15	65
R23	5.4	3.2	12	31
Average	5.6	5.0	12	50

Table 2-8: Yield of weeds for samples with soil %C at or above 0.7 and at or below 0.4

Sample	%C	TDM	pH	P	K
		t/ha		mg/kg	mg/kg
above 0.7					
R07	1.2	6.0	6.7	53	129
R19	0.7	5.1	6.4	7	147
R15	0.7	4.2	6.3	5	100
R10	0.7	5.3	6.9	9	103
Average	0.8	5.2	6.6	18	120
Below 0.4					
R13	0.4	4.4	6.1	11	70
R06	0.4	4.9	6.4	5	38
R31	0.4	3.3	6.1	3	32
R16	0.4	5.5	5.6	6	34
R17	0.4	1.3	6.0	8	51
Average	0.4	3.9	6.0	7	45

Yield was related to both phosphorus and potassium, particularly when P was below 4 mg/kg and K was lower than 40 mg/kg. Both these values would be recognised as being extremely low in cropping soils. The higher values of both constituents were related to higher weed growth. Table 2-9 shows yield related to phosphorus levels greater than or equal to 15 mg/kg and less than or equal to 4 mg/kg.

Table 2-9: Yields for samples with a phosphate concentration at or above 15 mg/kg and at or below 4 mg/kg

Sample	P	TDM	K	pH
	mg/kg	t/ha	mg/kg	
Above 15 mg/kg				
R07	53	6.0	129	6.7
R25	16	5.5	62	6.4
R 04	15	5.4	65	5.5
R 30	15	4.5	65	5.5
Average	27	5.4	80	6.0
Below 5 mg/kg				
R09	4	4.4	128	7.1
R 14	4	4.5	76	6.3
R31	3	3.3	32	6.1
R18	2	1.6	47	6.6
Average	3.3	3.5	71	6.5

Phosphorus concentrations over the rehabilitated field, which average 9 mg/kg, are generally much lower than what would be recommended for good arable cropping. Values at or below 4 mg/kg are particularly low and accordingly it is no surprise that yields with this level of soil P were significantly lower than yields with P of 15 mg/kg and above. Table 2-10 compares yields from soils with potassium levels below 40 mg/kg with soils with potassium levels in excess of 120 mg/kg.

Table 2-10 indicates that there was little correlation between soil potassium levels and weed yield, despite the concentration of potassium (40 mg/kg) being well below levels at which crop response would be expected. Potassium levels at the rehabilitated field were lower than in the unmined field.

There was great variability in yield that does not seem to be related to soil chemistry, and thus may rather be related to soil physical characteristics. For instance, Sample R17 had higher fertility than samples R06, R16 and R31, but a much lower yield. This may be the result of physical conditions affecting yield.

Table 2-10: Yields for samples with a potassium concentration of and higher and for lower than 40 mg/kg

Sample	K	TDM	P	pH
	mg/kg	t/ha	mg/kg	
Above 120 mg/kg				
R26	152	2.7	14	6.5
R19	147	5.1	7	6.4
R07	129	6.0	53	6.7
R09	128	4.4	4	7.1
Average	139	4.6	19	6.7
40 mg/kg and less				
R06	38	4.9	5	6.4
R16	34	5.5	6	5.6
R31	32	3.3	3	6.1
R23	31	3.2	12	5.4
Average	34	4.2	6.5	5.9

2.2.4.4 Relationship between vegetation cover and soil physical properties

Compaction normally results in restriction of root growth, and also downward movement of water and nutrients. Figure 2-10 represents the penetrometer readings of the four locations with the lowest yield and Figure 2-11 of the four locations with the highest yields.

Figure 2-10 and Figure 2-11 indicate that yield difference was related to soil resistance to penetration. Figure 2-11 indicates that a restricting layer was reached in every case before 300 mm, with some of the restricting layers starting at 100 mm depth. High yield samples showed some increase in resistance, but there were no fully restricting layers till a depth of

700 mm was reached. The soil resistance to penetration was much lower in the 200-600 mm depth interval in the higher yielding plots than in the low yielding plots. The four high yield locations are situated widely over the field and in a variety of soil types.

In the earlier section of this report where the relationship between soil chemical constituents and yield was examined, there were several low yields that could not be explained by their chemistry. For example, location R26 had high P and K concentrations compared to other samples, but lower yields. Figure 2-12 represents three average penetrometer samples from R26. Small and abrupt changes over a short depth indicates a boundary layer or compaction (over a longer distance) in the soil. The top 22 cm indicates normal soil with good penetration potential but below 22 cm, there was a clear boundary layer visible that indicated compaction.

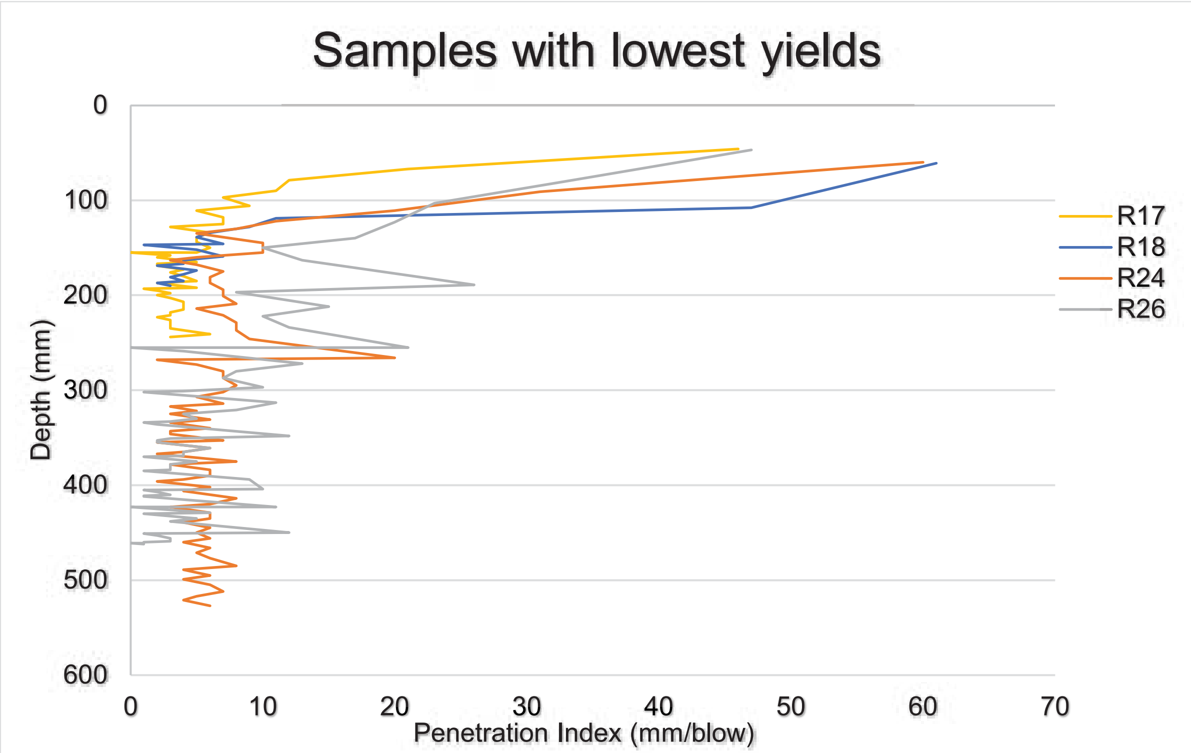

Figure 2-10: Average penetrometer readings of the four samples with the lowest yield

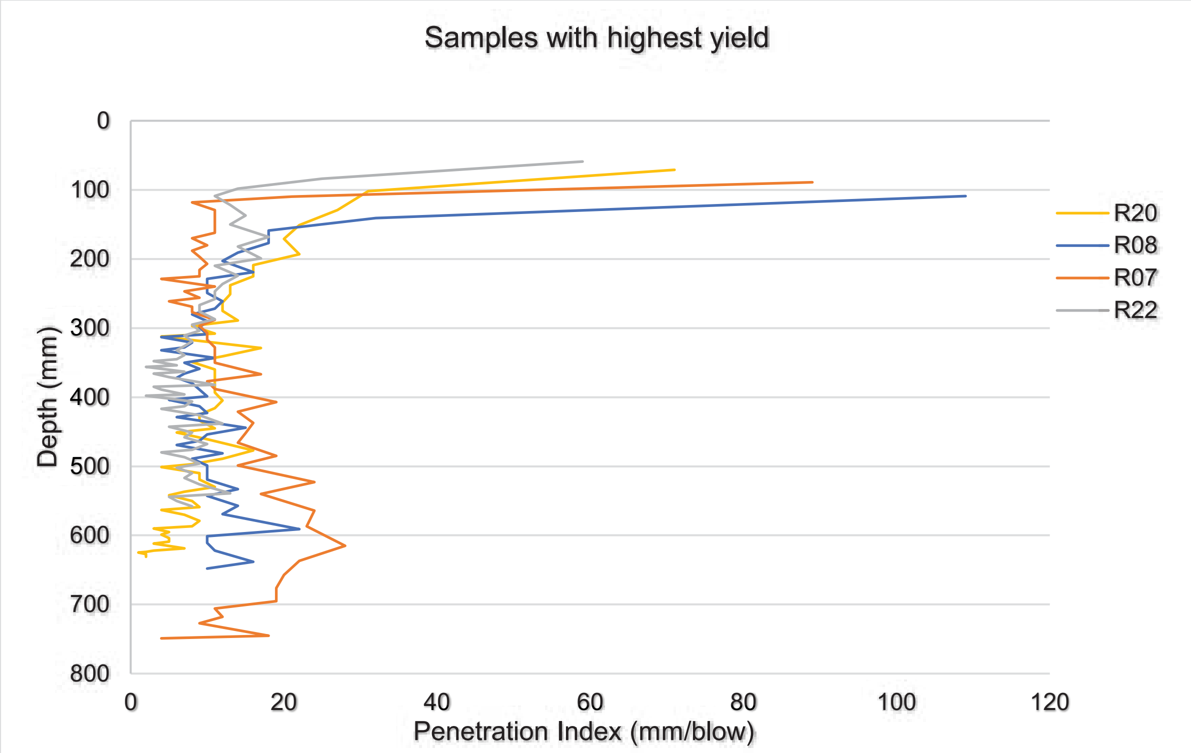

Figure 2-11: Average penetrometer readings of the four samples with the highest yields

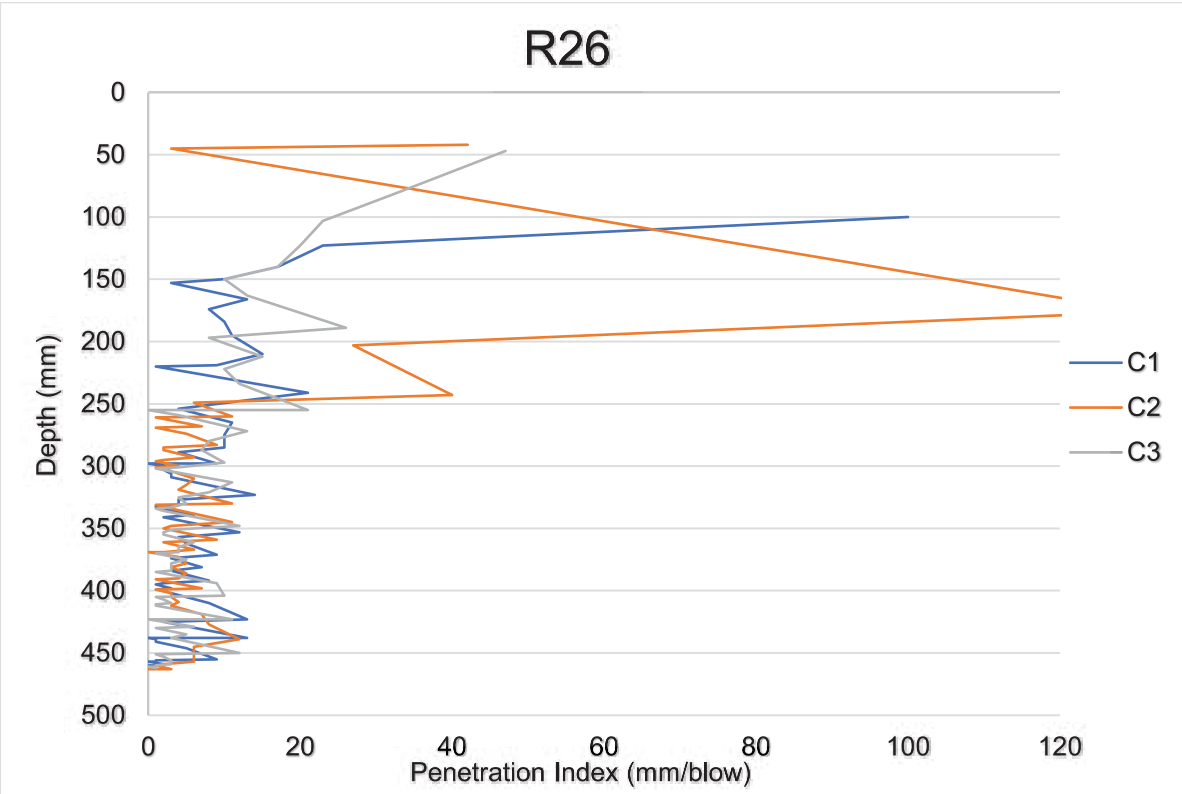

Figure 2-12: Penetrometer measurements at R26 indicating compaction

It is, therefore, possible that the lower yield from R26 was due to physical conditions and not fertility. The restricting layer in Figure 2-12 likely minimised the downward movement of water and/or roots. Figure 2-6 shows the location of the sampling points in the rehabilitated area. It is clear that at R26, soil was trucked in and levelled afterwards. This compaction was most likely due to the heavy machinery compacting loose soil, which had not been loosened sufficiently by ripping.

Figure 2-13 illustrates two average penetrometer results from R16 and two from R17 compared to each other. R16 had a yield of 5.5 t/ha, and R17 had a yield of 1.3 t/ha. R17 shows a restricting layer that starts from 10 cm and R16 only shows a layer below 60 cm. The lower yield of R17 may, therefore, be a result of compaction.

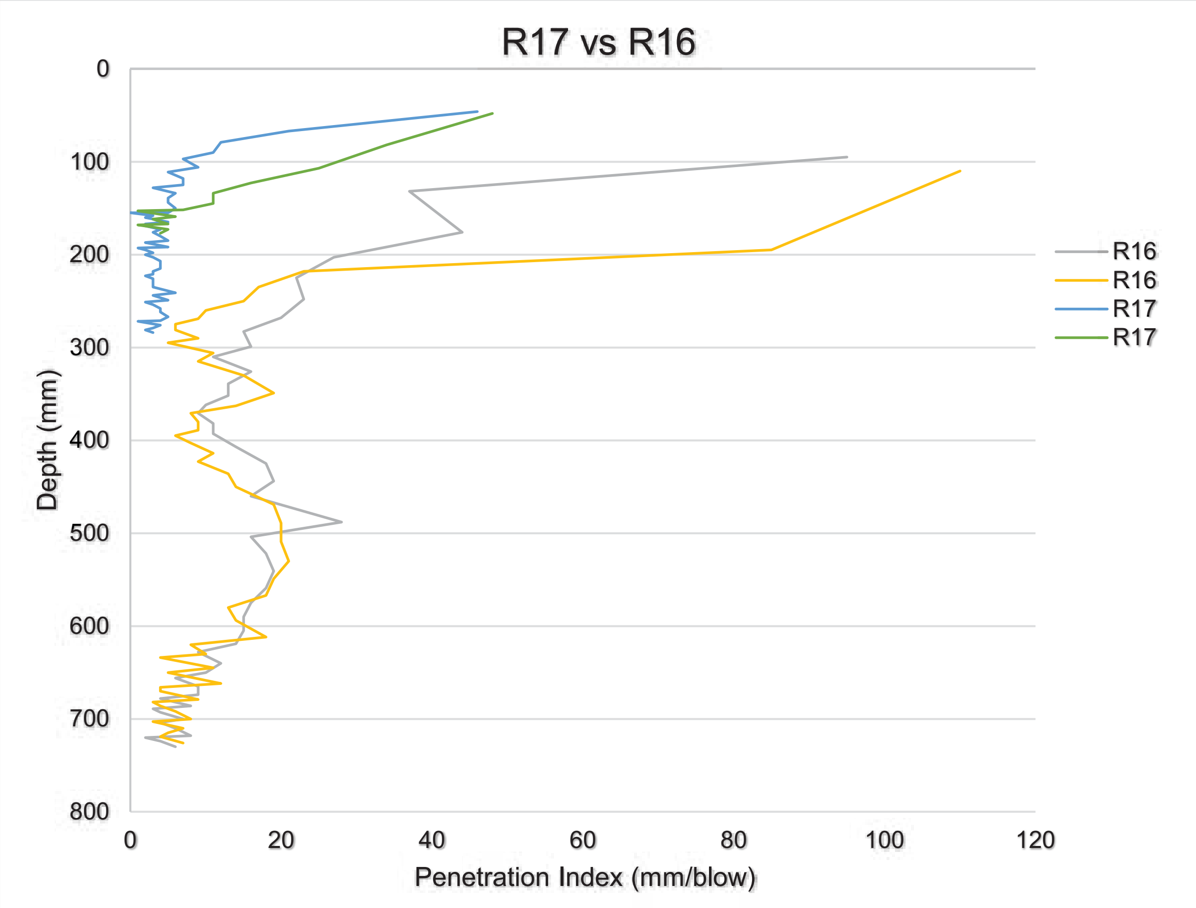

Figure 2-13: R16 and R17 penetrometer measurements compared

Water infiltration and root penetration were likely much better at R16 and provided a better medium for plant growth, even though the fertility was lower than R17. It can be concluded that for these two sample locations, plant growth was more affected by physical conditions than fertility.

2.3 Land capability classification of the rehabilitated site

Land capability refers to the potential of the land to support various land uses and is determined by the physical, chemical, and biological properties of the soil (LaRSSA, 2019). The South African Department of Agriculture, Forestry and Fisheries (DAFF) established land capability classes, as presented in Table 2-11. The classification used by the mining industries is indicated in the right column of Table 2-11. Pre-mining land capability is assessed before mining commences, and post-mining rehabilitation capabilities should meet the requirements and targets set in the pre-mining assessment. Agricultural land capability assessments are done prior to mining and provide the basis for determining the rehabilitation standard. Mines are obligated to ensure that there is no net loss in land capability (Limpitlaw et al., 2005).

Table 2-11: DAFF land capability classes compared with the four used by the mining industry (adapted from BFAP, 2015)

Land capability class	Soil depth (mm)	Classification by DAFF	Classification used by mining
I	>800	Arable land suitable for very intensive cultivation	Arable land
II	>700	Arable land suitable for intensive cultivation	
III	600-800	Arable land suitable for moderate cultivation	
IV	500-700	Arable land suitable for light cultivation	
V	400-600	Grazing land suitable for moderate grazing but not forestry	Grazing
VI	300-500	Grazing suitable for moderate grazing	
VII	100-400	Grazing land suitable for light grazing	
VIII	<100	Wildlife	Wilderness Wetland

The most important part of pre- and post-mining land assessment is a detailed evaluation of the land's capabilities, as it provides the only objective basis for establishing targets for post-mining land capabilities. This component of the study aimed to assess the land capability of the rehabilitated site and the suitability of the conventional classification system for assessing the irrigability of rehabilitated mined land. Additionally, an alternative approach to assessing the land capability that considers irrigability was used to classify the site.

With assistance from Red Earth Consulting, a detailed soil survey was undertaken to determine the land capability of the rehabilitated area for arable use. The system, as used by Red Earth, has been widely used in South Africa to determine the land use capability of rehabilitated land. A 50 m x 50 m soil sampling grid was used, and at each point on the grid, auguring was conducted using a 100 mm bucket auger to a maximum depth of 1.8 m. Figure 2-14 displays the 50 m x 50 m grid at the rehabilitated field.

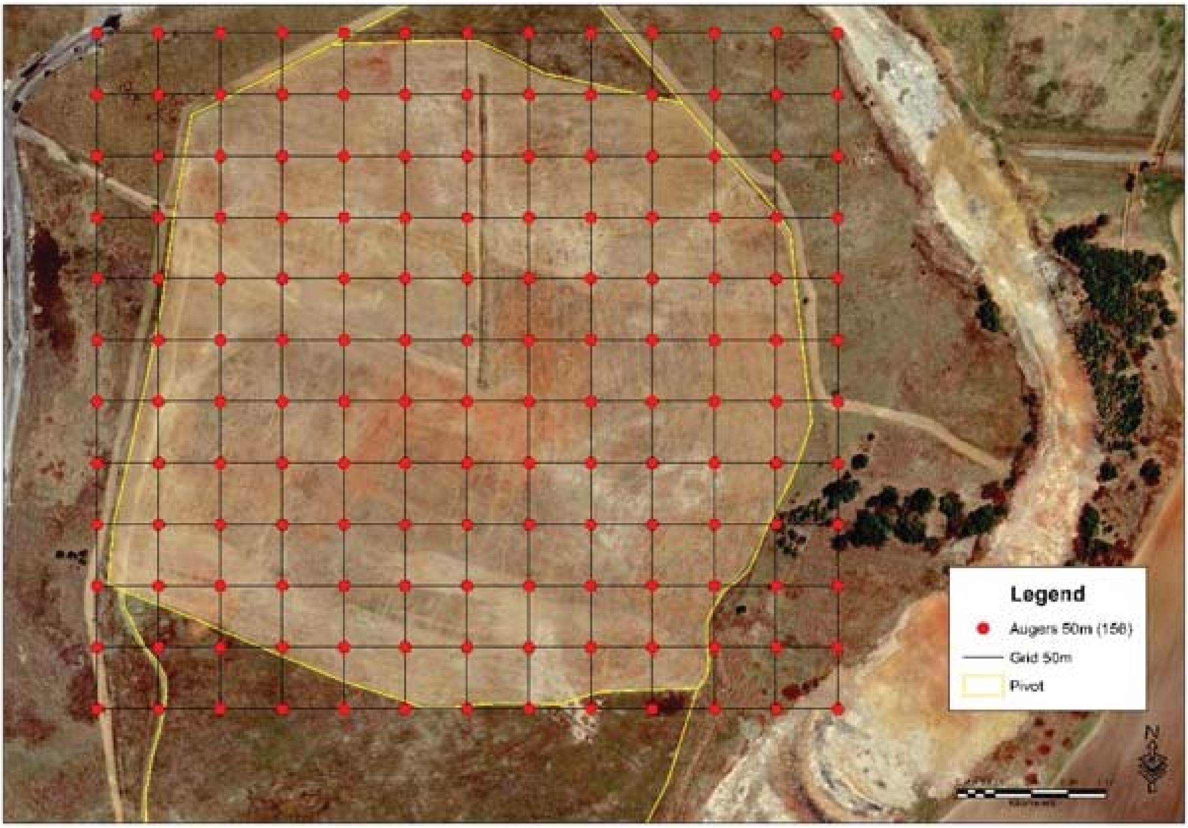

Figure 2-14: 50 m x 50 m sampling grid at the rehabilitated field

Data recorded on the field sheets included horizon name, depth, clay plus silt content estimate, sand grade estimate, colour code (according to the Munsell colour Chart), saprolite weathering status, structure, seasonal wetness hazard, cultivation factors and compaction/hard-setting. Figure 2-15 represents 1 of 120 soil auger points evaluated at the rehabilitated field site.

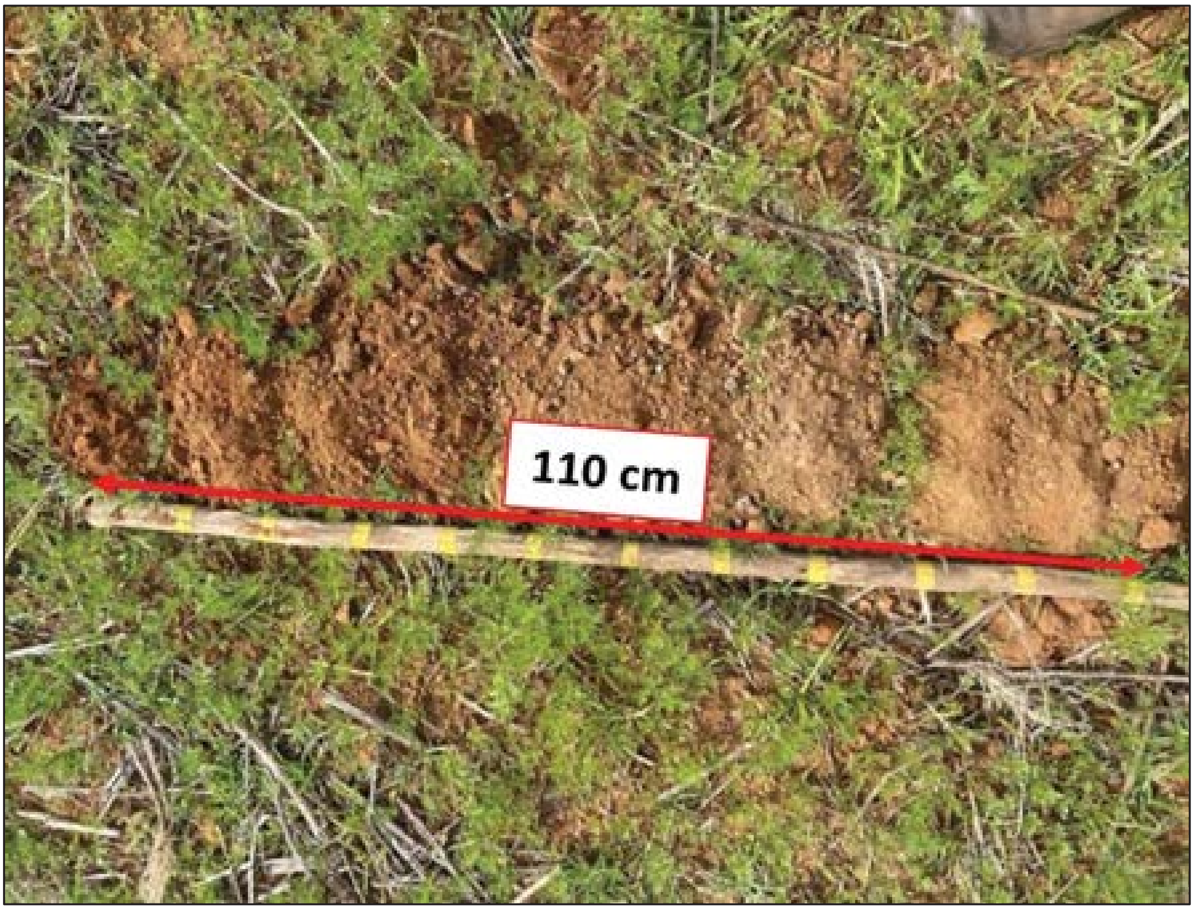

Figure 2-15: Soil extracted by auger at a single point from the surface to a depth of 110 cm.

After the soil surveying, maps were created from the results obtained in the rehabilitated field. The maps were produced at a 1:5000 scale and include the following:

- soil depth
- effective rooting depth (soil)
- cover soil type

These three maps were used to create the final land capability map, which includes arable, grazing, and evolving wetland classes.

2.3.1 Soil depth

Soil depth is a crucial factor that determines arable potential. Drainage past the root zone is crucial and is influenced by soil depth. In high-rainfall areas, drainage is required beyond the root zone. Without such drainage, a perched water table can form that may result in waterlogging and salinization of the root zone. With poorly rehabilitated areas, great variability in soil depth can be expected. The published mine land rehabilitation guidelines state that a soil reserve should be kept for amendments as necessary after rehabilitation. If this is not done, increasing soil depth will be very expensive once the rehabilitation process has been completed. Figure 2-16 represents a depth-to-spoil map (soil depth) of the rehabilitated area.

The variability in soil depth of the rehabilitated field is clearly visible. More than 70% of the rehabilitated field has a soil-to-spoil depth in excess of 900 mm, with less than 25% of the field exhibiting a depth ranging between 600 mm and 900 mm. Figure 2-16 indicates that at least 70% of the rehabilitated field meets the South African Institute of Irrigation (SABI) requirement of sufficient depth for classification as irrigable.

2.3.2 Effective rooting depth

Effective rooting depth (ERD) is limited by plant morphological characteristics or the depth of un-compacted soil, and in the case of rehabilitated mine-land, underlying spoil material is frequently relatively loose, or saprolitic material is incorporated within the rocky subsurface matrix, which can provide a medium that supports root growth. ERD determines the volume of soil that roots can explore to extract water and nutrients. Under dryland conditions, this may be the most significant factor in determining yield potential.

Soil texture also determines the effective rooting depth. The rehabilitated site at Mafube consisted of coarser material than the surrounding unmined soil. Generally, rehabilitated soil consists of more coarse material than it initially would. Coarse material can be defined as particles with a size ranging between 80 mm and 2 mm. Particle sizes between 2 mm and 0.075 mm are classified as sand. Coarse material may improve the infiltration rate of water in the soil, which can be beneficial where restricting layers and compaction are present, such as in the rehabilitated area. However, too high a content of coarse material decreases the water storage potential of the soil. Figure 2-17 indicates the ERD map created for the rehabilitated area. The ERD was determined by subtracting the percentage of coarse material from the soil depth of the profile. This map indicates the potential for water storage, which affects arable land potential. The irrigable potential is expected to be less affected by water storage potential than would be the case for dry land arable land.

As shown in the map in Figure 2-17, the water storage potential varies across the rehabilitated field. This is expected to result in variability in crop growth over the area under dryland conditions. The map in Figure 2-17 is expected to affect irrigable potential differently as the water in the profile can be easily maintained with irrigation. This demonstrates the significance of irrigation to provide more optimum soil conditions for growth and increasing yield potential.

Figure 2-16: Depth to spoil at the rehabilitated area

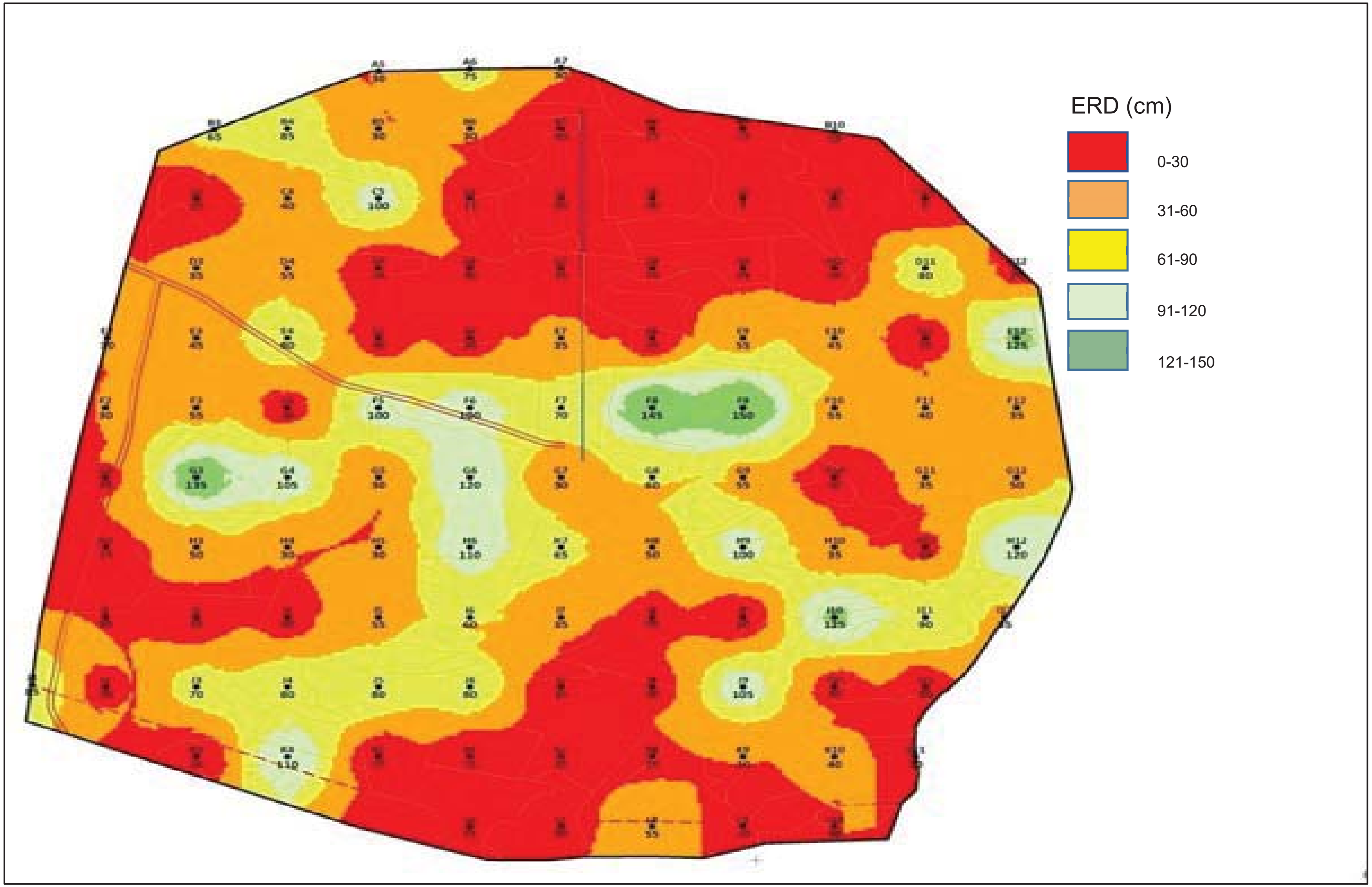

Figure 2-17: Effective rooting depth estimate for the rehabilitated field

2.3.3 Soil cover types

Soil cover types for rehabilitated fields tend to exhibit greater variability than undisturbed fields. Better rehabilitation practices will result in lower variability and more uniform soil cover. Table 2-12 represents the range of cover soil types and Figure 2-18 the distribution of the cover soil types over the rehabilitated field. Each soil type has its own unique characteristics, which differs in physical and chemical properties, contributing to the high variability of the field.

Table 2-12: Cover soil types at the rehabilitated field

COVER SOIL TYPES (INDICATED RANGE)			
Code:	**Description:**	**Code:**	**Description:**
Kr	Kandic red	Ky	Kandic yellow
Ny	Neocutanic yellow	Ni	Neocutanic intermediate
P	Plinthic	Nd	Neocutanic dark
G	Gleyic	Sy	Saprolitic yellow
		Sg	Saprolitic grey

Infiltrability and soil chemistry vary for each soil cover type and react differently to climate and irrigation conditions. Soil structure that is stable in water, in other words not dispersing, is preferable, or else soil crusting can develop. Fine textured soil, such as high silt or clay soils, are vulnerable to crusting. Crusting is discussed in more detail later in the chapter.

The areas marked in dark blue (gleyic) in Figure 2-18, are areas where a G-horizon was placed on the topsoil. This will limit water infiltration in these areas and most likely result in waterlogged topsoil, restricting aeration and infiltration into the soil. Low growth and yield potential are expected from these areas.

This is expected to be more of a problem in the high-rainfall summer than in the dry winter. Most gleyic areas were created when soil was trucked in after the rehabilitation process to fill up depression areas. In all of the gleyic areas, Ky (kandic yellow) soil was found beneath the top horizon, which is far more suitable for arable and irrigable conditions.

A map illustrating the arable land capability of the rehabilitation field was created by combining the soil cover type map and the ERD map. Table 2-13 shows the land capability classes and descriptions for each class for this dryland classification.

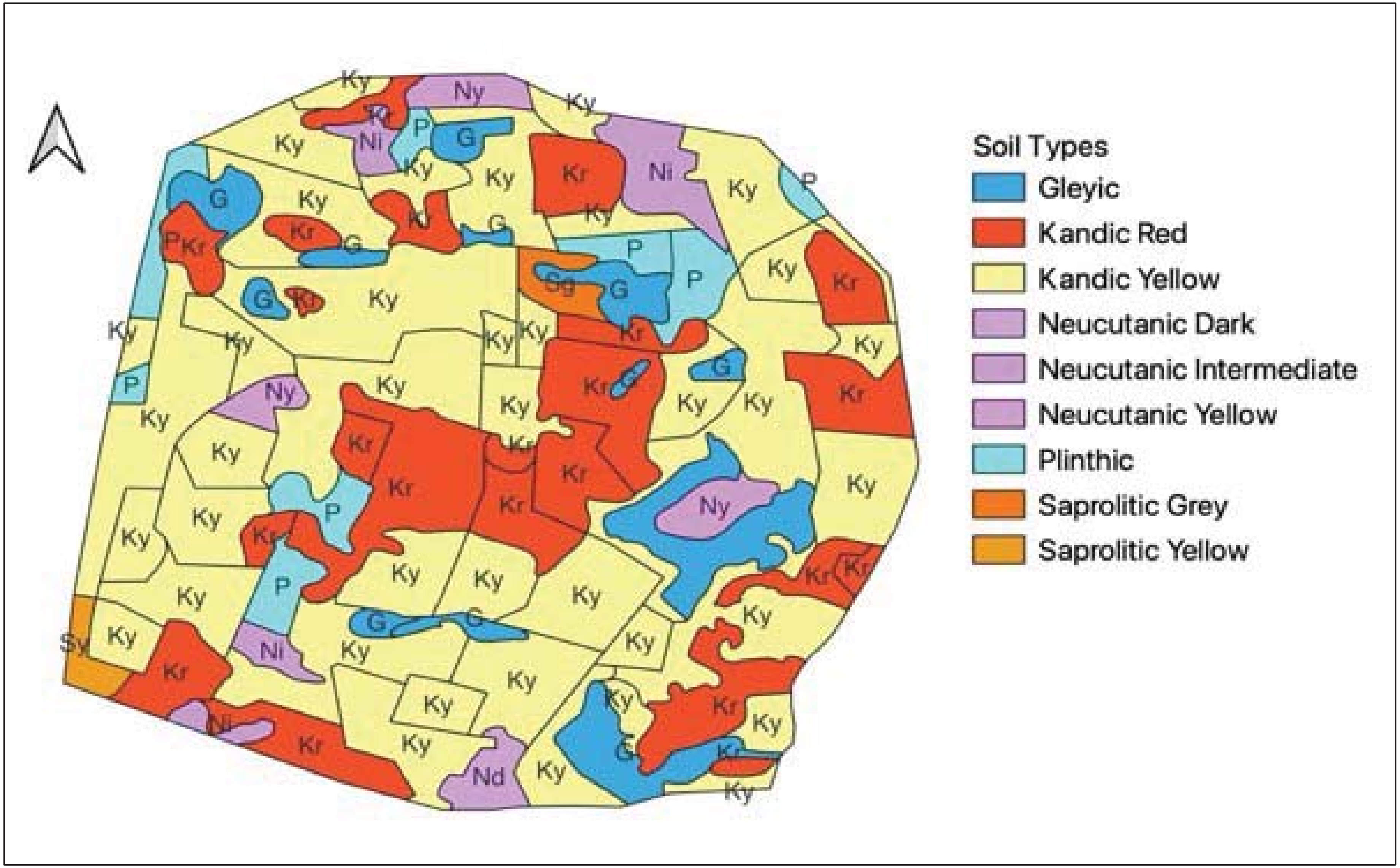

Figure 2-18: Soil cover types at the rehabilitated field

Table 2-13: Land capability classes at the rehabilitated field

Map Notation	Description	Explanation	Area			
			ha	%	ha	%
A	Arable	AERD > 60 cm	12.5	48.5	14.9	57.6
A-G	Arable - transitional Grazing	AERD 60 cm	1.9	7.4		
A-Wh.sp	Arable - transitional Wetland Human (soft plinthic)	AERD > 60 cm. Plinthic (soft plinthic B-horizon - with raised clay content - may prevent/limit rooting to deeper horizons) in top **40 cm** [Arable]	0.5	1.78		
G	Grazing	AERD 25-59 cm	5.2	20.2	5.21	20.2
Wh.sp-G	Wetland Human (soft plinthic) - transitional Grazing. i.e. Man-Made Wetland	AERD 25-59 cm. Plinthic (soft plinthic B-horizon - with raised clay content - may prevent/limit rooting to deeper horizons) in top **30cm** [otherwise Grazing]	1.11	4.3	2.2	8.7
Wh.sp-A	Wetland Human (soft plinthic) - transitional Arable. i.e. Man-Made Wetland	AERD > 60 cm. Plinthic (soft plinthic B-horizon - with raised clay content - may prevent/limit rooting to deeper horizons) in top **30 cm** [otherwise Arable]	1.1	4.4		
Wh.gc	Wetland Human (gley). i.e. Man-Made Wetland	ERD < 30 cm. Gleyic (G-horizon) in top 30 cm [will definitely prevent/limit rooting to deeper horizons; so AERD not indicated]	3.5	13.5	3.5	13.5
TOTALS			**25.8**	**100**	**25.8**	**100**

* AERD – Arable effective rooting depth

Figure 2-19 represents the land capability map for the rehabilitated area. Soil cover type contributed the most towards the capability classes, except where soil depth or ERD showed signs of high clay content in the top 0-60 cm layers, thus creating a duplex soil profile. Duplex soils occur when there is an abrupt change in texture between layers. The abrupt change can occur between low upper horizon clay and high lower horizon clay, or between high upper horizon clay and low lower horizon clay. It is the change in texture that minimizes water flow across the horizon change. Duplex soils are, in most cases, unsuitable for irrigation due to the low infiltration rate caused by the subsoil layers. The legend in Figure 2-19 is described in Table 2-13.

The map in Figure 2-19 indicates the land capability according to arable standards, where 57% is regarded as arable, and 20% as grazing. Only 13% of the field is classified as problematic, where water infiltration and root penetration are expected to be minimal. This is due to the high clay content (G horizon) in the surface layer. Water infiltration through a G-horizon is expected to be poor due to the high clay content. This can create an impenetrable layer, which will restrict water infiltration.

It is important to note that land classified as arable is not necessarily irrigable. Irrigable and arable land capability is expected to be different in the rehabilitated field. The land capability map is derived from soil properties that relate to the potential for arable production. Infiltration and good drainage are crucial properties for both dryland and irrigated agriculture, and are determining factors in selecting irrigable sites.

Two possible issues or shortcomings were identified with the dryland classification methodology for predicting the suitability of a site for irrigation. Firstly, the topography of the area is an essential factor in determining the irrigable potential, especially in rehabilitated areas where secondary subsidence is likely to occur within a few years after initial rehabilitation. Topography significantly affects water flow pathways, and areas prone to ponding may develop. Describing surface flow paths from the topography of an area can be regarded as the first step in determining the suitability of an area for irrigation, and this is not considered in the production potential assessment described above.

The second shortcoming identified was the presence of restrictive layers in the profile. Compacted layers in the profile are expected to affect root growth, infiltration and drainage. The penetrometer is a valuable tool to identify restricting layers in the profile. Adequate ripping should decrease the effect of compacted layers in the profile. The results of this chapter were used to classify monitoring points into different categories, which are used to determine the factors that influence the irrigability of a rehabilitated field.

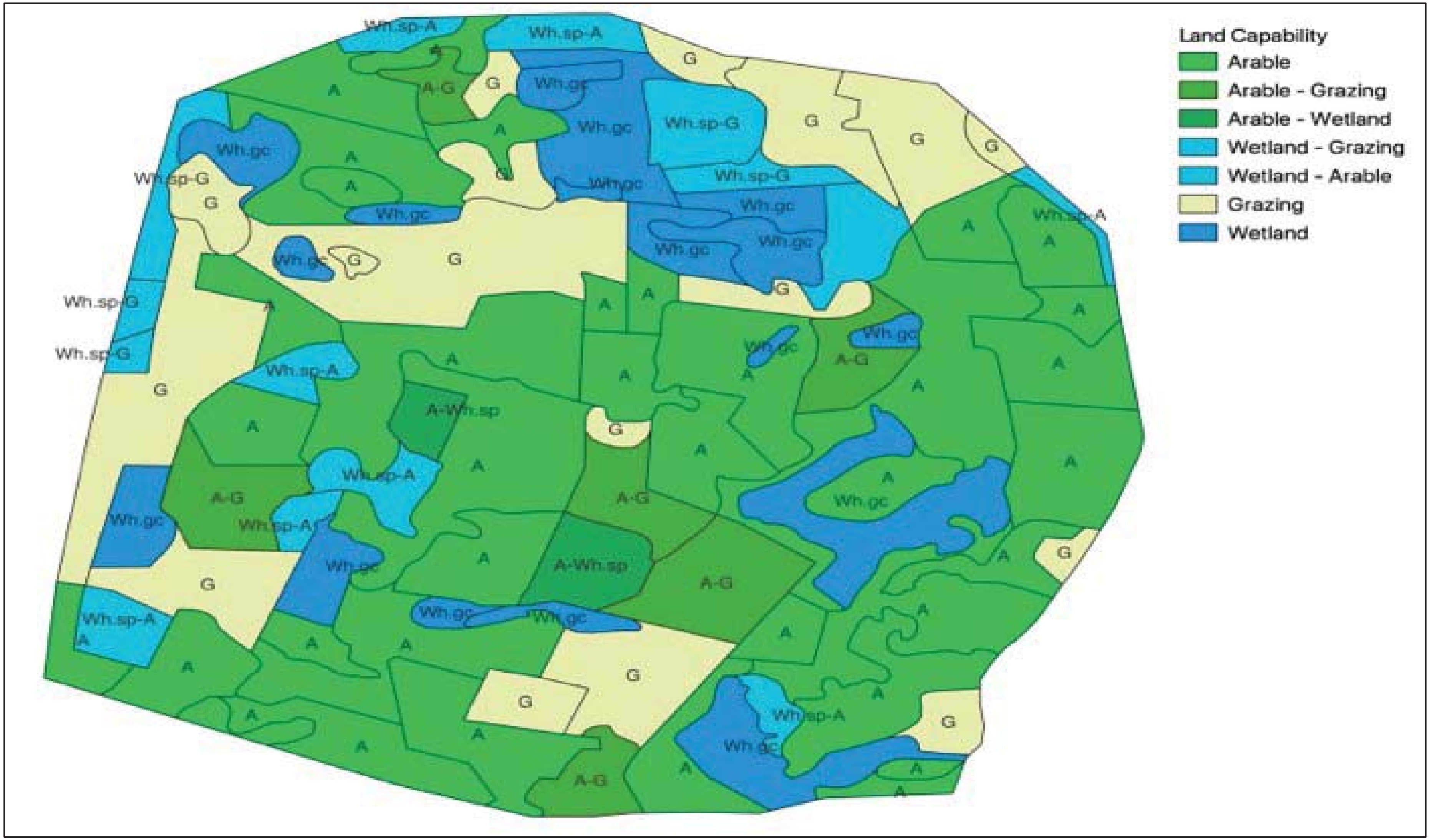

Figure 2-19: Land capability map of the rehabilitated field.

2.4 Irrigability assessment

According to the South African Irrigation Institute (SABI), several factors must be considered when investigating soils for irrigation purposes. This includes factors such as soil depth, texture, structure, chemistry, and colour. SABI states that any soil with a depth of 900 mm or more meets the soil depth requirements for irrigation and is most likely to be irrigable, depending on the soil surface type, soil chemistry and texture. Soils as shallow as 450 mm can also be irrigated, but good irrigation management and crops with a shallower rooting depth are recommended. Good infiltration and internal drainage are crucial for good irrigable potential, which is primarily linked to soil texture and structure.

This component of the study aimed to answer the two main questions:

1. "What defines the irrigable potential of rehabilitated areas?"
2. "Can a dryland classification system commonly used in the mining industry be used to define irrigability?"

The irrigable potential of rehabilitated land can best be assessed by monitoring actual crop growth and soil response to irrigation. A crop trial was established under irrigation on the rehabilitated field to monitor growth and yield, and the effect of variability in soil properties and position in the hydrological landscape on these parameters was assessed. The steps taken in conducting these assessments, along with the outcomes, are presented in the sections that follow.

2.4.1 Irrigation Uniformity Assessment

When the goal of rehabilitation is to achieve irrigable potential, several factors must be considered. These include topsoil material, soil texture, soil depth, compaction, topography, field variability, as well as soil chemistry and physics. Since most of these factors involve the movement of water, it is essential to ensure that the entire field receives water evenly; hence, irrigation uniformity had to be established.

The uniformity with which an irrigation system applies water has a significant effect on the effectiveness of the irrigation schedule and overall crop yield. This was especially important in this study, which aimed to investigate how variability in field conditions affects crop performance. Ensuring that irrigation efficiency would not be a limiting factor was essential. If the uniformity is not optimal, different parts of the field will receive varying amounts of water, which will significantly affect the yields produced and skew the monitoring results.

The irrigation system selected for the rehabilitated field was a centre pivot irrigation system. The basic structure of a central pivot is presented below (Figure 2-20). The structure consists of one or more spans (and sometimes an overhang) that hold multiple sprinklers that apply irrigation water as the motorized wheels on which the spans are mounted rotate around a pivot point over the irrigated field. Sprinklers are mounted on tubes that hang from each span, and a pressure regulator is often installed just before the sprinkler, ensuring that each sprinkler has the same water pressure. The wheels are positioned at different distances from the pivot point, meaning they must travel different distances for the entire system to function in unison. As a result, different spans must move at different speeds.

The pivot installed at the rehabilitated field has five spans irrigating a total area of 19 hectares. The different spans have varying lengths and various numbers of sprinklers. To achieve irrigation uniformity on a centre pivot, the sprinklers must apply water at different rates depending on their placement. The sprinklers must be fitted with nozzles of various sizes to ensure water is applied as required. Therefore, the selection and placement of the nozzle are crucial for effective irrigation. Uniformity assessments had to be performed to ensure that irrigation is applied uniformly throughout the pivot area.

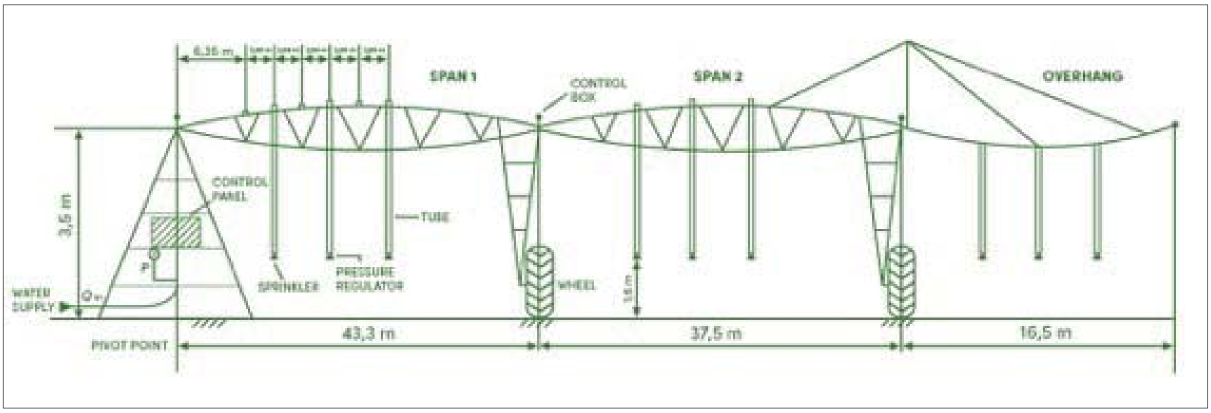

Figure 2-20: Diagram of a centre pivot irrigation system (Agrivi Farm Management Software, website)

2.4.1.1 Uniformity testing method

There are various methods for testing irrigation uniformity. The technique used in this study involved placing water-collecting containers along the length of the pivot in a straight line, at equal distances from each other, starting from the pivot point. Irrigation was then initiated, and the containers collected water applied by the pivot. The recorded water amounts were then graphed, and thiswas used to determine uniformity in combination with the calculated uniformity coefficients. The uniformity coefficients were compared to Table 2-14.

Table 2-14: Uniformity coefficient interpretation (adapted from University of Nebraska Extension)

Uniformity coefficient	**Interpretation**
90-100%	Excellent; no changes are required
85-90%	Good; no changes are required
80-85%	Fair; no changes required at this time, but the system should be monitored closely
Below 80%	Poor; improvements are required

Even though irrigators often aim for the highest possible uniformity coefficients, values of 80% or higher are generally accepted; however, uniformity tests need to be performed more frequently if uniformity is below 85%. To improve accuracy, the distances between each collection point should not be too great, and rain gauges are recommended for collecting irrigation water.

2.4.1.2 Uniformity test results

The initial pivot uniformity test at the rehabilitated field was conducted on June 3, 2022. Collection containers of equal size were placed in a straight line, 5 m apart, starting from the centre. The recorded water amounts were analysed using Excel and graphed (Figure 2-21). The results showed that the uniformity coefficient was only 68%, well below the required minimum of 80%. Figure 2-21 shows that the amount of water applied varied significantly and did not exhibit a clear distribution pattern, with measurements ranging from 4 mm to 10 mm. It was hypothesized that the variability may be due to incorrect nozzle placement during the pivot assembly.

The nozzles were rearranged to correct this, and the test was repeated. Except for two outliers, the second test showed good uniformity within the first 210 m (Figure 2-22). However, the amounts of water applied in this area were much lower than those at the edge of the pivot. Irrigation amounts varied from 4 mm to 17 mm, with the high application amounts observed in the outer edge of the pivot.

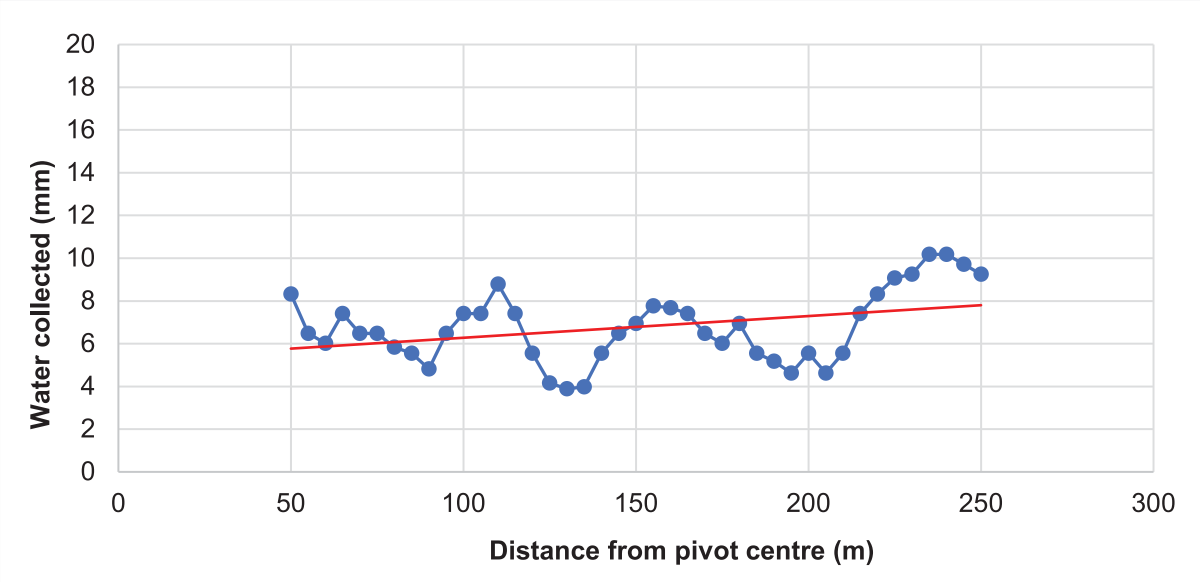

Figure 2-21: Uniformity test results from the first test

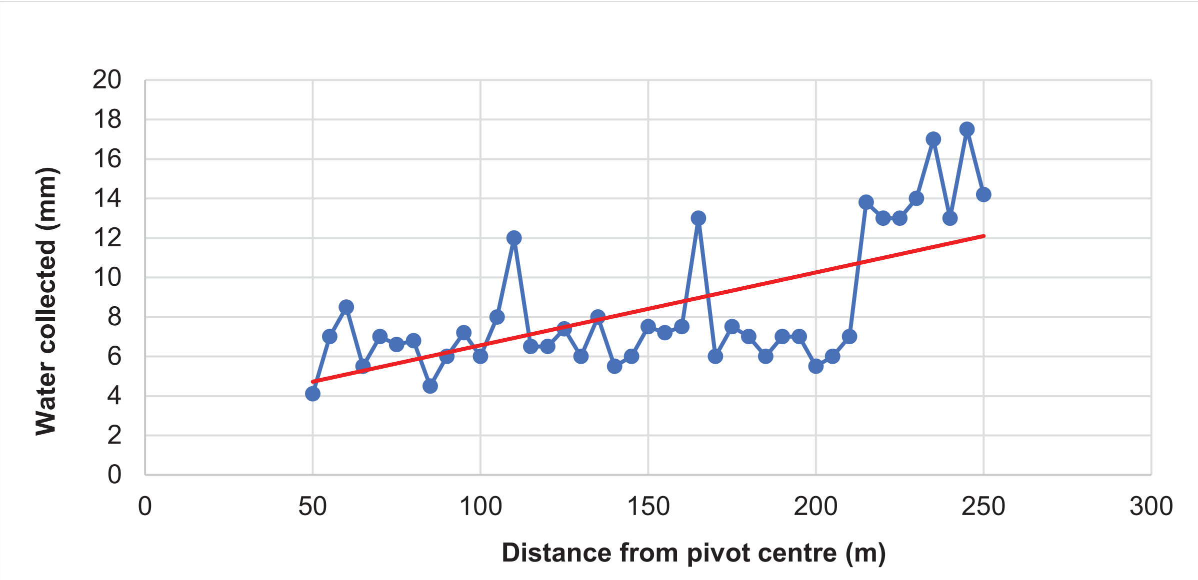

Figure 2-22: Uniformity test results from the second test

A third attempt was made at rearranging the nozzles using a different approach. The required nozzle size and placement were determined by calculating the amount of water each span needed to apply to achieve uniformity and the distance between the sprinklers. First, the pivot was mapped out and split into concentric circular areas based on the areas irrigated by each span (Figure 2-23). Then, the area within each circular area was divided into smaller circular areas based on the number of sprinklers each span held and the distance between each sprinkler. This information was used to calculate the required application rate of each sprinkler and, therefore, the size of nozzle required for each sprinkler. All the nozzles were removed and refitted according to the calculations, and new nozzles were purchased as needed. After this, the third pivot uniformity test was performed. The test showed that the pivot uniformity significantly improved, with application amounts ranging between 5mm and 6mm (89% uniformity coefficient), as indicated in Figure 2-24.

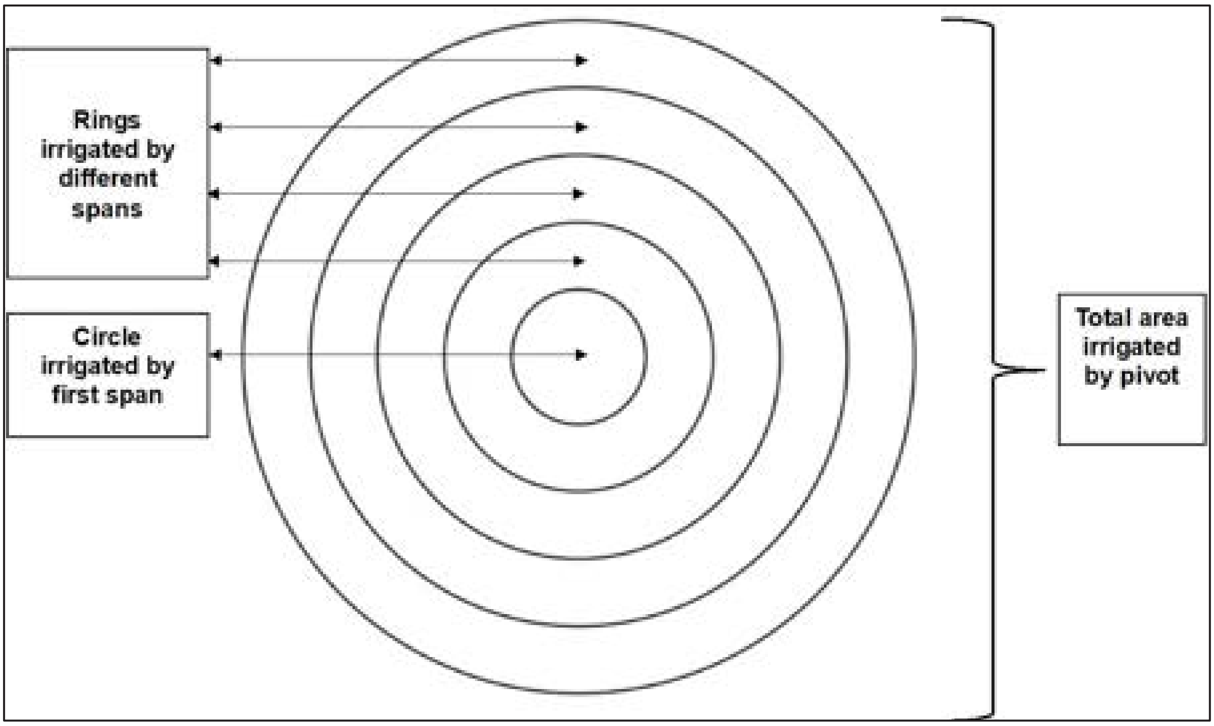

Figure 2-23: Irrigated field divided into rings according to spans

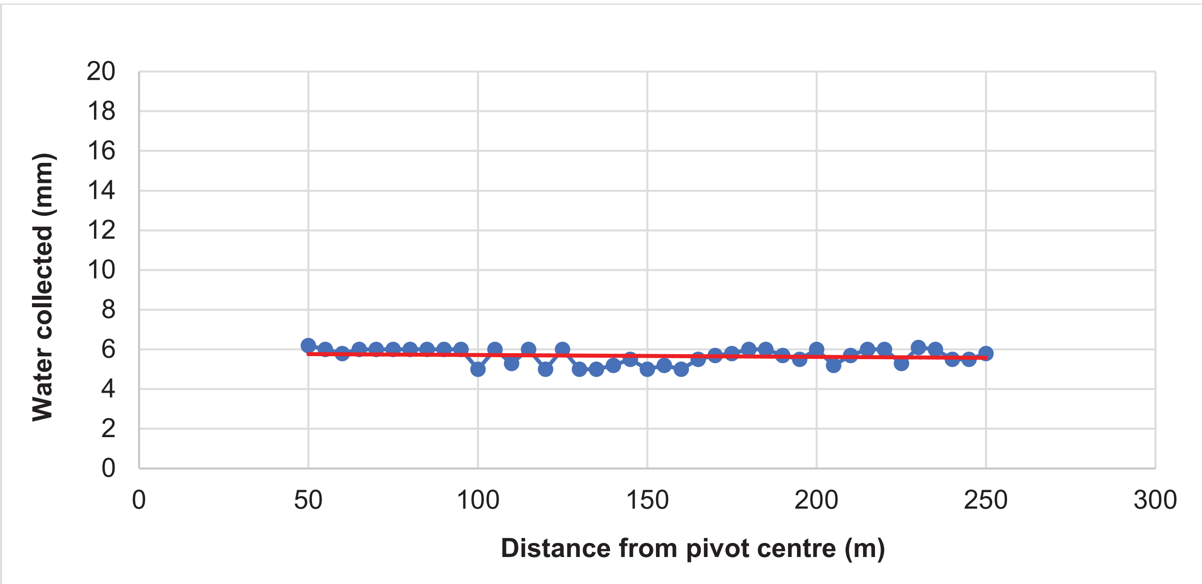

Figure 2-24: Uniformity test results from the third test

2.4.2 Topography

Topography is a key factor in determining the suitability of rehabilitated land for irrigation, as it influences hydrology. To better understand the topography of the rehabilitated site, a topographical survey was conducted. A Global Navigation Satellite System (GNSS) was used to perform the survey and create a topographical map of the study area. The GNSS survey, carried out between 11 and 15 December 2023, involved more than 500 data collection points.

2.4.2.1 Survey Method

Before the survey could begin, a control point with known x,y, and z coordinates had to be established. A control point enables the setup of a base station, which can then be used to calibrate the equipment, ensuring that the collected data is as accurate as possible. Since the base station cannot be moved during the survey, a control point was established near the study site. This enabled simultaneous surveying of the field and monitoring of the base station.

The setup consisted of two Stonex S850+ GNSS receivers, one Stonex SH5A Controller, a tripod stand for holding the base receiver, and a prism pole for holding the rover receiver and controller. One receiver was mounted on the tripod and used as part of the set up for the base station (Figure 2-26) and the other receiver was mounted on a prism pole, together with the controller (Figure 2-26 and Figure 2-27) and moved from point to point on a 25m x 25m grid taking longitude, latitude and altitude readings.

a) b)

Figure 2-25: GNSS survey equipment consisting of a) Stonex S850+GNSS receiver and b) Stonex SH5A Controller.

Figure 2-26: Full GNSS system set up

Figure 2-27: University researcher conducting field survey

2.4.2.2 Survey results

Figure 2-28 shows the topography of the rehab field and indicates that the field slopes downward from the north-western portion of the field to the south-eastern portion. The altitude in the field ranged from 1683 m to1695 m and concave areas which pose a ponding risk were identified. A 3-dimensional cross-section of the site was created to better visualize of the topographical shape and is presented in Figure 2-29. The current topography of the field could be attributed to the subsidence following rehabilitation.

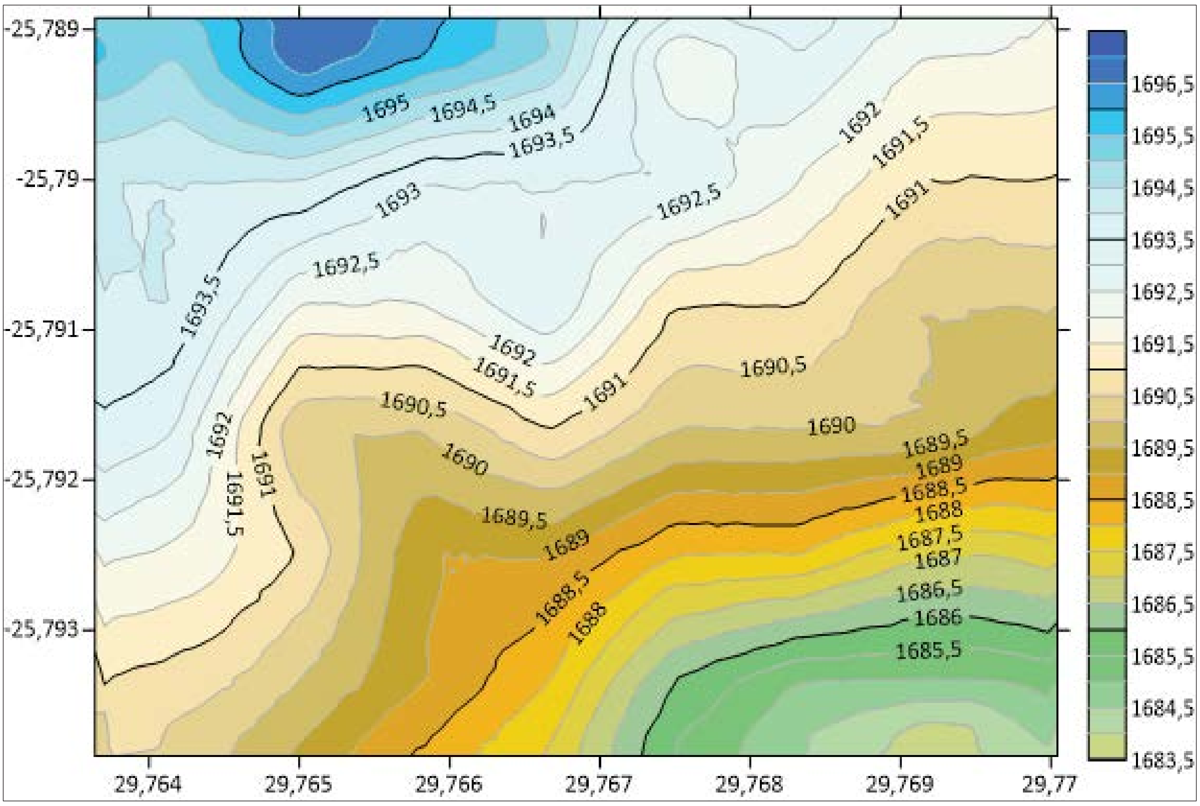

*Figure 2-28: Overhead topographical map of rehabilitated field *north facing*

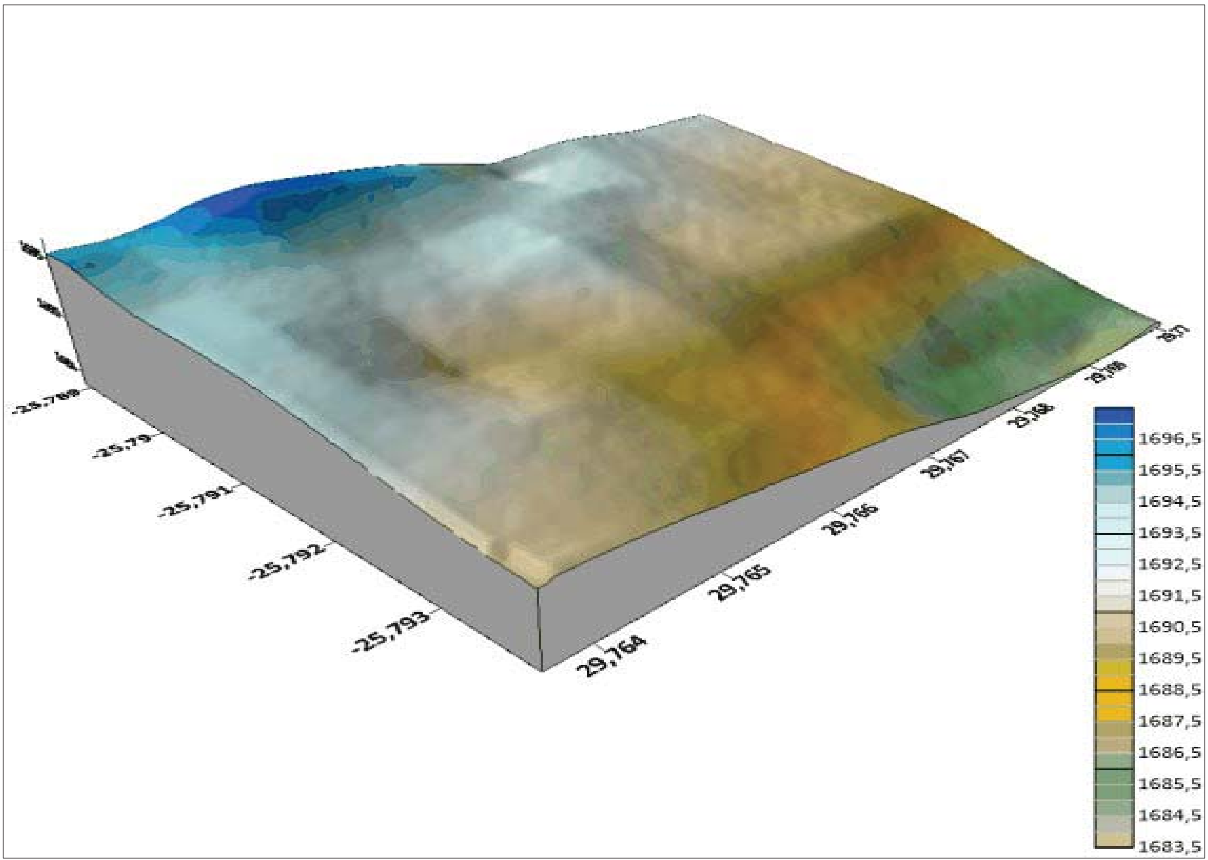

Figure 2-29: 3D Topographical map of rehabilitated field

2.4.3 Crop establishment

The pivot only became fully functional in March 2022, marking the first opportunity for soil preparation and seeding to commence for commercial-scale mine-water irrigation trials on rehabilitated land at Mafube. Our commercial maize farming partner was not prepared to risk incurring a loss with maize production on this field, as input costs are very high, and yields from rehabilitated fields are notoriously low. In addition, he was concerned that the ripping required to alleviate compaction might have brought boulders close to the surface, which could damage his expensive equipment; this was not a worthwhile value proposition for him. For this reason, the research team and mine management were responsible for cropping this field. For ease of management, and to avoid having to cultivate and seed this field each year, it was decided to plant a perennial pasture mixture, in the hope that once the field had settled in and the pivot had been proven reliable, that the commercial farmer may be prepared to take over the management of this site, either with the pasture or possibly as an additional irrigated maize field.

The mixture selected consisted of lucerne and fescue, both high-value forage crops for animal production when harvested or grazed. Lucerne is a summer crop, and a dormancy class 7 was planted. Lucerne, a leguminous crop, lies dormant during the cold winter months, but fescue is a temperate grass crop that thrives at cooler times of the year. The combination of these two pastures results in a permanent green canopy cover throughout the year, and this is expected to maximize the amount of irrigation water needed. Irrigating throughout the year is a very beneficial and sustainable method of utilizing as much mine water as possible. Typically, winter crops use more irrigation water than summer crops do because this is the dry season in the summer rainfall region, and most of the crop's water requirement needs to be supplied by irrigation. An added and very important benefit of including dry and wet season irrigation is that much less water storage is needed to hold mine water between supplemental irrigated summer seasons.

Lucerne is a deep-rooted, perennial pasture with a strong and aggressive rooting system. Due to its deep roots (> 2 m on suitable soil) and high water use, it can address rising water tables and possibly temporarily waterlogged soils. However, this crop is generally not favoured by overly wet soil conditions. The deep roots of lucerne are also more likely to penetrate deeper into compacted layers than most other crops, thereby possibly increasing water infiltration, deep drainage and assisting with alleviating compaction in the upper soil layers. Fescue has an extensive rooting system, but shallower than lucerne. Fescue/lucerne mixtures are common in areas with cold winters. Due to different rooting depths and systems, competition for water and nutrients between the crops is unlikely to occur. Both fescue and lucerne produce high yields under irrigation and also have relatively high drought tolerance, allowing them to survive longer periods under dry conditions than most other crops.

Soil was cultivated in March 2022, as shown in Figure 2-30. Seeding occurred directly after cultivation, as shown in Figure 2-31.

The planting mixture consisted of the following:

- Lucerne (Medicago sativa): Lima Grain, WL 458 HQ, Dormancy Class 7, 15 kg/ha
- Tall Fescue (Festuca arundinacea): Lima Grain, Charlem, 20 kg/ha
- Fertilizer: Kynoch, MAP (28), 140 kg/ha

Figure 2-30: Soil preparation at the rehabilitated field

Figure 2-31: Planting of the mixture and fertilizer application at the rehabilitated field

Seeding was completed within three days. Unfortunately, heavy rain occurred a week after seeding, which was not ideal for optimum growing conditions for Lucerne. Even with good soil conditions where drainage and infiltration are optimum, a total of 144 mm of rain will not be ideal and will most likely result in ponding or runoff. Figure 2-32 and Figure 2-33 show ponding areas that were still present in the rehabilitated field long after the heavy rainfall. Germination is also visible in Figure 2-32 around, but not within, the ponded areas.

Figure 2-32: Ponding at the Rehabilitated Pivot site

Figure 2-33: Water ponding due to surface subsidence and insufficient infilling

The ponding visible in Figure 2-33 was present for a long period of time, and whilst irrigation was at times necessary for the rest of the irrigated field, this continuously added water to ponded areas, further limiting germination in these low-lying areas.

Since lucerne, which is a perennial crop, requires 6 to 12 months to be well established, and some weeds and volunteer crops establish more rapidly than this, it is normally prudent to reduce weed pressure by mowing the pasture in the early stages of establishment. This is usually done after winter and is referred to as a “winter cut”. This was carried out from 1st to 3rd October 2022. Figure 2-34 and Figure 2-35 are from the winter cut at the rehabilitated field.

Some wheat and other temperate small grain crops germinated from previous failed attempts at establishing crops due to irrigation system challenges, and this was also removed with the winter cut, as can be seen in Figure 2-35. The regrowth of volunteer small grains in the warm season was, as expected, poor, giving the Lucerne/fescue mixture an ideal opportunity to establish. With each hay harvest hereafter, the weed population should decrease, and the pasture should become more dominant.

The growing period between each harvest varied between 6 to 8 weeks, dependent on weather and soil conditions. The first commercial hay harvest was scheduled for the first week of December 2022, but due to heavy and continuous rain throughout the month, cutting was delayed.

Figure 2-34: Winter cut at the Rehabilitated Pivot, early October 2022

Figure 2-35: Remnants of volunteer small grain regrowth cleared with the winter cut, early October 2022

2.4.4 Sampling methodology

Most of the sampling points are situated in the same location as the weed growth sampling points discussed in Section 2.2. By adding an extra set of data to these sampling points, a better understanding of system behaviour was gained.

A total of 21 sampling points (Figure 2-36) were identified and divided into different classes at the Rehabilitated Pivot.

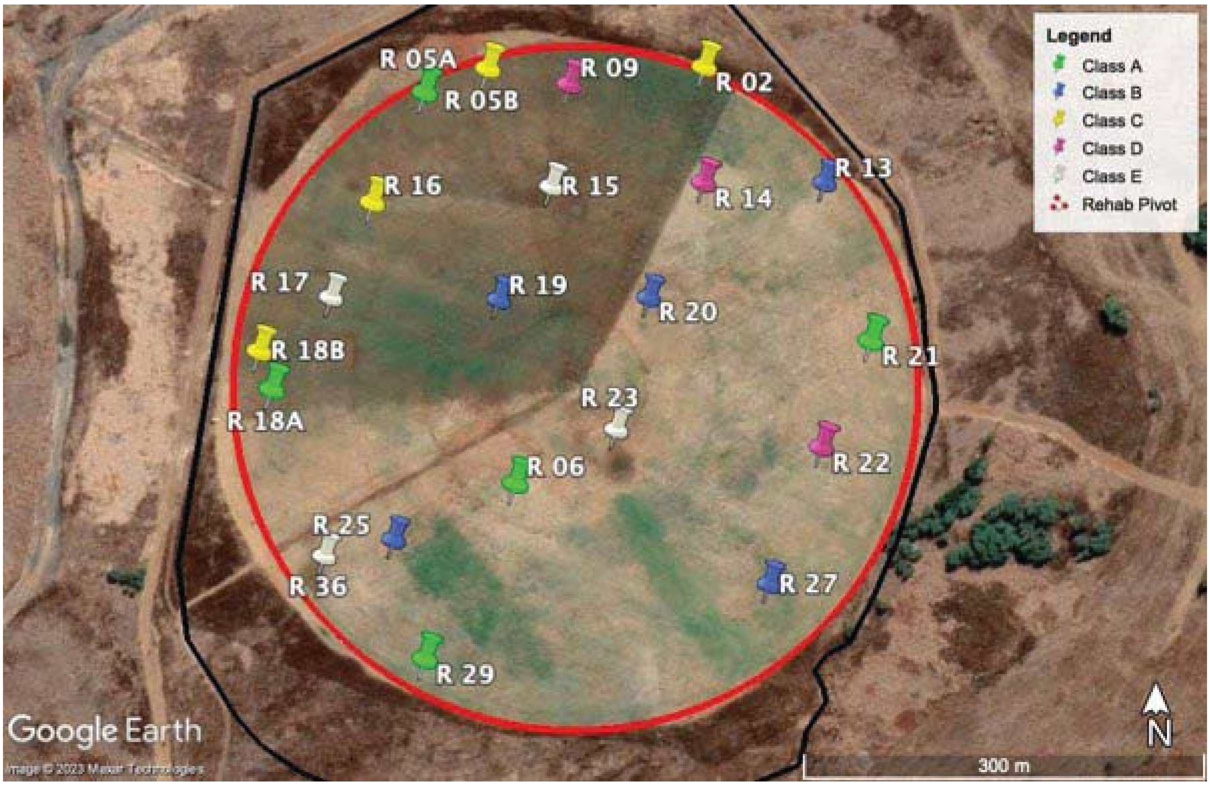

Figure 2-36: Sampling points classified in five irrigability classes at the Rehabilitated Pivot

Figure 2-37 illustrates the monitoring undertaken at each point, which includes the following samples:

- Three 1 m^2 samples of the plant material growth, cut at 7 cm above ground level.
- 0-300 mm soil samples taken in the centre of each of the 1 m^2 sampling squares and mixed to obtain a single soil sample per site.
- Leaf area index (LAI) at each sampling square.

The LAI was measured using the ACCUPAR LP-80 PAR/LAI ceptometer. Three readings per square were taken, before the material was cut, giving a total of 9 readings per site. The LP-80 measures photosynthetically active radiation (PAR) and uses the reading to give LAI for the plant canopy cover.

Soil samples were sent to Nvirotech Laboratories for the following analyses:

- Fertility (pH water and Bray II for P);
- Micro nutrients - Zn, Cu, Mn, Fe (Mehlich III)
- Particle size fractions (Clay, Silt, Sand)

Crusting was visible in some areas of the field, and therefore, soil texture was analysed to determine if the crusting occurred due to physical conditions.

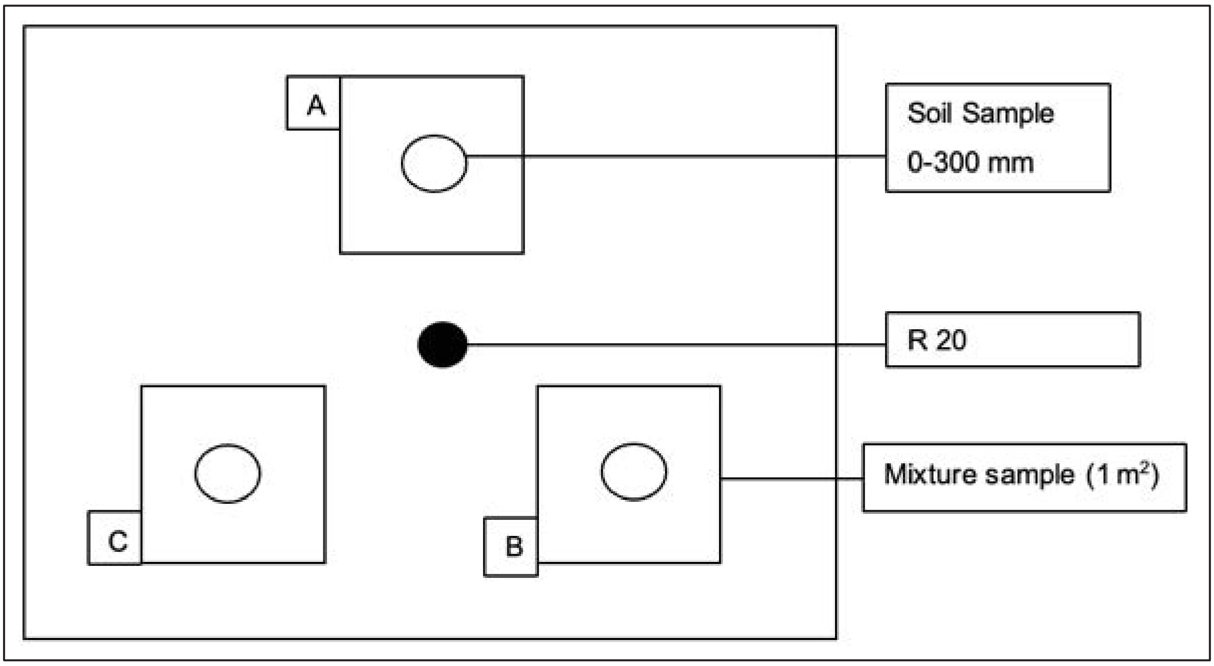

Figure 2-37: Sampling regime for Rehabilitated Pivot monitoring sites (R20 as example)

Plant samples were taken on 6-7 December 2022, the first opportunity to access the site after persistent rains. Samples were harvested 7 cm above the ground using a hedge trimmer. Figure 2-38 shows the sampling square where the material still needs to be raked up and collected after being cut. Samples were collected and dried at 65°C for 72 hours before being weighed.

Figure 2-38: Hedge trimmer and sampling square

2.4.5 Crop growth and Yield

Table 2-15 represents yield and LAI measured at the sampling points. The yield results for each sub-sample and the combined average for each monitoring point are presented. The average LAI is also included. Sampling points R23, R15 and R17 were situated in waterlogged areas which restricted access for measurements and sampling.

Table 2-15: Average pasture yield and LAI measured at the sampling points (December, 2022)

Sample	A	B	C	Average	LAI
	t/ha	t/ha	t/ha	t/ha	m^2/m^2
R 21	3.17	3.3	3.5	3.3	5.1
R 29	3.5	3	2.1	2.9	2.7
R 05A	2.8	1.2	1.8	1.9	2.4
R 18 A	1	1.3	1	1.1	0.6
R 06	1.7	2.3	1.7	1.9	2.3
R 20	2	1.5	1	1.5	1.1
R 25	0.8	1.3	1.1	1.1	0.3
R 13	1.4	0.8	0.8	1.0	1.2
R 19	1.4	2	1	1.5	1.1
R 27	1	0.6	0.6	0.7	1
R 02	2.8	3	2.3	2.7	3.7
R 05B	3.3	3.2	2.9	3.1	4.2
R 16	2.6	2	1.6	2.1	1.5
R 18B	1.9	1.9	2.1	2.0	2
R 09	0.7	0.6	0.7	0.7	0.1
R 14	0.7	0.9	1.1	0.9	0.2
R 22	2.7	1.9	2	2.2	2
R 20	2	1	1	1.3	1.1
R 23	-	-	-	-	-

R 36	0.2	0.3	0.2	0.2	0
R 15	-	-	-	-	-
R 17	-	-	-	-	-

2.4.6 Classification of sampling sites

Certain soil physical conditions and hydrological position in the landscape are expected to be important determining factors of the irrigable potential of the rehabilitated field. These were not explicitly included in the rain-fed rehabilitated site classification system used by Red Earth. Restricting layers due to compaction, and depression areas caused by subsurface subsidence, creating surface ponding and waterlogged areas, are expected to significantly affect irrigable potential.

With the assistance of Premier Mapping Africa, a detailed contour map of the rehabilitated area was used to identify surface water flow pathways and areas which are highly susceptible to ponding. Sampling sites were situated within these areas which can present valuable information on the effect of ponded areas on growth. Figure 2-39 indicates water pathways (blue lines), possible ponding areas (blue shapes) and the sampling sites (multi-coloured pins).

Restricting layers in the rehabilitated field were identified by using a penetrometer. Downward movement of water and roots are minimised by restricting layers in the soil. The penetrometer results along with those from the dryland classification system (Section 3.4) were used to categorize the sampling points into different irrigability classes (A to E). These were used to identify factors that influence the irrigability of the rehabilitated field. These classes are presented in Table 2-16. The second column consists of the dryland capability classification from Section 3.4, the third column displays irrigability, and the last column in the table lists the main reason(s) for the irrigabilty prediction.

Table 2-16: Sampling points categorized into different classes to define what influences the irrigabilty of the rehabilitated land

Site	Dryland Classification	Irrigabilty	Irrigabilty Classification Reason
Class A			
R 21	Arable	Yes	No restricting layer
R 29	Arable	Yes	No restricting layer
R 05A	Arable	Yes	No restricting layer
R 18A	Arable	Yes	No restricting layer
R 6	Arable	Yes	No restricting layer
Class B			
R 20	Arable	No	Layer (30cm), compacted profile
R 13	Arable	No	Layer (30cm), compacted profile
R 25	Arable	No	Layer (30cm), compacted profile
R 19	Arable	No	Layer (30cm), compacted profile
R 27	Arable	No	Layer (35cm), compacted profile
Class C			
R 2	Grazing	Yes	Good surface infiltration expected
R 05B	Grazing	Yes	Good infiltration, no restricting layer
R 16	Grazing	Yes	Good surface infiltration expected
R 18B	Grazing	Yes	Good surface infiltration expected
Class D			
R 09	Gleyic – low potential	No	Duplex soil – Gleyic surface
R 14	Gleyic – low potential	No	Duplex soil – Gleyic surface
R 22	Gleyic – low potential	No	Duplex soil – Gleyic surface
Class E			
R 23	Arable	No	Water ponding and waterlogged soil expected
R 15	Grazing	No	Water ponding and waterlogged soil expected
R 17	Arable	No	Water ponding and waterlogged soil expected
R 20	Arable	No	Water ponding and waterlogged soil expected

Class A refers to areas where good arable and irrigable potential are expected.

Class B indicates areas where the topsoil and subsoil were identified as being good for arable conditions during the dryland evaluation. However, penetrometer measurements indicated compacted layers in the profile to an extent where resistance in downward movement is expected and therefore, classified as being of poor suitability for irrigation.

Class C refers to areas that were classified as grazing under the dryland classification system due to poor water-holding capacity. However, these areas were classified as suitable for irrigation, as water can be applied frequently with an appropriate irrigation system, and the soil profile does not require a large water storage capacity for crops to overcome dry spells. Due to the higher content of coarse material in the profile and on the surface, water infiltrability is expected to be high. The coarse material content is not so high that growth is expected to be negatively affected.

Class D represents areas where both dryland and irrigation suitability are classified as poor. These are the areas that were covered with gleyic material to fill up depression areas. Low water infiltration is expected due to the high clay content characteristic of gleyic soils. Gleyic soils are commonly found in wetlands and are not suitable as topsoil for crop production.

Class E represents sites located in areas prone to ponding. Very poor crop growth is expected in these areas, and waterlogged soil conditions were expected and observed throughout most of the year. Blue lines in Figure 2-39 indicate water-flow pathways and the blue polygons show areas where water will accumulate and possibly pond. Figure 2-39 illustrates the monitoring points in the rehabilitated land categorized into different irrigability classes.

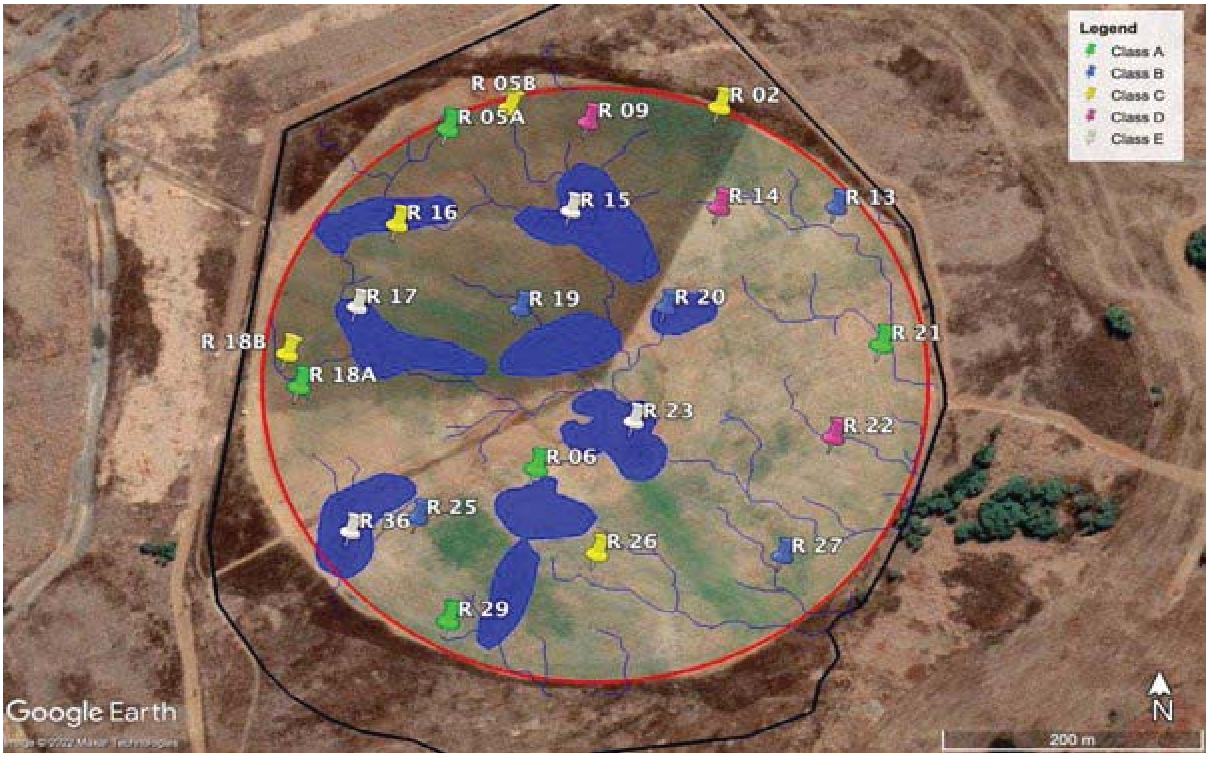

Figure 2-39: Google Earth image of the Rehabilitated Pivot indicating irrigability classes of monitoring points

The results from the sites presented in Table 2-16 and irrigability classification in Figure 2-39 are presented together in Table 2-17.

Table 2-17: Dry mass and LAI for the monitoring sites in different irrigability classes at the rehabilitated field

A			B			C			D			E		
Site	**t/ha**	**LAI**	**Site**	**t/ha**	**LAI**	**Site**	**t/ha**	**LAI**	**Site**	**t/ha**	**LAI**	**Site**	**t/ha**	**LAI**
R 21	3.3	5.1	**R 20**	1.4	1.1	**R 02**	2.7	3.7	**R 09**	0.7	0	**R 23**	-	-
R 29	2.9	2.7	**R 25**	1.1	0.2	**R 05B**	3.1	4.2	**R 14**	0.9	0.2	**R 15**	-	-
R 05A	1.9	2.4	**R 13**	1	1.2	**R 16**	2	1.5	**R 22**	2.2	2	**R 17**	-	-
R 18A	1.1	0.6	**R 19**	1.6	1.1	**R 18B**	2	2	-	-	-	**R 20**	1.4	1.1
R 06	1.9	2.3	**R 27**	0.7	1	-	-	-	-	-	-	-	-	-
Ave	2.2	2.6		1.2	0.9		2.5	2.9		1.3	0.7		1.4	1.1
Std Dev	0.9	1.6		0.4	0.4		0.5	1.3		0.8	1.1			

Class A had an average yield of 2.2 t/ha with a relatively good LAI of 2.6. Growth at these sites was as expected for areas suitable for dryland and irrigated production. Irrigation suitability and arable classification were similar for sites with no restricting layers or no severe within-profile compaction. Sample site R 18A was the exception, as a low yield and LAI were recorded.

Class B represents sites which were classified as arable with the dryland classification system but were not deemed suitable for irrigation. The results show that yield and LAI were very low for these areas and correspond with the irrigation suitability prediction. No outliers were recorded for class B within the five sampling sites. The poor growth was most likely due to the physical restrictions (layers and compaction) that were present in the sampling point profiles. Only when these physical limitations are addressed through adequate ripping will the suitability for irrigated production improve. For class B, the physical restrictions had a severe impact on pasture growth and yield.

Class C was classified as areas with only grazing suitability under the dryland classification system, but were deemed suitable for irrigation. Yield and LAI were highest for class C, with an average of 2.5 t/ha and 2.9 m2/m2, respectively. Good infiltration and drainage were expected due to the greater amounts of coarse material in the profiles for these sites. This seemed to be the case, and it was the reason for the higher growth in these areas. Most of the sampling classified as “grazing” showed more promising results than the areas classified as arable. Figure 2-40 is from site R 05B, where good growth of the pasture is visible with a yield for the first harvest of 3.1 t/ha.

Class D was classified as wetland areas with poor arable potential according to the dryland system. Poor irrigation suitability was also predicted. R 09 and R 14 recorded very poor growth and low yields as expected. The G horizon (very high clay content) formed a sealing layer limiting aeration and water infiltration which resulted in poor growth. Figure 2-41 shows site R 09 where only 0.7 t/ha was recorded. This indicates the high variability in the rehabilitated field, as the areas depicted in Figure 2-40 and Figure 2-41, are situated less than 30 m apart.

Site R 22 produced high yields and good growth which was not expected. Cracks in the clay surface were observed, and different types of clay react differently to water. The cracks in the clay at R 22 are likely the result of the ability of the clay to swell and shrink. These cracks allow better water infiltration and aeration. This was not observed for sites R 09 and R 14, so it appears that R 22 had a different clay type. Figure 2-42 represents site R 22. Fescue dominated lucerne at this site because the legume is more sensitive to soil with low infiltrability, and this indicates that although the mixture yield was high, infiltration was low enough to affect lucerne germination.

Figure 2-40: Site R 05B with a yield of 3.1 t/ha

Figure 2-41: Poor growth at R 09

Figure 2-42: Fescue dominated over lucerne growth at site R 22 (December, 2022)

Class E represents sampling points in areas that are prone to ponding. Only site R 20 was accessible for sampling. The rest were constantly ponded with no growth to sample. Topography analysis indicates several areas that are prone to ponding. These areas were constantly ponded to such an extent that sampling was not possible. R 20, which is also a site allocated to class B, was the only ponded site that was accessible. Below average yield was recorded for R 20 of 1.4 t/ha. Even if a surface depression area exhibits high infiltrability, ponding is bound to occur in a high-rainfall area like Mpumalanga.

Figure 2-43 presents normalised average yield and LAI for the various monitoring sites, arranged from lowest to highest LAI. This data was normalised to more easily compare trends between canopy cover and dry matter production. The graph indicates a correlation between yield and LAI. As the LAI measurements increased the yield also increased.

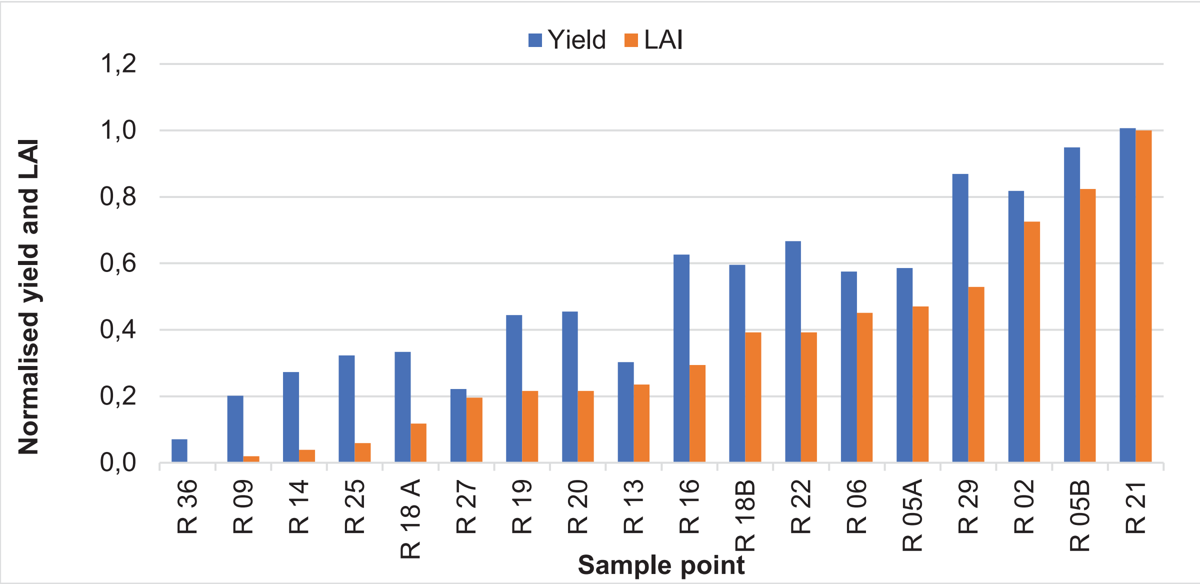

Figure 2-43: Normalised LAI and yield for the sampling points

A clear relation between LAI and yield can be seen in Figure 2-43. Areas that measured a high yield but a lower LAI, were mainly dominated by fescue. Fescue has a lower canopy cover than lucerne. Despite this, there was still a clear correlation between LAI and yield.

2.5 Conclusion

The spatial variability of soil properties in the rehabilitated irrigated field at Mafube is much higher than for unmined areas. The high variability can be directly related to the rehabilitation processes. Both physical and chemical variability was high, but physical properties tend to be more difficult to ameliorate. The variability mentioned only refers to the Rehabilitated Field at Mafube, but this may not be the case for all other sites. Variability could probably be less if rehabilitation guidelines are meticulously followed, but this is not an easy task, so variability is likely to be an inherent property of rehabilitated mine lands. Whilst much spatial variation is not ideal for commercial crop production, it does present an ideal research site, where differences can be studied.

It can be concluded from the baseline soil and vegetation assessments, that although there were good relationships between soil phosphate, organic carbon and growth, physical properties had a more significant effect on growth and yield than soil chemical properties did. The growth and yield results obtained from the planted pasture also indicated a strong relationship between physical properties and dry mass harvested. The severe effect of compaction and restricting layers in the profile was seen in weed growth and the pasture mixture. If sufficient ripping of the rehabilitated land was done initially, this may not have been such a determining factor. The compaction and restricting layers present in the Rehabilitated

Field are good examples of how soil properties can be affected if the guidelines are not meticulously followed. This signifies the importance of following the guidelines created for opencast coal mining as physical properties are very expensive to ameliorate after the rehabilitation process.

The land capability and irrigability assessments indicate dryland classification system does not include all of the factors necessary to determine the irrigability of rehabilitated land. Additional physical properties and topography need to be included to create a more accurate assessment of the suitability for irrigation and some of the measured parameters of the dryland system considered should be interpreted differently.

The final topography of rehabilitated land can be identified as arguably the most important factor for determining suitability for irrigation. Surface subsidence is mainly the reason for the change in topography post rehabilitation, and is difficult to predict, so a specific area’s irrigability classification may change over time. Correct topographical reshaping will ameliorate the effect of surface subsidence and can even prevent it from occurring. This highlights the importance of reserving additional topsoil to fill any depression areas that may form. This advice is included in the 1980, 2007 and 2019 Rehabilitation Guidelines, so it should be an accepted practice in the mining industry. The results of not having reserved topsoil to fill depressions can be seen in some areas at the Mafube Rehabilitated Field. The effect of using the wrong soil type to fill depression areas is also evident and has been shown to create unsuitable conditions for crop production under both dryland and irrigated conditions.

If key issues regarding the irrigability of rehabilitated land are addressed to create more suitable areas for irrigation, then irrigating rehabilitated land with suitable mine water could be an effective and economical way to utilise mine water, thereby increasing the area of rehabilitated land available for agriculture. This will be a breakthrough for both mining and agriculture, as thousands of hectares are potentially available for mine-water-irrigated agricultural production, which will save large amounts of money on alternative water treatment, produce crops, and create jobs, with limited environmental impact. It is certainly worth investing effort into addressing any limitations to this practice. The work conducted as part of this study provided a foundation for the development of the Guidelines for Rehabilitating Mined Land to Irrigable Standard (Patoussius et al, 2024).

CHAPTER 3: EVALUATION OF IRRIGATION WITH UNTREATED OR PARTIALLY TREATED ACID MINE DRAINAGE

Several collieries in Mpumalanga pump excess AMD to a centrally located water treatment plant that uses hydrated lime ($Ca(OH)_2$) to neutralise the water and remove metals through a High Density Sludge (HDS) process, before further treatment to potable standards using Reverse Osmosis (RO). AMD is stored in two ponds, one with less acidic water (pH ~ 3.5, and total dissolved solids (TDS) ~ 4 910 mg L^{-1}) and the other with extremely acidic water (pH ~ 2.5, and TDS~ 5 130 mg L^{-1}). These waters go through the same treatment processes but are managed separately. Feed pumps first deliver AMD to HDS oxidation and neutralisation reactors, where the pH is raised to approximately 9, with trace metal precipitation as hydroxides. This produces "unclarified" saline water with a high level of suspended solids (48 400 mg L^{-1}), and Total Dissolved Solids (TDS) of ~3 750 mg L^{-1}. This then overflows into clarifiers for solid-liquid separation. Some of the Fe- and Mn-rich sludge leaving the clarifiers is diverted back to the reactors for densification, and the rest is sent to sludge storage bays.

The clarified, neutralised solution with a pH of ~ 8.5, TDS ~ 3 560 mg L^{-1}, then passes through self-cleaning strainers to remove most of the remaining suspended particles, before passing through ultrafiltration membranes (RO pre-treatment) to remove residual suspended solids for the production of low Silt Density Index (SDI < 3) RO feed water. The solution is acidified to a pH of 7.5 to protect the RO membranes from scaling and degradation. The RO feed water has a TDS of ~ 3 320 mg L^{-1}. This pre-treated water is then pumped through RO membranes, where it is desalinated, yielding 65% permeate recovery with a low TDS < 200 mg L^{-1}. The RO reject water undergoes secondary treatment (precipitation, solid/liquid separation, clarification, ultrafiltration, and another round of reverse osmosis), again with a 65% recovery and TDS < 200 mg L^{-1}. The secondary treated RO reject water undergoes tertiary treatment that delivers TDS < 400 mg L^{-1} with a 60% recovery. Reject RO water after tertiary treatment is stored as brine. Brine produced from the treatment of less acidic water has a TDS of ~ 9 400 mg L^{-1}, and that from extremely acidic waters is around 15 400 mg L^{-1}.

The process of RO for AMD treatment to meet potable standards is very expensive and has raised questions about its carbon footprint due to its high energy requirements (Thisani et al. 2021). In addition, the water treatment plant produces large volumes (200 tons per day) of calcium and sulphate-rich sludges, rich in Fe, Mn and Al oxides, which must be managed

(UNFCCC, 2012). Owing to the high cost of mine water treatment and the challenges of managing by-products, alternative mine water management options are sought. One proposed option is irrigation with untreated or partially treated mine waters. Due to the salinity and high concentrations of suspended solids and metals in mine waters, irrigation is expected to affect soil quality and productivity (Deinlein et al., 2014; Page et al., 2021). Therefore, there is a need to assess and meet certain quality standards for irrigation (Almeida et al. 2008).

Mine water can serve as an alternative resource to alleviate agricultural irrigation water scarcity. However, effects on agricultural production and off-site environmental impacts are poorly understood. This component of the study was aimed at assessing the fitness for use of various mine waters for irrigation and to investigate crop and soil responses to irrigation with untreated AMD (highly acidic and less acidic waters) and partially treated waters from an HDS treatment plant (unclarified neutralised, clarified neutralised and RO pre-treatment waters). Moreover, the safety of the produce for consumption was evaluated.

3.1 Modelling long-term irrigation with selected untreated and partially treated mining-influenced waters

The site-specific, risk-based Irrigation Water Quality Decision Support System (IrrigWQ-DSS), developed by du Plessis et al. (2023)The 1996 South African Water Quality Guidelines (SAWQG) were used to assess whether untreated AMD, BSR-treated, and clarified neutralised waters could be used for irrigation. The DSS assesses the likely effects of water quality on soils, crops, and irrigation equipment, using four fitness-for-use (FFU) classes. The output is made intuitive by using colour-coded labels indicating ideal, acceptable, tolerable, or unacceptable. IrrigWQ operates at two Tiers. At Tier 1, only water quality is required, and a conservative, generic water-quality assessment is performed, indicating potential problems that may be encountered if water of a specified quality is used for irrigation. At Tier 2, the user can select site-specific parameters (cropping system, climate, and soil) and evaluate how the application of specific management strategies (irrigation frequency and amount, and irrigation system selection) is expected to influence the suitability of water for irrigation.

3.1.1 Water qualities

Table 3-1 shows the average water qualities of the different waters used in this experiment. These water quality parameters were obtained by averaging the analyses to estimate the chemical composition.

Table 3-1: Average chemical composition of the waters used at the eWRP irrigation trial.[6]

Constituent	Highly Acidic	HDS Clarified	BSR treated
pH	2.5	8.5	7.6
EC (mS/m)	407	350	336
Al (mg/L)	68	0.09	0.1
As	<0.01	<0.01	BDL
Cd	0.004	<0.003	BDL
Ca	412	683	264
Cl	11	31	NA
Cu	0.03	<0.01	0.01
F	<0.2	0.64	0.4
Pb	<0.01	<0.01	BDL
Mg	201	114	193
Mn	21	0.08	0.07
Hg	<0.001	<0.001	NA
Ni	0.46	0.06	0.03
Se	0.02	<0.01	0.00
Na	187	131	70
SO_4	2871	2394	800
Fe	638	31	1.02
Zn	1.50	0.03	0.52
Alkalinity	25	21	3050
TDS	4910	3752	NA
TSS	200	96	NA

[6] BDL= Below the detection limit of 0.01 mg/L for Cu, As, Pb and 0.003 mg/L for Cd; NA= Not analysed

3.1.2 Model parameterization

A Fitness-for-Use (FFU) assessment was performed for the three waters obtained from eWRP using the IrrigWQ DSS of du Plessis et al. (2023). This was done before the experiment commenced in order to establish the predicted site-specific suitability of these untreated and partially treated mine waters for irrigation and to identify any constituents of potential concern. Tier 2 mode was selected to simulate 45 years of irrigation using the water quality values given in Table 3-1. A 1 m deep sandy loam soil was evaluated using overhead irrigation (to assess whether foliar scorching may be problematic), with irrigations to field capacity (FC) when the deficit to FC was at least 20 mm. Long-term daily weather data from a weather station located near the water treatment plant was selected.

A rotational cropping system with moderately salinity-tolerant crops was simulated, with soybean representing summer crops and wheat representing winter crops. The model was parameterised to plant soybeans on October 23rd and wheat on June 1st. Expected crop performance is summarised as the percentage of time (45 years) that the relative yield is expected to fall within the four FFU categories, as affected by soil salinity. Potential trace element accumulation and the predicted effects of the selected waters on irrigation equipment were also evaluated. Accumulation of trace elements in the top 0.15 m of soil, assuming no leaching, is calculated by multiplying the average annual irrigation amount by the concentration of these elements in the water. A calculation is then made to determine how long such irrigation can be practised before internationally specified soil threshold values are exceeded (du Plessis et al. 2023).

The Langelier Saturation Index (LI) was used to assess the likelihood of corrosion and scaling of irrigation infrastructure. This method estimates the extent of $CaCO_3$ saturation in water by subtracting the hypothetical saturation pH (pHs) from the measured pH (pHa). The pHs is the theoretical pH at which water with a specified bicarbonate and calcium ion concentration, and TDS content at a given temperature, would be in equilibrium with solid $CaCO_3$. A positive LI signifies that the water is oversaturated, and scaling is probable, whereas a negative LI suggests that the water is undersaturated with respect to $CaCO_3$ and may be corrosive (du Plessis et al. 2023).

3.1.3 Potential root zone effects on wheat and soybean yield

Figure 3-1a) and b), show the predicted effects of salinity on wheat and soybean yields relative to the expected potential yield with good quality water. With AMD irrigation, soybean was simulated to produce unacceptable yields (relative yield < 70%) 24% of the time, tolerable yields 11% of the time, acceptable yields 7% of the time, and ideal yield levels just over half of the time (58%). Wheat was generally predicted to suffer higher yield penalties than soybean, despite being a more salt-tolerant crop. This is because the winter wheat season in Mpumalanga is a dry time of year, whereas soybean is grown in the wet summer season, which naturally results in a higher leaching fraction. The DSS predicted that wheat would produce unacceptable yields 18% of the time, tolerable relative yields 16% of the time, acceptable yields about a third of the time (38%), and ideal yields slightly less than a third of the time (29%).

The treatment of mine waters in HDS and BSR treatment plants improved water quality. For both wheat and soybean crops, simulations using partially treated mine waters from the HDS plant showed that yields were ideal (relative yield > 90%) throughout the 45-year simulated period. In contrast, when using BSR-treated water, the outcomes were ideal 89% of the time, acceptable 7% of the time, and either tolerable or unacceptable for the remaining 4% of the simulated timeframe for soybean. Predicted yields were ideal 89% of the time for wheat and acceptable 11% of the time when irrigation with BSR-treated water was simulated. These simulations prove that the treatment processes were effective in treating AMD and demonstrate the potential for irrigation with mine waters from the Mpumalanga Coalfields.

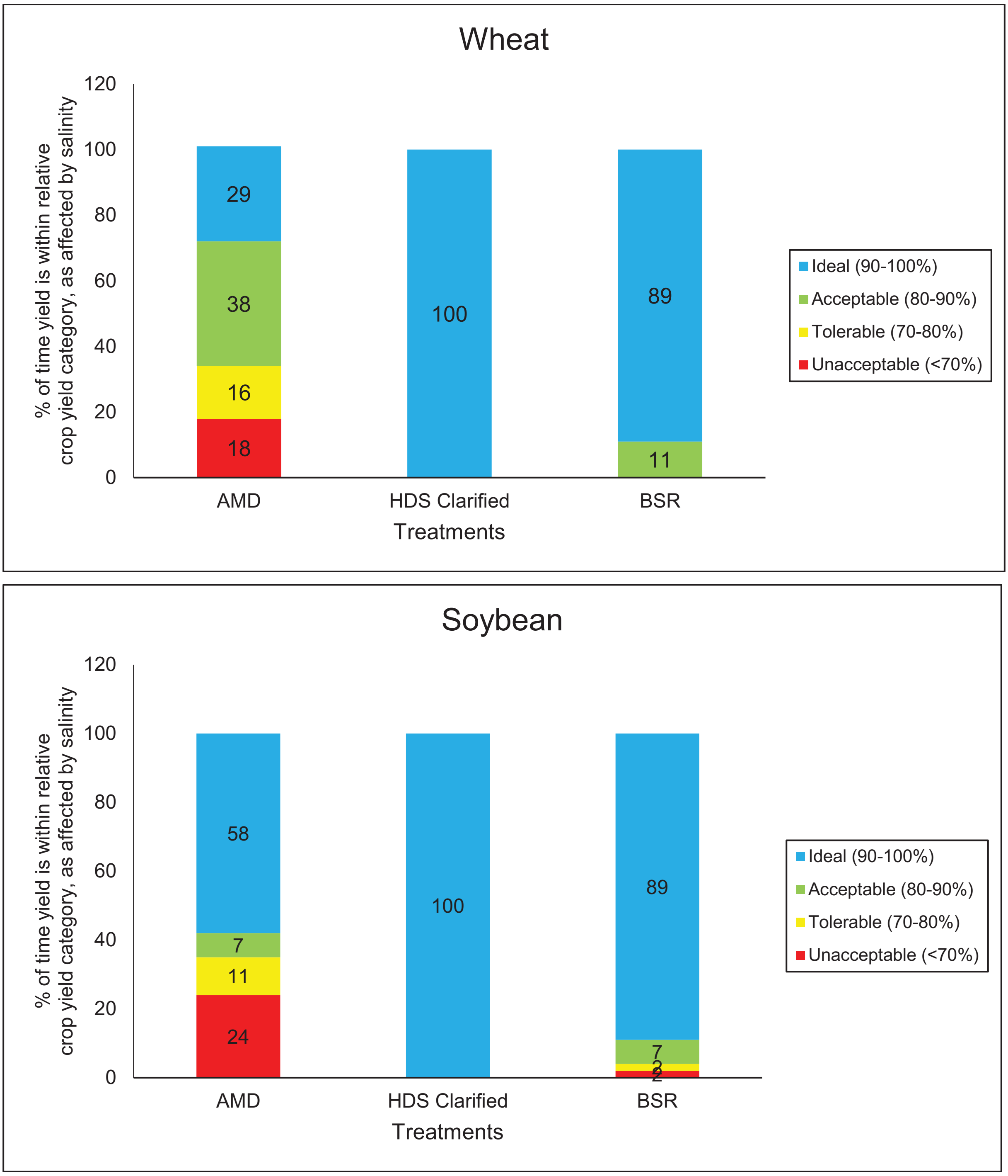

Figure 3-1: Percentage of time wheat (a) and soybean (b) yields are predicted to fall within a particular Fitness For Use relative yield category, as affected by soil salinity.

3.1.4 Potential trace element accumulation

The DSS output for trace elements is presented in Table 3-2. Iron, Al, Mn, Co, Ni, and Zn would all reach the soil accumulation threshold in less than 100 years when soil is irrigated with untreated AMD. The levels of these elements in the AMD waters are therefore deemed to be unacceptable. However, with the BSR water, all the elements highlighted by the model as of concern were expected to take more than two centuries to reach soil accumulation thresholds, which is considered ideal. With HDS-clarified water, most elements are also expected to take more than two centuries to reach soil accumulation thresholds. The exception was Co, which was predicted to accumulate to the threshold in just over a century (110 years).

Table 3-2: Number of years of irrigation of a soybean-wheat rotational cropping system in Mpumalanga with an effective annual 18% leaching fraction before trace elements reach internationally published accumulation thresholds.

Ideal	> 200 years to reach soil accumulation threshold
Acceptable	150 to 200 years to reach soil accumulation threshold
Tolerable	100 to 150 years to reach soil accumulation threshold
Unacceptable	< 100 years to reach soil accumulation threshold

Trace Element	Threshold (mg/kg)	pH 2.5	pH 7.5	BSR
Al	2500	8	>1000	> 1000
Co	25	16	110	> 1000
Fe	2500	1	>1000	537
Mn	100	1	219	313
Ni	100	53	365	877
Se	10	240	219	> 1000
Zn	500	84	>1000	212

3.1.5 Potential corrosion or scaling of irrigation equipment and clogging of drippers

Untreated AMD and HDS clarified waters are expected to be unacceptably corrosive to irrigation infrastructure and BSR water was predicted not to be corrosive, but rather mildly scaling (Table 3-3). Mine waters often contain various contaminants, including heavy metals and acidic compounds (Masindi and Muedi, 2018). These waters can accelerate corrosion, causing deterioration and structural damage when they come into contact with irrigation equipment composed of metals, such as steel or iron (Jeong et al.2016). Corrosion-resistant materials, such as stainless steel, polyvinyl chloride, and fibreglass-reinforced plastic, are less prone to corrosion and can withstand the impact of mine-impacted waters. Therefore, the use of these materials is recommended.

Table 3-3: Fitness for Use Category determined by the corrosion or scaling potential, as indicated by the Langelier Index.

Parameter	pH 2.5	pH 7.5	BSR
Langelier Index (LI)	-7.48	-3.10	1.63
Corrosive or Scaling	Corrosive	Corrosive	Not Corrosive

Colours indicate FFU [red = unacceptable (LI is > + 2 or < − 2), yellow = tolerable (LI is − 1.0 to − 2.0 or + 1.0 to + 2.0) and blue = ideal (LI is 0 to − 0.5 or 0 to + 0.5)]

Manganese and Fe concentrations are also too high (> 1.5 mg L^{-1}) for AMD to be used with drip irrigation. The BSR water was predicted not to be a problem if used for micro-irrigation systems, as its suspended solids, pH, and Mn are ideal (suspended solids < 50, pH < 7, Mn < 0.1 mg/L) and only tolerable levels of Fe (0.5–1.5 mg/L).

Table 3-4: Fitness for Use Category determined by the potential of an irrigation water constituent to cause dripper clogging.

Parameter	pH 2.5	pH 7.5	BSR
Suspended Solids (mg/L)	40	2	40
pH	2.6	6.8	7.6
Manganese (Mn)	21.6	0.1	0.1
Total Iron (Fe)	600	0.1	1

Colours indicate FFU classes [red = unacceptable (suspended solids > 100, pH is > 8, Mn and Fe are > 1.5 mg/L), yellow = tolerable (suspended solids 75-100, pH is 7.5–8, Mn and Fe are 0.5–1.5 mg/L), green = acceptable (suspended solids 50-75, pH is 7–7.5, Mn is 0.1–0.5 mg/L and Fe is 0.2–0.5 mg/L) and blue = ideal (suspended solids <50, pH is < 7, Mn is < 0.1 mg/L and Fe is < 0.2 mg/L)]

3.2 Crop and soil response to irrigation with a range of untreated and partially treated acid mine drainage in glasshouse pot trials

Two pot experiments were conducted in a glasshouse to assess crop and soil responses to irrigation with various mining-influenced waters. The experiments were conducted at the University of Pretoria's Innovation Africa Farm in the winter of 2023 and the summer of 2023/24. A sandy loam soil was obtained from the farm, from a profile classified as a deep Hutton, loamy, kaolinite, mesic, typic Eutrustox soil (Soil Classification Working Group, 1991), which was used as growth medium. Irrigation waters were collected weekly from the mine water treatment plant in Mpumalanga. Table 3-5 presents the average water qualities of the different waters used in this experiment. Target Water Quality Ranges (TWQR) for irrigation, as specified by the Department of Water Affairs (1996), are provided for each element. The shaded values indicate the constituents that fell outside these ranges. The table shows that, apart from the acidic mine waters, where Al, Fe, Mn, Zn, and Ni were flagged as potentially problematic, metal concentrations were generally low, with the majority falling below threshold levels. The only exception to the circumneutral to alkaline waters was for Fe and Mn in the HDS waters, whether clarified or not, and for Mn in the slightly acidified HDS water.

3.2.1 Experimental design and treatments

Treatments consisted of a municipal freshwater control, highly acidic and less acidic AMD, HDS unclarified and clarified neutralized mine waters, and RO pre-treatment water (Table 3-5). Wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), and stooling rye (*Secale cereale* L.) were planted in winter, and sorghum (*Sorghum bicolor* L.) and soybean (*Glycine max* L.) were planted in summer. These crops were selected based on their tolerance to salinity and/or adaptation to slightly acidic conditions. Tapered 6 L pots with a top diameter of 24 cm, a height of 22 cm, and a base diameter of 18 cm were used. Each treatment was replicated three times and arranged in a Randomized Complete Block Design (RCBD). Pots were placed on a rotating table in the glasshouse in order to eliminate environmental bias.

Table 3-5: Average chemical composition of municipal and mine waters used in the irrigation trials, as well as Target Water Quality Ranges set by the Department of Water Affairs, South Africa (1996).

Constituent	**Freshwater**	**Highly Acidic**	**Less Acidic**	**HDS Unclarified**	**HDS Clarified**	**RO pre-treatment**	**TWQR**
pH	7	2.5	3.5	9.0	8.5	7.5	-
EC (mS/m)	22	488	425	336	350	344	-
Al (mg/L)	0	93	65	0.22	0.09	0.09	5
As		<0.01	<0.01	<0.01	<0.01	<0.01	0.1
Cd		0.004	0.003	<0.003	<0.003	<0.003	100
Ca	20	546	526	717	683	664	-
Cl		11	15	30	31	32	100
Cu		0.03	0.02	<0.01	<0.01	<0.01	0.2
F		<0.2	<0.2	0.69	0.64	0.63	2
Pb		0.06	<0.01	<0.01	<0.01	<0.01	0.2
Mg	8.96	308	448	120	114	121	-
Mn	0.39	25	22	0.12	0.08	0.10	0.02
Hg		<0.001	<0.001	<0.001	<0.001	<0.001	0.002

Constituent	Freshwater	Highly Acidic	Less Acidic	HDS Unclarified	HDS Clarified	RO pre-treatment	TWQR
Ni		0.46	0.41	0.06	0.06	0.06	0.2
Se		0.02	0.01	<0.01	<0.01	<0.01	0.02
Na	3.27	102	227	131	130	136	-
SO_4		3658	3243	2326	2394	2369	-
Fe	0	638	600	28	31	0.11	5
Zn		1.50	1.30	0.06	0.03	0.02	1
TDS		4910	5130	3750	3560	3320	
TSS		200	52	48406	96	<2	

Shaded cells indicate values above SAWQG threshold levels.

3.2.2 Trial establishment and management

Plant populations of 100 kg wheat or barley, 70 kg stooling rye, 20 kg sorghum, and 300 000 seeds for soybean per hectare were used. Plant populations were calculated based on the surface area of each pot, which was filled with 7 kg soil. Limestone was applied to counter the high acidity levels of the AMD irrigation treatments. An estimated irrigation volume of 700 mm per season was used to determine the amount of limestone required for neutralization. The limestone application rates were based on the total acidity of the irrigation water, expressed as $CaCO_3$, necessary to neutralize the water to a target pH of 8.3. The water with a pH of 3.5 had an acidity of 221 mg L^{-1} as $CaCO_3$, while the water with a pH of 2.5 had an acidity of 2 015 mg L^{-1} as $CaCO_3$. Limestone applications were based on pot surface area, giving 9 g (pH 3.5) and 79 g (pH 2.5) per pot.

3.2.3 Irrigation management

The amount of irrigation water to apply with each irrigation was determined by filling the pots with soil, irrigating them sufficiently to cause free drainage, and covering the soil surface with plastic. After 72 hours, pots were weighed to determine field capacity. Irrigation amount was determined by weighing each pot, and the difference to reach field capacity was the amount to be applied plus a leaching fraction (LF) to minimize salt accumulation in the soil profile (Table 3-6). Leaching fractions were calculated based on the EC of each water source and the salinity tolerance of each crop (Equation 3.1), according to the method of Rhoades and Merrill (1976)

$$\mathrm{LF} = \frac{\mathrm{EC_W}}{5(\mathrm{EC_e}) - \mathrm{EC_W}} \qquad \text{(eq. 3.1)}$$

LF is the minimum leaching fraction to control salinity within crop tolerance levels.

EC_w is the salinity of the applied irrigation water, and

EC_e is the average maximum threshold soil salinity (saturated extract) tolerated by the crop.

Crops were irrigated once a week after emergence. Irrigation frequency was increased to every three days as the water demand increased with growth. Amount applied with each irrigation to each pot ranged from 1 to 1.8 L. Pots were placed on saucers to collect percolate and cork stoppers were used to lift pots above the leachate to avoid capillary uptake.

Table 3-6: Crop tolerance to salinity and leaching fractions (%).[7]

	Crop Salinity Tolerance (ECe)	Barley (800 mS/m)	Wheat (600 mS/m)	Stooling Rye (1140 mS/m)	Sorghum (680 mS/m)	Soybean (500 mS/m)
Irrigation Water pH	Irrigation Water EC (mS/m)	Leaching fraction (%)				
7	22	1	1	0	1	1
2.5	407	11	16	8	14	19
3.5	425	12	17	8	14	20
9	336	9	13	6	11	16
8.5	350	10	13	7	11	16
7.5	344	9	13	6	11	16

[7] *Crop salinity (*saturated extract) *tolerance thresholds, indicated in parentheses, were obtained from* FAO (1994); Guan et al. (2014); Hussain (2019).

3.2.4 Fertilization

Inorganic fertilizer was applied to the soils before planting to increase soil P and K status to optimum levels, and meet individual crop requirements. Maximum levels of 150 kg N ha^{-1}, 60 kg P ha^{-1}, and 30 kg K ha^{-1} were applied based on soil analysis and maximum crop requirements. Nutrient deficiencies were observed despite adequate NPK application at planting due to the leaching fractions that were applied, and therefore, a hydroponic nutrient solution with the concentrations listed in Table 3-7 was applied every fourth irrigation at 0.5 L per pot, which was less than the deficit to field capacity to ensure no nutrient solution would leach at the time of application. Irrigation with a 0.5 L nutrient solution applied 7.6 kg N, 4.7 kg P and 23 kg K per hectare with each irrigation.

Table 3-7: Composition of the nutrient solution.

Element	Solution concentration (mg L^{-1})
N	68
P	42
K	208
Mg	30
S	64
Fe	1.25
Mn	0.30
Zn	0.15
Cu	0.02
B	0.37
Mo	0.04

3.2.5 Data collection and analysis

Crop height was measured weekly, and at physiological maturity, plant biomass and economic yield were determined, with plants cut off at ground level and oven-dried at 65 ˚C for 48 h. Plant tissue analyses were performed on the dried material to determine the concentrations of potentially toxic elements in biomass and grains. Soil samples representing each treatment were analysed at the end of the experiment to determine accumulation of trace elements applied through irrigation. The data were statistically analysed using Microsoft Excel and GenStat. Means separation was performed using Duncan's multiple range test, with the least significant difference (LSD) tested at a 95% confidence level ($P < 0.05$).

3.2.6 Effects of mine waters on soil chemical properties

3.2.6.1 Soil pH and EC

Soil analysis was conducted at the end of the experiment, and the results after two seasons of irrigation are reported. Soil pH was measured in KCl instead of water, as it was important to account for soluble and exchangeable acidity. After two seasons, untreated AMD significantly ($P < 0.05$) reduced soil pH from 5.5 to 3.5 (highly acidic water) and to 4.4 (less acidic water) (Figure 3-2). The significant reduction in soil pH showed that untreated AMD had an acidifying effect on the soil, even after the application of 1.6 and 14 t ha^{-1} limestone per season.

A possible reason for the decrease in pH might be that the amount of limestone applied was insufficient and/or limestone particles did not dissolve quickly enough to neutralize waters. Another reason could be that the amount of irrigation applied was more than 700 mm, which was used to estimate the limestone. When AMD is applied to the soil through irrigation, sulphuric acid and dissolved metals, which are commonly found in high concentrations, can lead to soil acidification and affect the availability of some plant nutrients (Lin et al. 2005; Nukpezah et al. 2017). Furthermore, the interaction between clays and AMD can lead to the dissolution and movement of clays out of the soil profile (Vazquez 2009), making acidic waters potentially problematic for irrigation.

Salinity, measured as ECe, was obtained using a soil:water ratio of 1:2.5 to determine the EC and a conversion factor (2.5) to calculate the ECe value. The application of mine water for irrigation resulted in a significant increase in salinity (Figure 3-2). This was due to the increased salt concentrations resulting from elements such as Ca, Mg, Na, SO_4, Mn, Al, and K. Water with a pH of 9 had the highest ECe (806 mS m^{-1}), even though it contained large amounts of limestone, which could precipitate salts out of solution. Sludge deposition with this unclarified water contributed significantly to the increase in ECe.

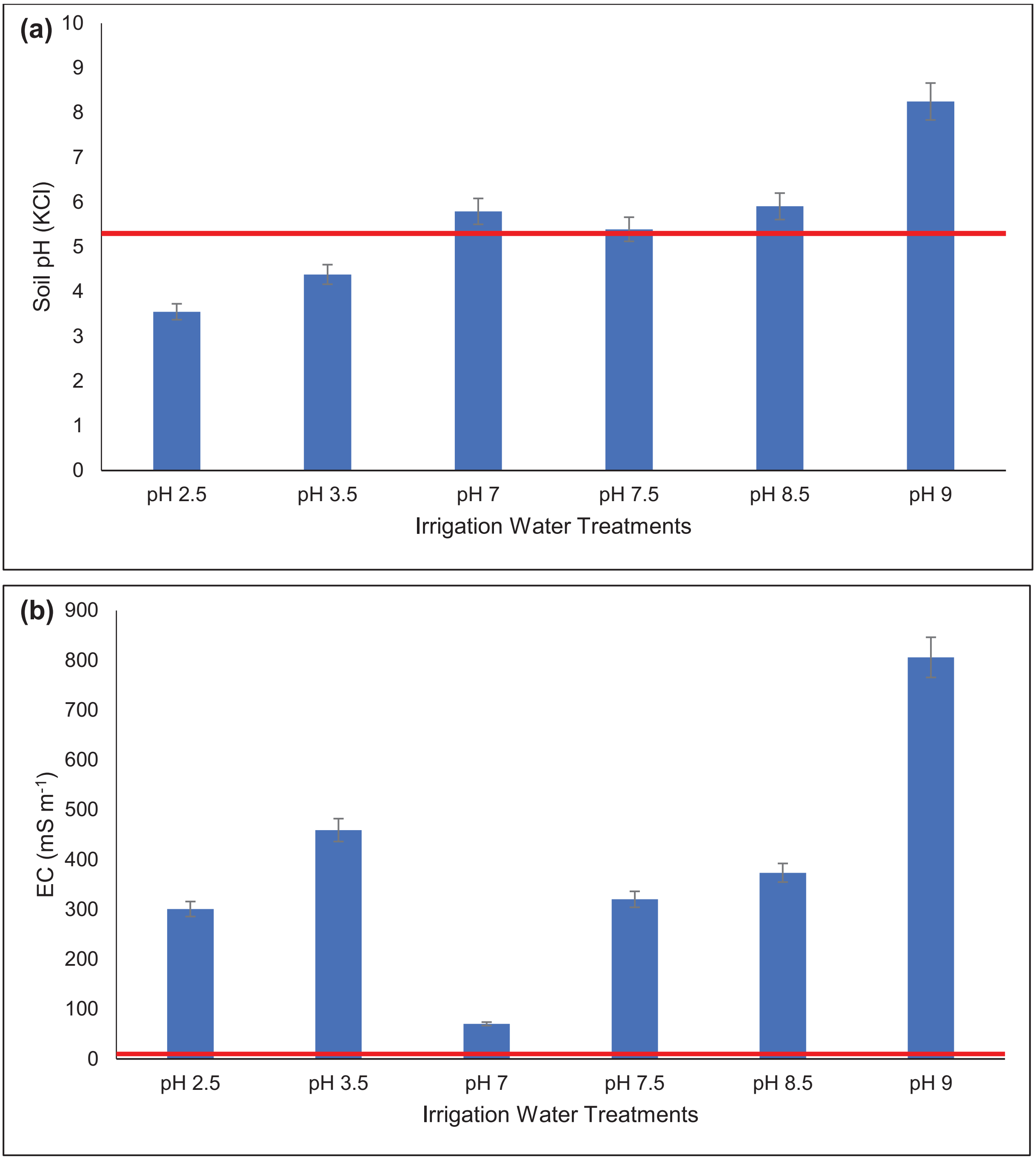

Figure 3-2: Soil pH (a) and salinity (b) affected by irrigation with mining-influenced waters after two seasons. The horizontal red lines represents the initial pH and EC. Error bars indicate statistical significance at P <0.05.

3.2.6.2 Selected element concentration in soil.

Table 3-8 shows seasonal average elemental enrichment for selected elements as highlighted by the DSS as of potential concern. When compared with initial soil conditions, irrigation with untreated acidic water resulted in an unacceptably rapid accumulation of metals (Al, Co, Fe, Mn, Ni, and Zn). These elements are more soluble in acidic environments, and their availability increases, especially that of Al, when the pH falls below a threshold value (pH 4) (Khan et al., 2015). The pH 2.5 treatment had the highest elemental enrichment of Al (3 190 mg kg-1), Co (8.5 mg kg-1), Fe (23 622 mg kg-1), Mn (966 mg kg-1) and Ni (18 mg kg-1) per season. This increased accumulation highlights potential environmental and health risks, particularly concerning the safety of agricultural produce grown in such soils. The concentrations of Al, Fe, and Mn were far above the international threshold levels specified in the 1996 South African Irrigation Water Quality Guidelines, even before irrigation. According to Sposito (2008), these concentrations are not of concern as they can be converted into various oxidation states in soil, limiting their mobility and toxicity.

Table 3-8: Average seasonal elemental accumulation in soils irrigated with untreated and partially treated mine waters with threshold levels from the 1996 South African Irrigation Water Quality Guidelines.

Element	Threshold	Initial	pH 2.5	pH 3.5	pH 7.0	pH 7.5	pH 8.5	pH 9.0
	*Elemental enrichment (mg/kg)							
Al	2500	25080	3190	2134	3	3	6	3190
Fe	2500	26820	23622	21889	4	1078	863	23622
Mn	100	145	966	874	3	4	4	966
Zn	500	12	46	47	0.6	0.9	1.6	46
As	50	0.6	0.26	0.24	0.11	0.13	0.18	0.26
Cd	5	0.4	0.15	0.12	0.07	0.08	0.09	0.15
Co	25	-	8.5	9.5	5	6	16	8.5
Hg	1	0.02	0.04	0.04	0.015	0.02	0.02	0.04
Ni	100	6	18	16	1.3	2.3	2.1	18
Pb	100	3	2.3	1.4	0.08	0.34	0.38	2.3

*Elemental enrichment refers to the increase in concentration of elements in the soil through irrigation water.

3.2.7 Crop responses to irrigation with mine waters.

3.2.7.1 Growth and development.

Plant height was measured during the growing season for all crops and is presented in Figure 3-3. Plant height showed a similar trend from emergence to maturity for all crops irrigated with either untreated or partially treated mine waters. Variations in plant height were not noticeable for barley, stooling rye and wheat. Crops irrigated with untreated acidic waters showed signs of stunting 21 days after planting (DAP) for sorghum and 56 DAP for soybean. At the end of the experiment, plant height was not significantly different between the partially treated waters and the control treatment, and a significant reduction was observed with the untreated AMD waters. Nitrogen deficiency symptoms were observed in treatments irrigated with untreated AMD, although the same nutrient regime was followed with a hydroponic solution for all treatments. Irrigation with acidic waters with leaching fractions (8 - 21%) increased the solubility of potentially toxic elements (Al, Fe and Mn) that could render essential nutrients such as N, P, K, Ca and Mg less available for plant uptake due to competition, precipitation and leaching (Eynard et al. 2005).

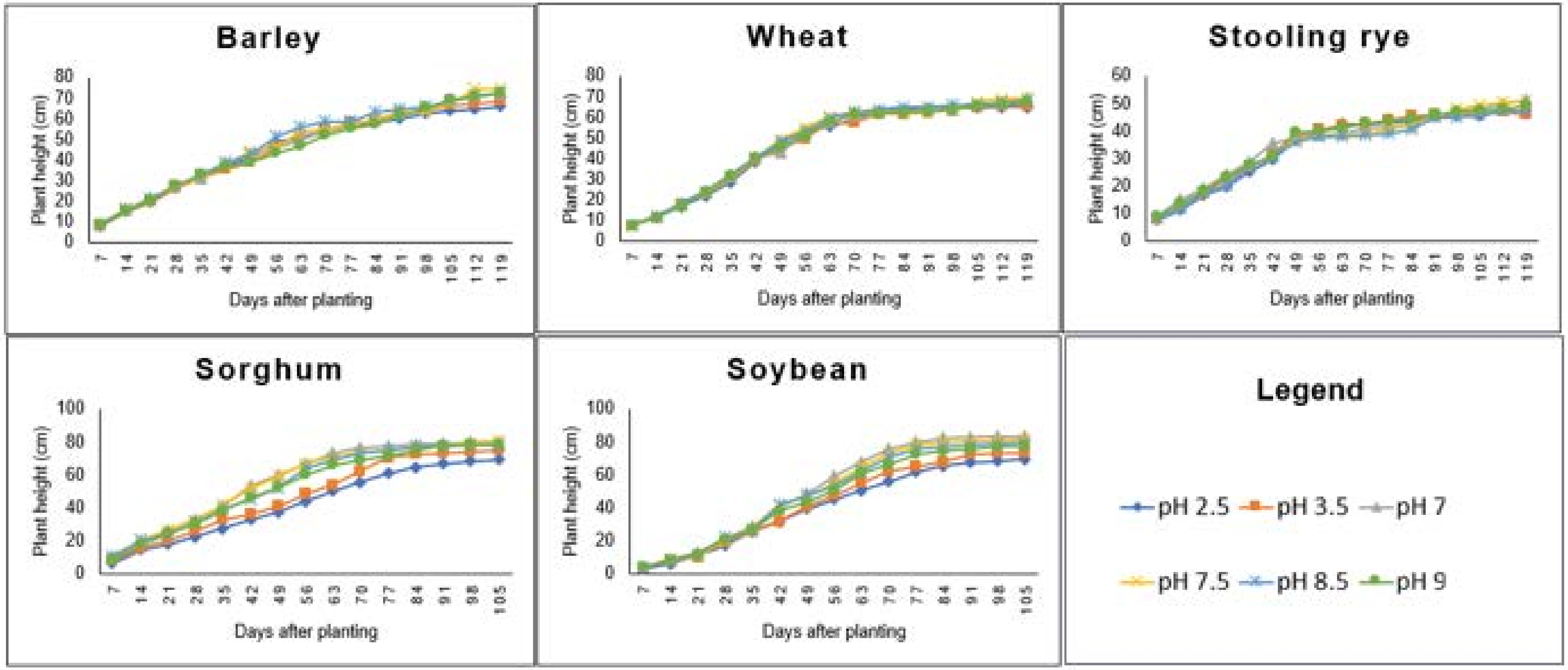

Figure 3-3: Height of crops as influenced by irrigation with untreated and partially treated mine waters.

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3.2.7.2 Biomass accumulation and grain yield

Generally, the use of mine waters for irrigation reduced biomass production and overall yield for summer and winter crops (Figure 3-5 and Figure 3-6). However, no differences were visually observed (Figure 3-4), and no statistically significant differences were found in the dry biomass of stooling rye between the six treatments. According to Francois et al. (1989), stooling rye is categorized as a salt-tolerant crop, with a biomass yield unaffected up to an electrical conductivity of 1140 mS m^{-1} (ECe). This plant species has evolved mechanisms, such as the exclusion of ions from the roots or compartmentalization within plant tissues, which enable it to withstand high concentrations of elements (Hoffmann and Galisa 1999). Grain yield was significantly reduced in treatments irrigated with untreated mine waters (Figure 3-6). At pH 2.5, a yield penalty of ~40% was recorded for barley and sorghum, and 30% for wheat and soybean, compared to the control.

Biomass and yield were slightly reduced at irrigation water pH levels of 7.5, 8.5, and 9 compared to the freshwater treatment. This may be due to excess water applied keeping the soil wetter than in other treatments, and therefore at a higher matric potential. This more constant wetness likely made it easier for plants to access water, reducing the uptake of salts, as water was always available, and the plants did not need to rely on salty reserves for hydration. Irrigation with sludge-laden water resulted in sediment buildup, creating a crust layer on the surface and preventing water infiltration into the soil. This could affect water distribution owing to reduced soil permeability. Overhead irrigation with this water could also be problematic, as the solids deposited on the leaves may reduce photosynthesis by hindering gaseous exchange, which could impact the plants' ability to produce assimilates efficiently. Therefore, careful consideration of irrigation with sludge-laden water is essential to prevent such adverse effects.

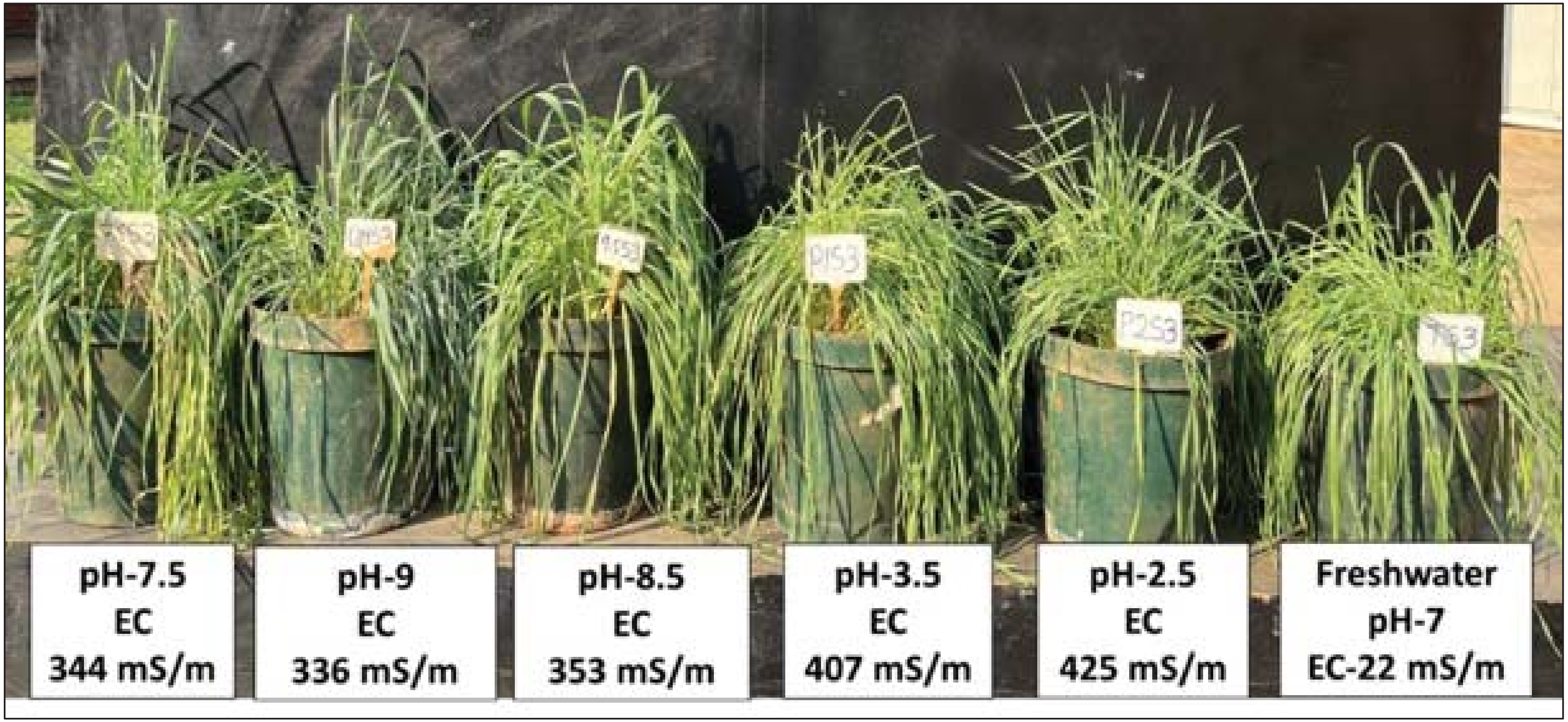


Figure 3-4: Stooling rye treatments eight weeks after planting.

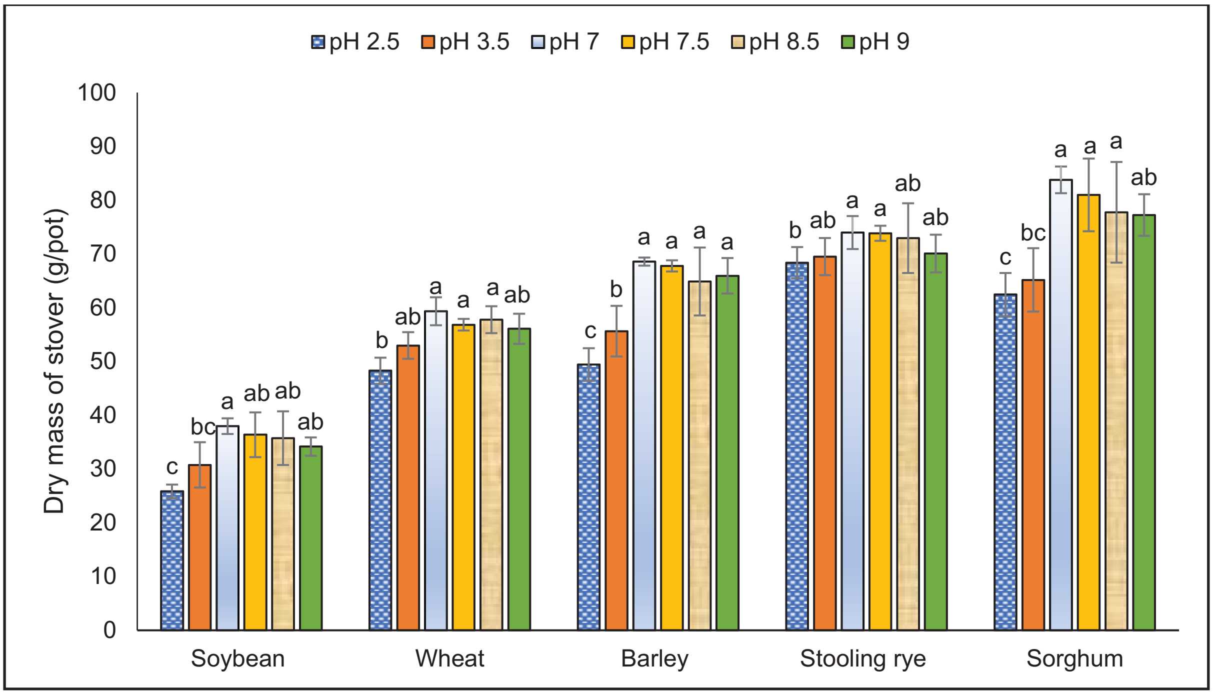


Figure 3-5: Vegetative dry mass of crops irrigated with untreated and partially treated mine waters.

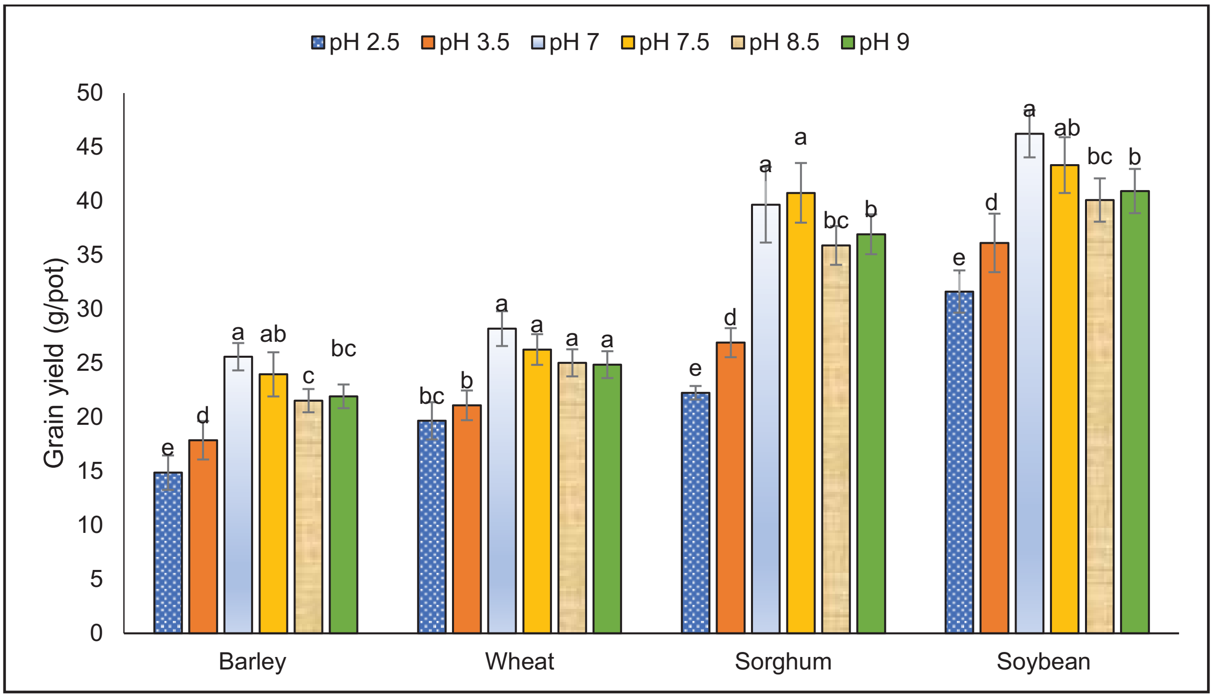


Figure 3-6: Grain yields of crops irrigated with untreated and partially treated mine waters.

3.2.8 Food and feed safety

Many trace elements are present in mine waters, which can potentially pose a hazard. This raises safety concerns regarding the consumption of crops irrigated with mine waters. From a food safety perspective, plant tissues were analysed for As, Cd, Pb and Hg, as they have been listed as potential elements of concern in the CCCF (Codex Committee on Contaminants in Food (CCCF) 2019). The use of mine water for irrigation in this experiment has been shown to significantly increase metal concentrations in both vegetative and reproductive plant parts.

Figure 3-7 shows the chemical composition of stooling rye plant tissue irrigated with untreated and partially treated mine waters. The red horizontal lines represent permissible limits for fodder safety. Concentrations of Cd, Hg, Ni and Pb were below these limits after a single season of irrigation and can therefore be deemed safe to consume by livestock, at least in the short term. However, these elements are expected to accumulate in the soil profile over time, suggesting that the level of elemental concentrations in plant tissues may increase to unacceptable levels very quickly. The pH 2.5 water exhibited the highest elemental accumulation compared to the other treatments.

Concentrations of Cd, Hg, Ni, and Pb in the grain of all the other crops studied are presented graphically in Figure 3-8. Untreated acidic waters generally resulted in the highest elemental concentrations in grains. Concentrations of Pb were above the permissible limit stipulated by the Codex Alimentarius (2006) in grains of all crops irrigated with untreated, highly acidic water (pH 2.5), even after just two seasons. This poses a threat to humans, as it can cause physiological, morphological, and genetic defects, including reduced growth, mutagenesis, and increased mortality (Khan et al., 2010; Li et al., 2010; Luo et al., 2011).

When compared to the soil concentrations, plant tissues showed significantly lower concentrations of trace elements despite being exposed to high levels in the soil. This may be due to the plants having evolved mechanisms, such as root exclusion, to limit the uptake and internal accumulation of these potentially toxic elements, which is crucial in minimizing the transfer of these elements into the food chain (Antoniadis et al., 2017).

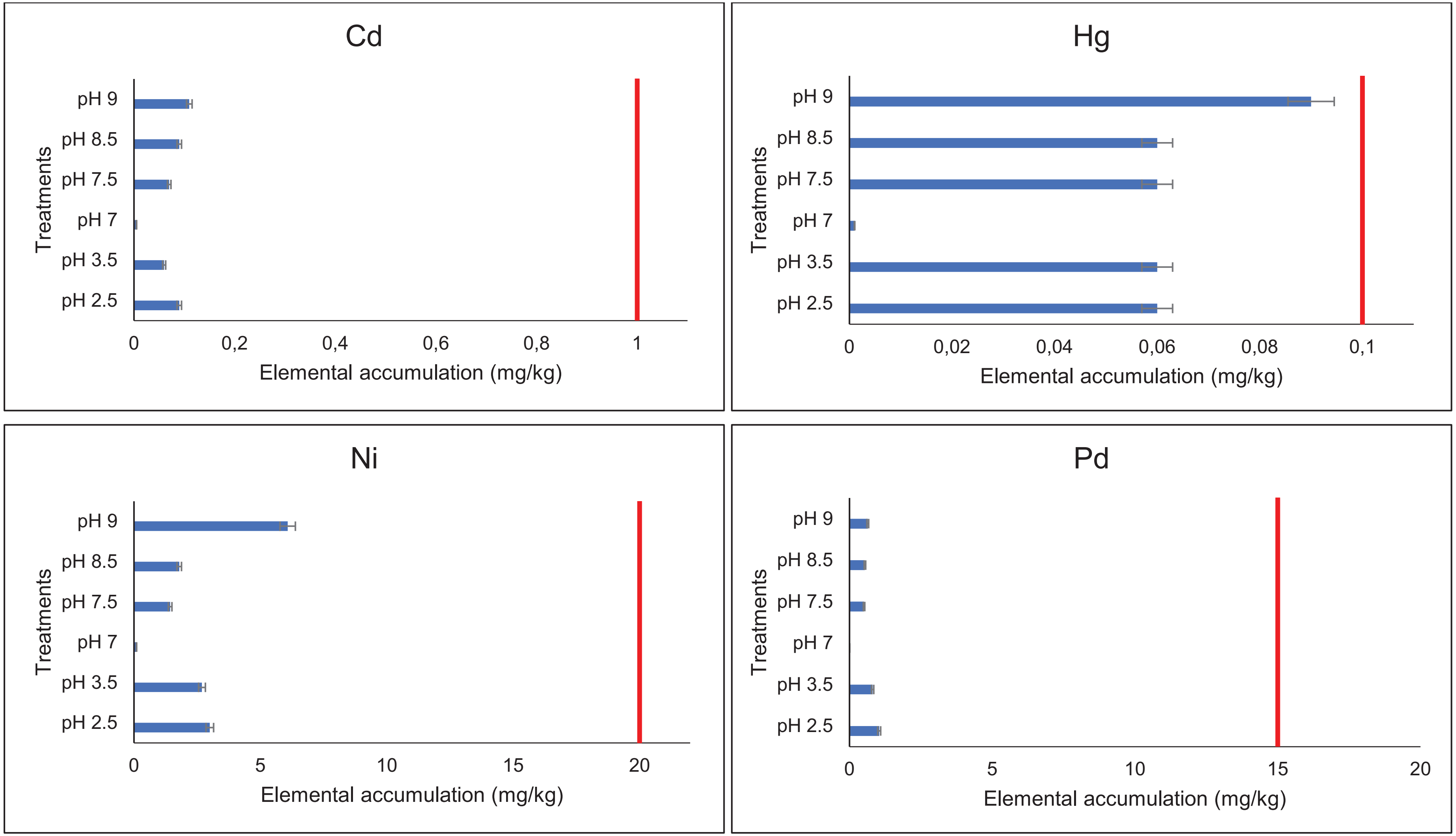


Figure 3-7: Cd, Hg, Ni and Pb concentrations for fodder safety evaluation of stooling rye irrigated with mine waters for one season.

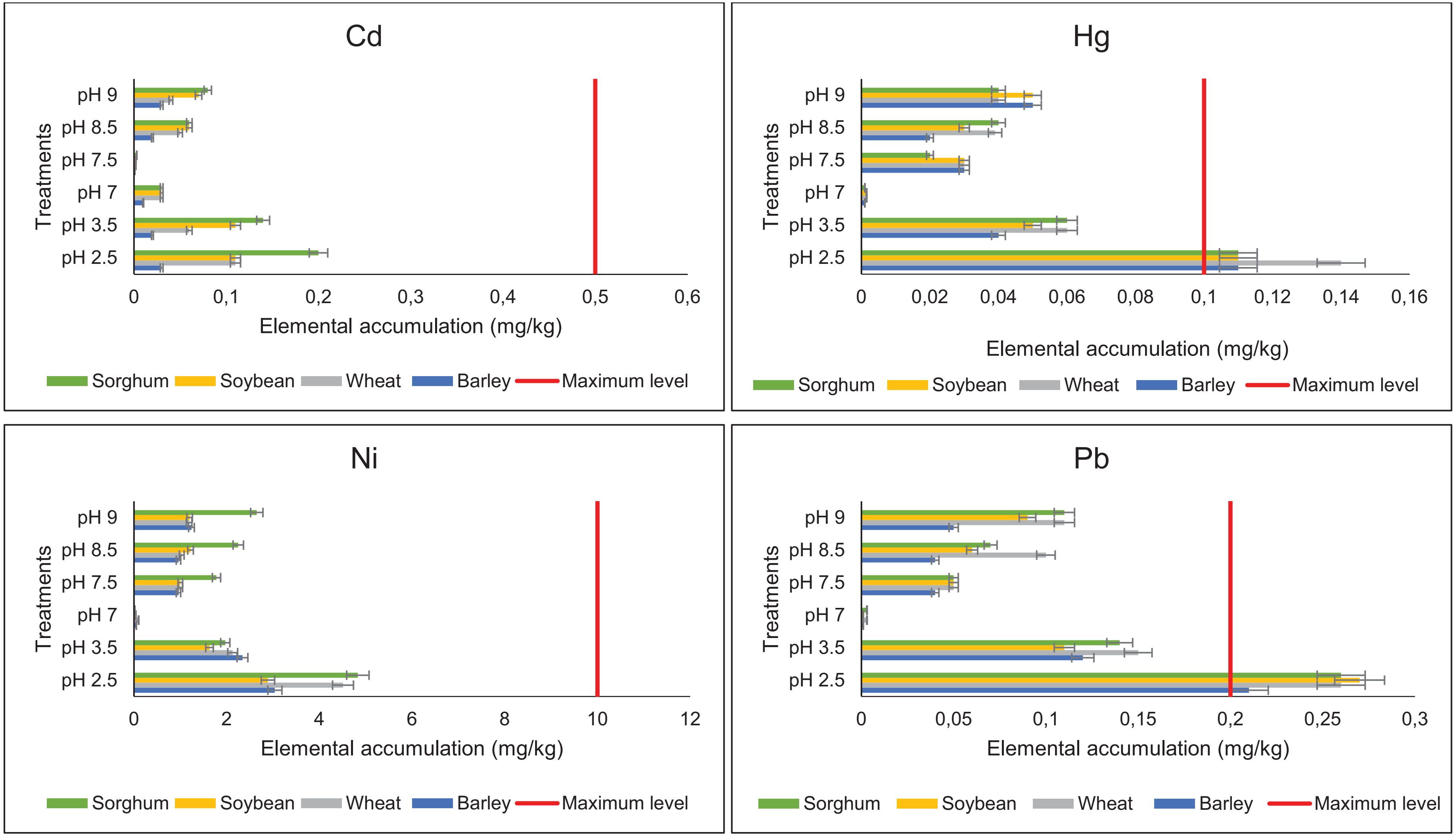


Figure 3-8: Cd, Hg, Ni and Pb concentrations in grains of barley, wheat, soybean and sorghum irrigated with mine waters.

3.3 Long-term effects of irrigation with neutralized acid mine drainage from a high-density sludge treatment plant

Unclarified water is produced in the Stage 1 reactor of the HDS treatment process, where hydrated lime ($Ca(OH)_2$) is added to AMD to produce water with a pH of approximately 9. This water is rich in Al, Fe, Mn, and gypsum ($CaSO_4.2H_2O$) due to the use of Ca-based liming material and the high sulphate content of AMD. The sludge contained in this water is referred to as GypFeMn, indicating an Fe- and Mn-rich gypsum product. Unclarified neutralized mine water from the mixing tank is pumped through self-cleaning strainers to remove coarse and fine particles before passing through ultrafiltration membranes (reverse osmosis pre-treatment). The solution is called neutralized clarified water and has approximately 98 percent gypsum (coarse fraction), referred to as Gyp, and a fine fraction referred to as GypB, representing gypsum with brucite ($Mg(OH)_2$).

The use of unclarified neutralized mine water for irrigation can eliminate the need for clarification, ultrafiltration, and RO, thereby reducing the running costs of treatment plants. Additionally, the sludge material present in these waters can serve as a fertilizer for crops, as it contains dissolved nutrients and elements that can aid in the metabolic activity of microorganisms in the soil, potentially enhancing soil fertility and crop productivity (Pratap et al., 2023). However, the continuous use of mine-impacted water poses a long-term risk to soil ecosystems (Ma et al., 2015) because it may deposit phytotoxic elements in the soil profile (particularly Al, Fe, and Mn). When accumulated in substantial amounts, these elements can be detrimental to crops and accumulate in plant tissues to levels that are unsafe for human or animal consumption.

Literature suggests that when the gypsum content of the soil exceeds 25%, it may negatively impact crop growth and yield (Delbari et al., 2019). The limitations of crop growth and yield at these gypsum levels have been attributed to gypsum affecting soil physical properties and causing nutrient imbalances to such an extent that the root zone becomes an inhospitable environment for crop roots. Nutrient deficiencies were observed by Sukati et al. (2020), who noted that when sludge was used as a soil amendment, phosphorus (P) became unavailable due to the presence of iron oxides and Calcium phosphates.

Over the past few decades, researchers have examined the viability and sustainability of irrigating crops with calcium and sulphate-rich mine water. The results showed that crop production under these conditions was feasible with proper management. According to Annandale, et al. (2007), irrigation with calcium and sulphate-rich mine water can result in higher yields than dry land cultivation when done correctly. However, this becomes more feasible if a high leaching fraction is permitted, which helps remove surplus salts from the soil profile, lowering root zone salinity and eventual salt stress.

The long-term use of calcium- and sulphate-rich mine water for irrigation has not been widely demonstrated. Most studies published in recent years have focused on the short-term impacts of mine wastewater irrigation on soil and crops. Therefore, this component of the study was conducted to gain a better understanding of the responses of soil and crops to long-term irrigation with partially treated mine waters containing calcium- and sulphate-rich sludge.

3.3.1 Experimental design and treatments

A pot trial was set up to assess the response of winter wheat (*Triticum aestivum* L.) and summer sorghum (*Sorghum bicolor* L.) to long-term irrigation with unclarified neutralized mine waters, specifically sludge loading, and clarified neutralized mine waters. The crops were chosen based on their tolerance to salt and acidity (Table 3-9). The experiment focused on crop and soil responses, as well as potentially toxic elemental concentrations in plant tissues. Plant tissue analysis was conducted to determine the elements that influence plant growth.

Table 3-9: Wheat and sorghum acidity and salinity tolerance (adapted from Jovanovic 1998, Agricol 2016, and Pannar Product Catalogue 2013)

Crop	Species	Growth	Optimum pH	Salinity Tol. (mS m^{-1})	Rainfall (mm)
Wheat	*Triticum spp.*	Annual	5.5-6.5	600	-
Sorghum	*Sorgum bicolor*	Annual	-	680	400-600

3.3.1.1 Sources of soil and sludge and development of mixtures.

Hutton soil from the University of Pretoria's Experimental Farm was analysed (Table 3-10) and used for the experiment. Sludge samples were collected from the eMalahleni Water Reclamation Plant and analysed. The mineral compositions are listed in Table 3-11, and chemical analyses of the sludges are presented in Table 3-11.

The sludge rich in brucite was designated as GypB and the Fe- and Mn-rich sludge was designated as GypFeMn. Gypsum sludge (Gyp) was not included in this study because it consisted almost entirely of gypsum and was not anticipated to have any significant impact on long-term accumulation. To develop soil-sludge mixtures, sludges were applied at 0%, 25%, 50%, 75%, and 100%. A consistent mixture of soil and sludge was obtained by mixing each sludge level with soil on a mass basis. The mixtures were then transferred into pots of 17 cm top, 13 cm bottom diameter, and 15 cm height. The application rates were determined by assuming that long-term continuous irrigation with sludge-laden water results in extremely high levels of sludge accumulation in the soil profile. For example, to achieve 25% sludge accumulation, an annual irrigation of 700 mm was assumed, with a solid concentration of 2% mixed through tillage over time to a depth of 0.15 m. It was estimated that it would take approximately only four years to enrich the top 0.15 m soil layer with sludge to this level.

Table 3-10: Selected chemical properties of soil used in the pot trial.

Parameter	Level/ Content	
pH (H_2O) at 20 solution/solid ratio	5.3	
Conductivity at 25°C (mS m^{-1}) at 2.5 solution/solid ratio	10	
	Extractable elements (mg kg-1)	**acid digestion (mg kg-1)**
Ca	265	296
Mg	75	163
K	82	423
P	27	214
Sulphur	76	131
Cd	0.19	0.34
Fe	42	29697
Al	665	12320
Mn	126	145
Na	53	209
Ni	1.8	26
Pb	3.4	3
Zn	3.4	20

Table 3-11: Materials contained in the three sludge samples from the eWRP.

Sample ID	Gypsum	Brucite	Amphibole	Calcite	Estimated Amorphous Content*
	$CaSO_4 2(H_2O)$	$Mg(OH)_2$	$Ca_2(Mg,Fe^{2+})_5Si_8O_{22}(OH)_2$	$CaCO_3$	
Mass %					
GypFeMn	64.5	7.6	2.7	4.6	20.5
GypB	80.8	16.6	0.5	2	0
Gyp	98.6	1.1	0.0	0.3	0.0

*Amorphous content was estimated based on unaccounted chemistry based on mineralogy

Table 3-12: Selected chemical properties and total elemental contents of the two sludges used in the pot trial from eWRP.

Parameter	GypFeMn	GypB
pH (H_2O) at 20 solution/solid ratio	8.5	9.5
Conductivity at 25°C (mS m^{-1}) at 20 solution/solid ratio	285	273
Total Alkalinity as $CaCO_3$ (mg kg^{-1})	632	548
Concentrations extracted by acid digestion (mg kg^{-1})		
Ca	204354	174077
Mg	46819	46660
K	87	126
P	81	259
Total Sulphur %	223265	154500
Metals		
Cd	<0.01	<0.01
Fe	164401	2393
Al	19186	5606
Mn	4781	1238
Na	535	425
Ni	59	6
Pb	<0.01	<0.01
Zn	213	18

3.3.1.2 Experimental design and treatments

The experiment had a Randomized Complete Block Design (RCBD), with nine treatments (Table 3-13) replicated four times. The treatments consisted of a control treatment (soil only) and two sludges. The number preceding the sludge abbreviation is the percentage composition on a mass basis of the soil-sludge mixture.

Table 3-13: Treatments for the pot trial with different soil-sludge mixture combinations as growth media.

Treatments	Treatment's description
SO	Soil only (Control)
25GypB	25% GypB
50GypB	50% GypB
75GypB	75% GypB
100GypB	100% GypB
25GypFeMn	25% GypFeMn
50GypFeMn	50% GypFeMn
75GypFeMn	75% GypFeMn
100GypFeMn	100% GypFeMn

3.3.1.3 Crop management.

Wheat and sorghum were planted and irrigated with tap water. Wheat was planted in winter, and the same soil-sludge mixtures were used for sorghum in summer. Ten seeds of both crops were planted and thinned to five plants (planting density of 2 500 000 plants ha^{-1}) at the three-leaf stage. Chemical fertilizers N (100 kg/ha), P (40 kg/ha), and K (40 kg/ha) were applied to ensure sufficient nutrition. The amount of irrigation water applied was determined by filling the pots with soil-sludge mixtures, irrigating them to saturation, and covering them with plastic. After 72 hours, the pots were weighed to determine the soil's field capacity. Irrigation was then determined by weighing, and the difference between the current moisture level and field capacity was the amount to be applied.

3.3.1.4 Data collection and analysis

Crop growth data were measured weekly. Due to crop failure, wheat was terminated at eight weeks and sorghum at six weeks. Plant biomass accumulation was determined by cutting at ground level and oven-drying for 48 hours at 65°C. Plant samples were then ground and analysed to determine the concentrations of potentially toxic metals in plant biomass. The soil and sludge mixtures were analysed for pH, salinity, and elemental concentrations (Ca, K, Mg, P, S, Al, Fe, Na, Mn, Si, Zn, As, Se, Cd, Ni, and Pb) as recommended by the Soil Science Society of South Africa (1990). The collected data were subjected to statistical analysis using Microsoft Excel and GenStat. Mean separation was performed using the least significant difference (LSD) test at a 5% significance level.

3.3.2 Influence of sludges on soil properties

3.3.2.1 Soil pH

Soil pH was determined in the soil samples before planting. Figure 3-9 shows that the soil pH increased significantly ($P < 0.05$) with the application of both GypFeMn and GypB sludge materials. The GypB sludge treatment at 25% had a pH increase of 3.04 and the GypFeMn had an increase of 2.05 at the same application rate. At a 75% application rate, the GypB treatment recorded a pH of 9.3 and the GypFeMn sludge was 8.9. This increase in pH was due to the alkalinity of the sludge materials, suggesting an acid buffering mechanism. The lime ($Ca(OH)_2$) used in the neutralization process increased soil pH and exchangeable Ca and Mg, thereby reducing total acidity (hydrogen ions and Al).

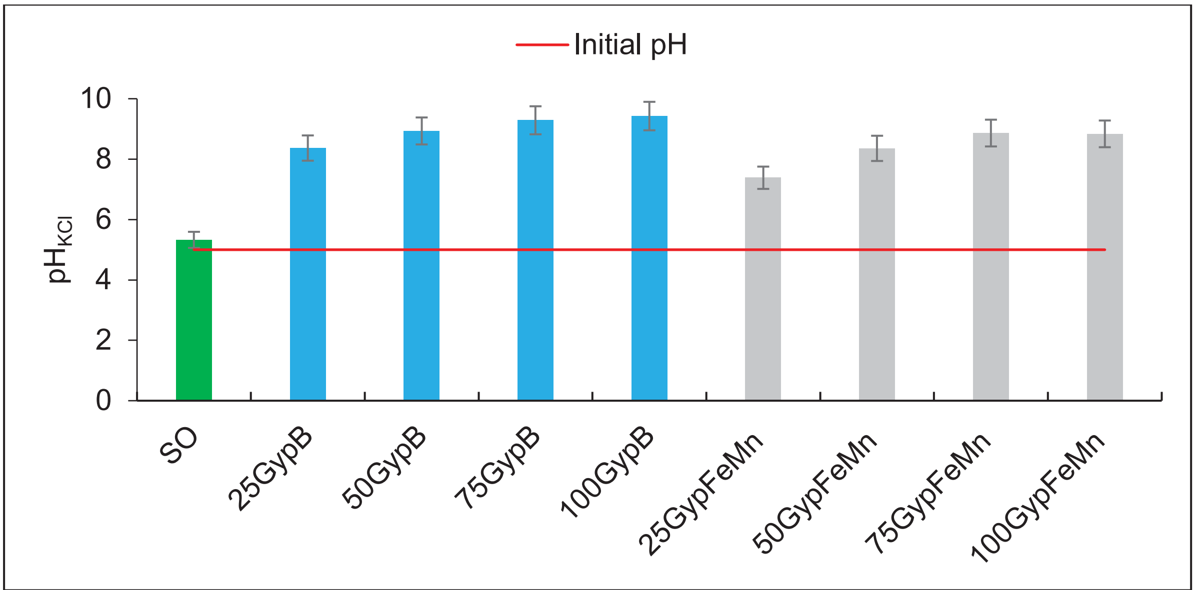


Figure 3-9: pH of soil, sludge, and soil-sludge mixtures measured before planting. Error bars indicate statistical significance at $P < 0.05$.

3.3.2.2 Soil ECe.

Although sludges contain Fe oxides known to adsorb elements, they also contain a variety of salts such as Ca, Mg, Na, SO_4, Mn, Al, and K, which might potentially increase soil salinity to levels harmful to plants, soil, and ecosystems. Soil salinity was determined by measuring the saturated paste electrical conductivity (ECe). A significant ($P < 0.05$) increase in ECe was observed with the application of both sludge types (Figure 3-10). The results showed that both sludges applied at 25% increased ECe from 19 mS m^{-1} in the control treatment to 500 mS m^{-1} in the GypB treatment and 538 mS m^{-1} in the GypFeMn treatment. In the pure sludge treatments, ECe increased to 887 mS m^{-1} under the GypB treatment and to 1080 mS m^{-1} under the GypFeMn treatment. The application of 50% or more sludge increased ECe levels above the moderately tolerant threshold (600 mS m^{-1}), suggesting that only tolerant crops can successfully grow under these conditions. According to Kotuby-Amacher (2000) and Shaygan and Baumgartl (2022),high CEC and poor drainage, sorption, and precipitation could explain why salts did not leach out of the soil profile.

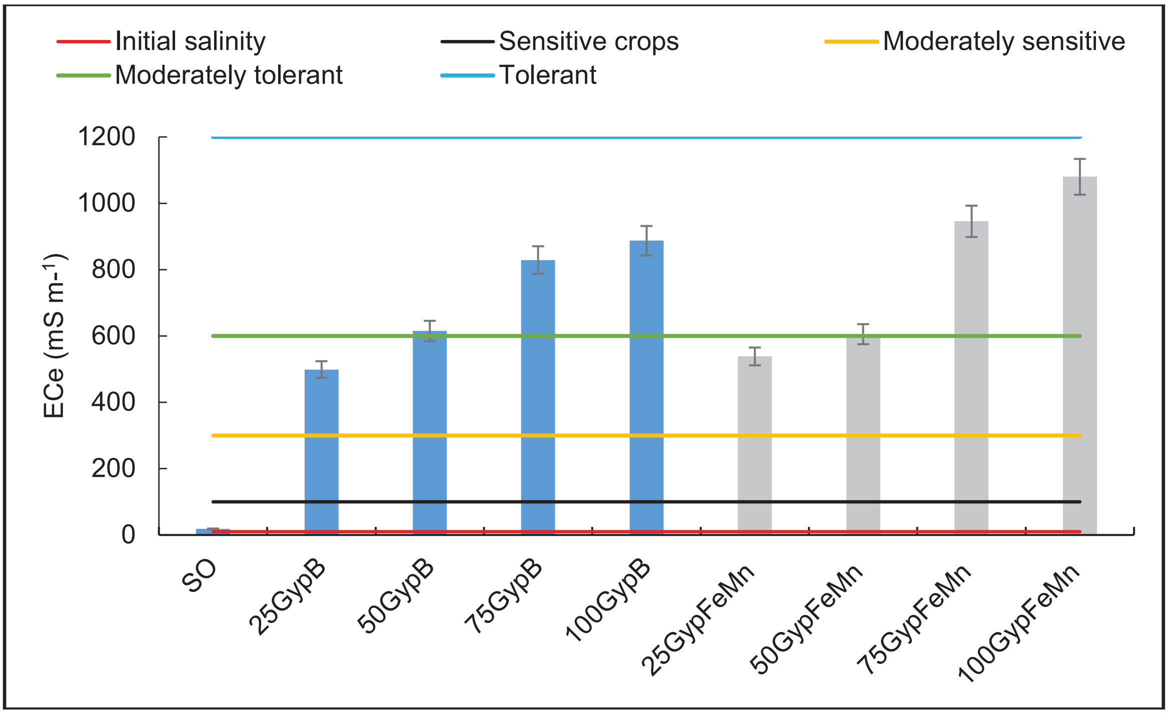


Figure 3-10: Electrical conductivity of saturated paste (mS m^{-1}) for soil, sludge, and soil-sludge mixtures measured before planting. Error bars indicate statistical significance at $P < 0.05$.

3.3.3 Selected constituents of the soil-sludge mixture and the availability of P

Figure 3-11 shows the extractable and total concentrations of Al, Fe, and Mn in the soil-sludge mixtures. The results indicated that both extractable and total elemental concentrations increased with an increase in the percentage of sludge applied. The GypFeMn treatments had higher concentrations of Fe, Al, and Mn than GypB treatments. These elements are required by plants for normal growth; however, high concentrations may result in a deficiency of essential nutrients, such as P.

The precipitation of P with Ca and other elements, especially GypB, and the adsorption of phosphate onto the Fe oxides present in GypFeMn reduced the P availability. Phosphorus is known to form a binuclear bridging complex on the hydroxylated surfaces of ferric hydroxides, where it coordinates with Fe atoms on OH groups, thereby limiting its bioavailability (Guzman et al., 2009, Guzman et al., 1994). In this study, an increase in the amount of sludge increased the content and availability of Ca and S in all treatments (Figure 3-11d and e). However, this gradually reduced the total and available P (Figure 3-11f). The GypFeMn treatment reduced

P by 97% at a sludge application rate of 75 %, and the GypB treatment reduced P by 59% at the same application rate.

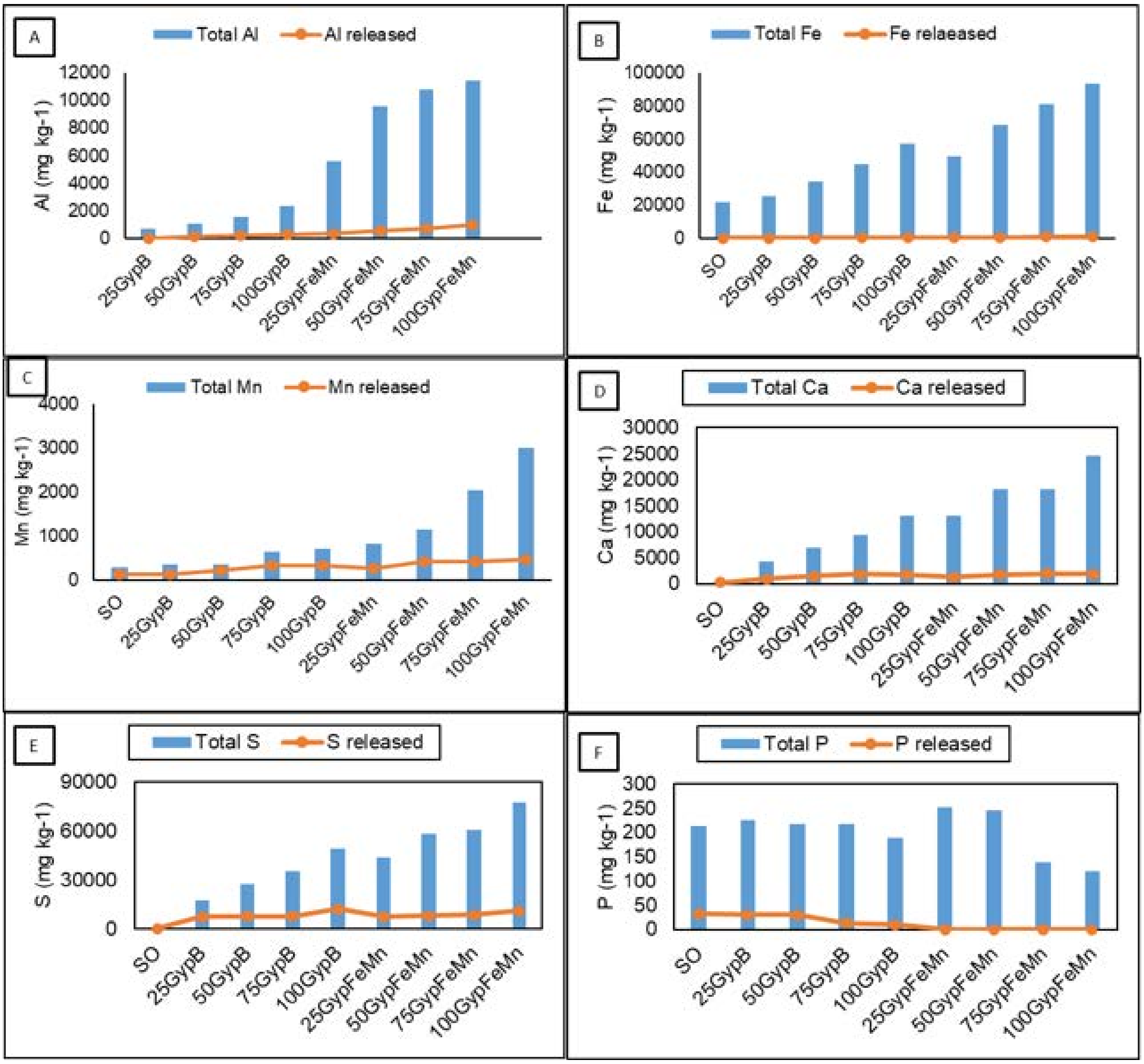


Figure 3-11: Selected total and extractable elements in soil-sludge mixtures.

3.3.4 Sludge effects on crop growth and yield

3.3.4.1 Seed germination

The results showed that the germination percentage was significantly reduced by the application of both GypB and GypFeMn sludge (Figure 3-12). Poor seed germination suggests that the environment was not conducive for germination. The results further showed that the GypB treatment had the lowest germination percentage compared to GypFeMn in both wheat and sorghum crops. It was observed that seeds in the sludge-soil mixture treatments took the longest (7-10 days) to germinate, compared to only 5 days for the treatment with no sludge applied. This was likely caused by the salt concentration, which inhibits seed germination due to osmotic and/or ionic toxicity, which can inhibit the mobilisation of stored energy reserves or directly influence the structural organisation and protein synthesis of the germinating embryo (Almansouri et al., 2001; Keiffer and Ungar, 2002).

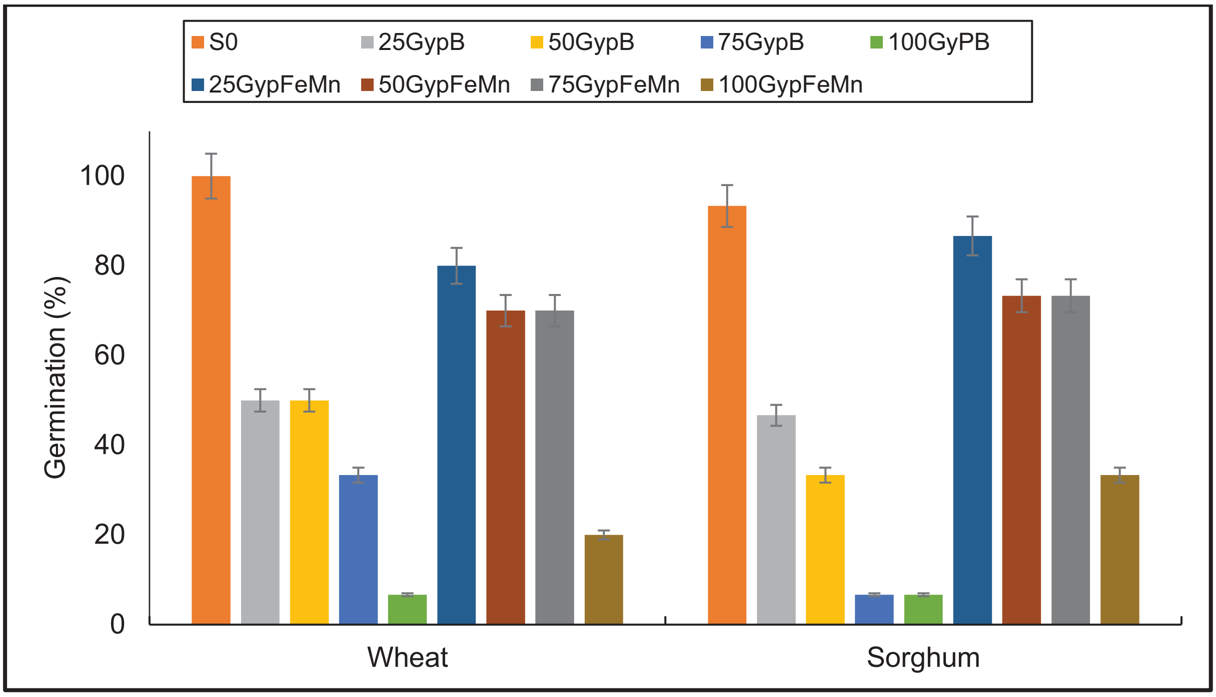


Figure 3-12: Germination assessment (%) in the pot trial with different sludge-soil treatment combinations as the growth medium. Error bars indicate statistical significance at P < 0.05.

3.3.4.2 Crop growth and biomass accumulation.

Figure 3-13 shows the plant height of wheat and sorghum crops, which decreased significantly in response to increasing sludge concentrations. The control (S0) and 25 GypFeMn treatments recorded plant height increase of more than 50 cm, whereas all other treatments with sludge showed signs of stunting on wheat. Sorghum plant height increased rapidly from germination in all treatments; however, slow growth was observed 28 days after planting (DAP). At 42 DAP, the control had a plant height of 40 cm, whereas the application of either sludge resulted in less than 20 cm.

Data on biomass accumulation (Figure 3-14) showed that wheat and sorghum biomass were also significantly reduced with both sludge treatments at the time of trial termination (eight weeks for wheat and six weeks for sorghum). Although biomass accumulation was significantly reduced in the sludge treatments, the GypFeMn treatments performed better than the GypB treatments at all application rates. These sludge materials are a good source of nutrients for crops. However, the high salt concentration created an inhospitable environment.

Salt stress restricts plant growth by reducing the osmotic potential of the soil and lowering root water uptake (Shaygan and Baumgartl, 2022). If salts are taken up by the plant, they build up in the shoot, which eventually limits plant growth by slowing photosynthesis and further retards the growth of specific plant organs and alters general plant morphology, such as the root: shoot ratio (Munns and Tester, 2008). These salt-induced morphological alterations affect the performance of plants in saline environments (Julkowska and Testerink, 2015).

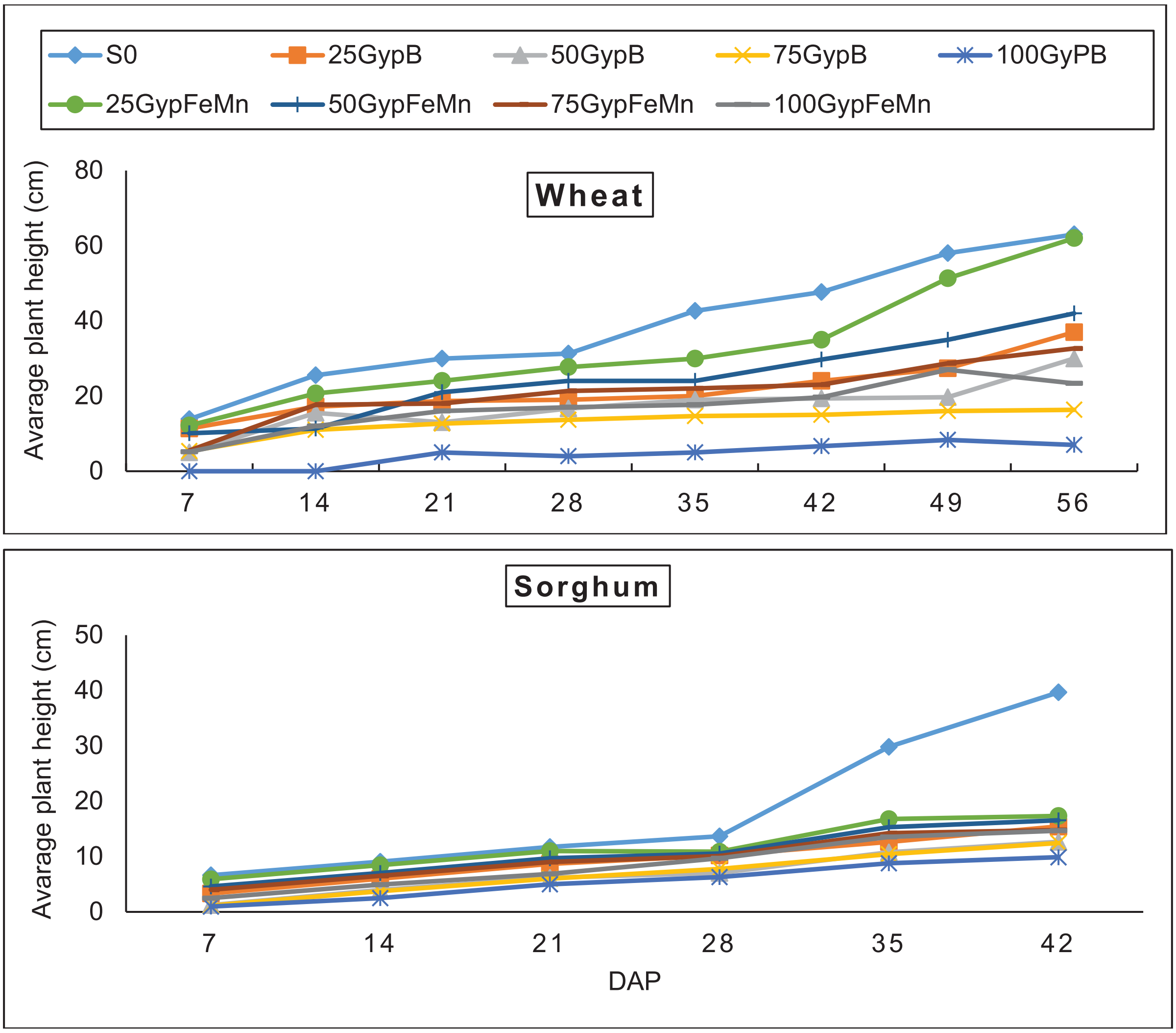


Figure 3-13: Average plant height in the pot trial with different sludge-soil treatment combinations as growth media.

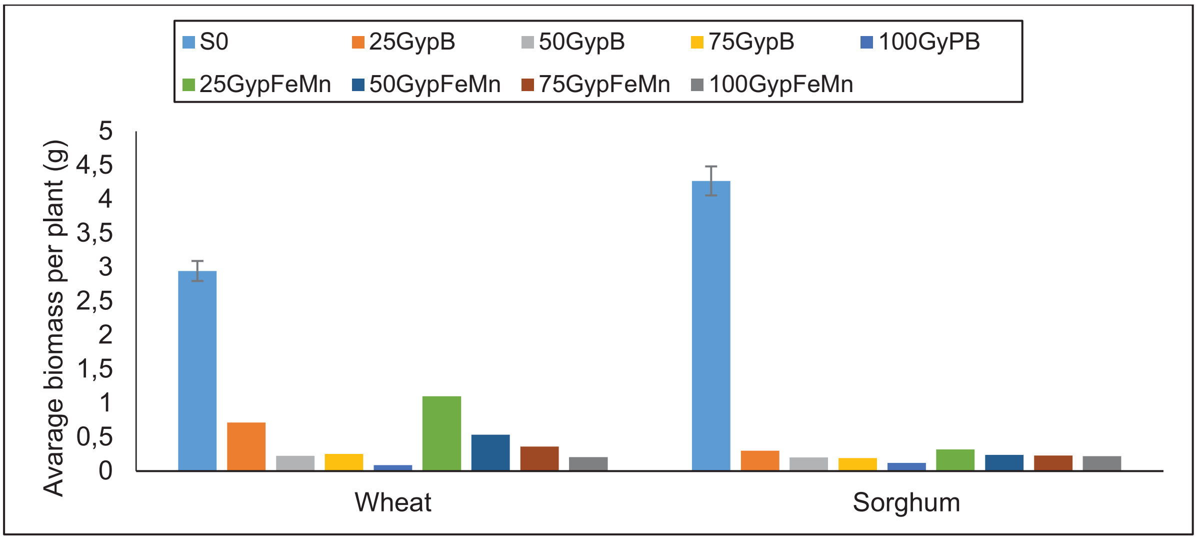


Figure 3-14: Biomass accumulation with different sludge-soil treatment combinations as growth medium.

3.3.5 Foliage chemical composition

3.3.5.1 Al, Fe, Mn, Ca, S, and Zn concentrations in plant tissues

Wheat and sorghum were harvested before maturity due to crop failure. Plant tissue analysis was conducted to determine the levels of elements that contributed to plant failure under high sludge loading rates. This section focused on selected major plant nutrients (Ca, S, and P) and trace elements (Al, Mn, Fe and Zn), as Ca, S, Al, Mn, Fe and Zn were expected to come from both sludges, except for P. Generally, the application of either sludge increased the amount of nutrients (Al, Fe, Mn, Ca, and S) above the threshold values for both wheat and sorghum crops (Figure 3-15 and Figure 3-16).

Higher sludge loading rates resulted in the highest elemental concentrations, with the control treatment recording low levels in all crops. The concentration of elements in plants resulted in toxicity, which was observed through foliar symptoms. Symptoms included leaf chlorosis, leaf abnormalities, reduced leaf expansion, and necrotic brown spots on leaves and stems. According to Bhoomika et al. (2013), these are symptoms of Mn, Fe, and Al toxicity. Further observations included brown spots that initially appeared on the lower leaves and subsequently progressed to the upper leaves due to Zn toxicity (Reichman, 2002).

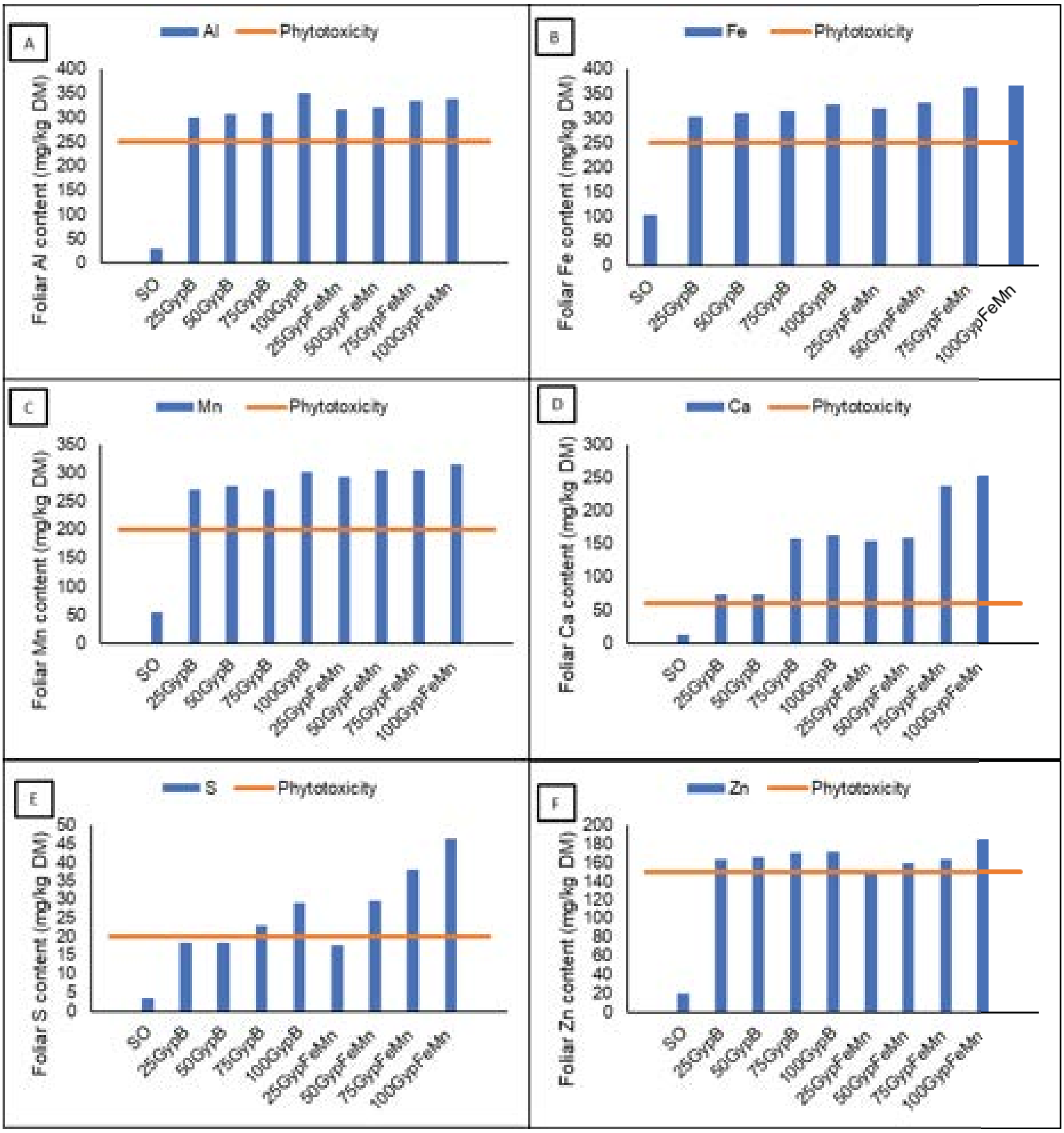


Figure 3-15: Al, Fe, Mn, Ca, S, and Zn content in sorghum plants grown on soil-sludge mixtures.

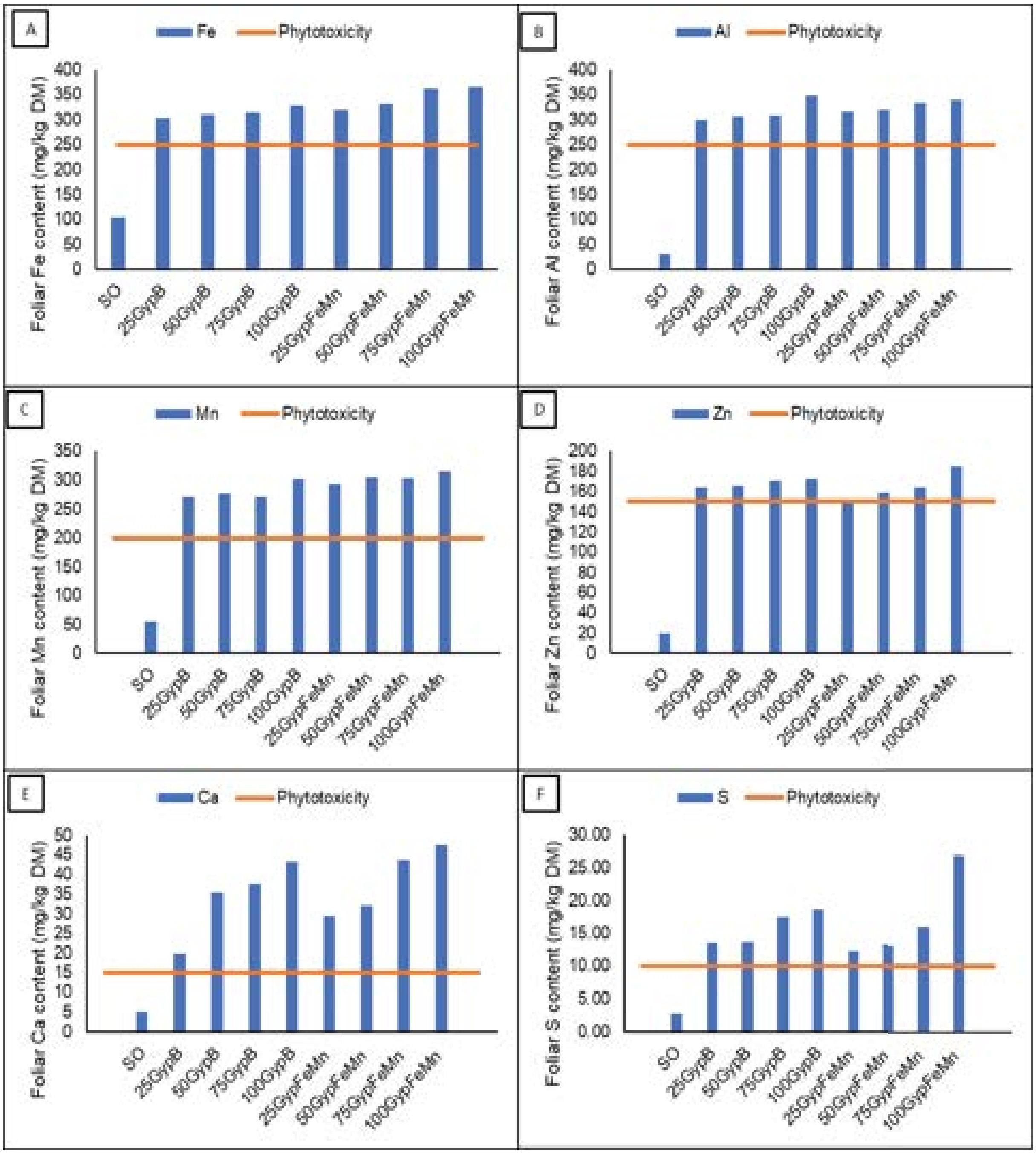


Figure 3-16: Al, Fe, Mn, Ca, S, and Zn content in wheat plants grown on soil-sludge mixtures.

3.3.5.2 Sufficiency levels of phosphorus

Phosphorus analysis in plant tissues was conducted to evaluate the potential adsorption mechanisms of this element. Figure 3-17 indicates that the P availability in plant tissues was below the sufficient range when sludge materials were added to soil. This shows that P was deficient under these treatments and might have been a limiting factor for the growth of wheat and sorghum. As reported by Sibrell et al. (2009) in a study on the removal of P from agricultural wastewaters, most AMD sludges containing Fe and Al hydroxides exhibit a strong affinity for P. This is supported by the P deficits in the plant material despite there being sufficient P in the soil.

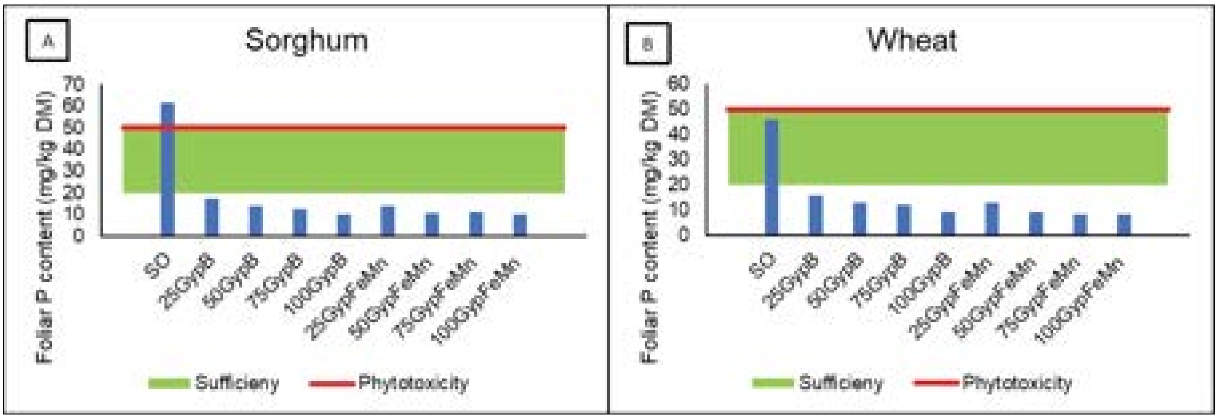


Figure 3-17: Phosphorus content in sorghum and wheat crops grown on soil-sludge mixtures.

3.4 Small plot field evaluation of irrigation with untreated or partially treated acid mine drainage

As a first step in investigating the feasibility of irrigating crops with untreated and partially treated mine waters, the research team established small-scale trials to screen several food and fodder crops for their productivity and quality when irrigated with these waters under sprinkler irrigation. Several attempts were made to establish trials at Mafube and Kromdraai; however, due to various challenges, including theft, fires, vandalism, and an overall unsafe environment, these efforts were unsuccessful. Eventually, the project team identified the eMalahleni Reclamation Plant as a potential site for conducting the small plot trials.

The eMalahleni Water Reclamation Plant (eWRP) treats AMD from various mines to potable standards using the HDS process and RO. In addition to the HDS and RO plants, a Biological AMD demonstrationtreatment plant that utilizes cloSURE^{TM} technology had also been commissioned at the site as a potential alternative treatment option for AMD. This made the eWRP an ideal site for establishing small-scale trials to investigate the response of the soil and selected cereals, legumes, and pasture grasses to irrigation with untreated mine water, as well as to two partially treated mine waters (clarified circumneutral water treated with HDS and BSR-treated water).

3.4.1 Planning and design

3.4.1.1 Site selection

As part of the planning and design component of the project, the project team conducted several site visits to select a suitable location for the trials. Due to security reasons, it was not possible to establish the trial outside the plant security perimeter. Eventually, it was agreed to use the subsoil stockpile site located in the southwestern portion of the plant (red outline in Figure 3--18). However, the area required considerable work to bring it to a suitable condition for planting. The details of the preparatory work are discussed in a separate section.

Figure 3-18: Map image of the trial area (red outline).

3.4.1.2 Water quality

The eWRP has several sources of mine waters, making it an ideal site for the study. However, due to space limitations, the team was unable to investigate all the available waters. It was, therefore, decided to begin with the most acidic untreated mine water and the more alkaline HDS-treated mine water, as well as the BSR-treated mine water. The rationale behind starting with the most acidic untreated mine water and the more alkaline HDS-treated mine water was that they represent “worst case” scenarios. If irrigation were successful with these waters, it would likely be successful with the less acidic untreated mine water and the less alkaline HDS-treated mine water. If irrigation with the “worst case” waters were found to be unsuccessful, the team would stop irrigation with these waters and continue the trials with the less acidic untreated mine water and the less alkaline HDS-treated mine water. Table 3-14 shows the expected quality of the selected waters. These “expected” water qualities were obtained by averaging previously recorded analyses to estimate the chemical composition of the different waters received at eWRP.

Table 3-14: Average chemical composition of the waters to be used at the eWRP irrigation trial.

Constituent	Highly Acidic	HDS Clarified	BSR treated
pH	2.5	8.5	7.6
EC (mS/m)	407	350	336
Al (mg/L)	68	0.09	0.1
As	<0.01	<0.01	0.0
Cd	0.004	<0.003	0.0
Ca	412	683	264
Cl	11	31	-
Cu	0.03	<0.01	0.01
F	<0.2	0.64	0.4
Pb	<0.01	<0.01	0.0
Mg	201	114	193
Mn	21	0.08	0.07
Hg	<0.001	<0.001	-
Ni	0.46	0.06	0.03
Se	0.02	<0.01	0.00
Na	50	130	70
SO_4	2871	2394	800
Fe	638	31	1.02
Zn	1.50	0.03	0.52
TDS	4910	3752	-
TSS	200	96	-

3.4.1.3 Crop selection

This trial aimed to screen agronomic and pasture crops that are economically important and well-suited for the Highveld region. The goal was to identify crops that could produce profitable yields when irrigated with water of poor quality. Due to space limitations, the selection of crops for screening was restricted, and the team had to consider several factors in their decision-making process.

One of the main factors requiring serious consideration was the type of irrigation system that could be installed. One of the concerns raised when irrigation with acidic mine waters was proposed was foliar scorching that occurred when the water was applied overhead. To assess whether irrigation with these mine waters would cause foliar scorching, a sprinkler irrigation system was installed. The maximum height of the sprinklers that could be installed was 1 m, which meant that shorter crops had to be planted to facilitate easier overhead irrigation.

Another critical factor for consideration was the type of cropping system that could be used. For irrigation to be effective as a mine water management strategy, a summer-winter crop rotation system was adopted. This type of cropping system requires irrigation throughout the year, thereby decreasing the storage capacity needed if water is only used for part of the year.

The team also took crop tolerances to acidity and salinity into consideration. Previous pot trial studies conducted by the University of Pretoria have shown that crop responses to irrigation with acidic and saline mine waters vary based on the tolerance to mine water constituents. The results of these studies also indicated that crops can successfully be grown under irrigation with untreated AMD if the soil is adequately limed. To validate these findings in the field, crops with varying tolerances to acidity and salinity were selected.

Based on these collective considerations, the following crop rotation systems were selected, as described in C1 to C4.

- C1- Soybean-wheat
- C2– Lucerne– annual ryegrass
- C3– Grain sorghum – stooling rye
- C4– Teff – canola

Characteristics of the selected crops are summarized in Table 3-15.

Table 3-15: Summary of selected crop characteristics.[8]

Crop	Specie	Growth	Minimum pH threshold	Salinity Tol. (mS m^{-1})	Water requirement (mm)
Summer Crops					
Soybean	*Glycine max*	Annual	5.5-6.5	500	-
Teff	*Eragrostis tef* [Zucc]	Annual	4.5-8.5	750	432-559
Lucerne	*Medicago sativa*	Perennial	>5.6	400	600-1000
Sorghum	*Sorghum Bicolor*	Annual	>5.5	680	400-600
Winter Crops					
Wheat	*Triticum spp.*	Annual	5.5-6.5	600	-
Stooling rye	*Secale cereale* L.	Annual, temperate	> 4.9	1140	>300
Tall fescue	*Festuca arundinaceae*	Perennial, temperate	4.7-9.5	390	375-750
Annual ryegrass	*Lolium multiflorum*	Annual, temperate	5.0-8.0	760	762-1270

[8] Adapted from Jovanovic (1998), Agricol (2016), Fageria et al (2010) and Pannar Product Catalogue 2013

3.4.2 Soil quality

To assess the fertility of the soils and determine the amount of fertilizer required for the selected crops, composite samples of the topsoil and the subsoil in the reconstructed trial plot were collected for analyses. Soils were analysed for soil pH (measured in KCl), electrical conductivity (ECe) measured in a saturated soil paste extract, phosphorus (P) determined using the Bray 1 method, potassium (K), sodium (Na), calcium (Ca) and magnesium (Mg) measured in ammonium acetate extracts. The results are presented in Table 3-16 below.

Table 3-16: Analysis of pH, EC and major cations in sampled soils

Parameter	Topsoil	Sub Soil	Optimum range
pH (KCl)	7.65	7.66	4.5-8.5
ECe (mS/m)	121	163	<200
P (mg/kg)	4	2	15-30
K (mg/kg)	56	39	80-160
Na (mg/kg)	35	24	
Ca (mg/kg)	3620	1432	300-2000
Mg (mg/kg)	159	46	80-300

One of the concerns raised when irrigation with mine water is proposed, is off-site environmental impacts, particularly in areas where groundwater is heavily relied on for agricultural and domestic use. The trace elements found in the eWRP mine waters are generally not expected to be very mobile in well-drained, well-aerated soils and therefore not of great concern, provided the soil accumulation thresholds are acceptable (Hartemink and Barrow, 2023, Zeng, et al., 2011).

Total concentrations of selected trace elements in the soils were also determined by analysis using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES), to establish baseline values for assessing accumulation. Results of these analyses are presented in Table 3-17. The selection of elements analysed includes potentially phytotoxic elements and those identified as potentially harmful to people and animals in the National Environmental Waste Act (NEMWA) Norms and Standards (published in the Government Gazette, No. 37603, Vol. 331, 2 May 2014). The Norms and Standards propose two Soil Screening Values (SSV1 and SSV2) that may be used as benchmarks to determine if the metals have accumulated to unacceptable levels. SSV1 refers to soil quality values that are protective of both human health and ecotoxicological risk for multi-exposure pathways, inclusive of contaminant migration to the water resource, making it relevant to this study. SSV2 only assesses the risk to human health associated with certain elements in soils, in the absence of a water resource pathway.

Table 3-17: Total concentrations of environmentally significant elements in the sampled soils

Parameter	Topsoil	Subsoil	SSV1
Concentrations of total elements (mg kg^{-1})			
Al	9189	8411	-
As	0.14	<0.1	5.8
Cd	0.48	0.35	7.5
Co	4.4	3.4	300
Cr	32	29	46000 (III)
Cu	6.8	3.56	16
Fe	7398	6234	-
Hg	<0.1	<0.1	0.93
Mn	1353	79	740
Ni	17.41	17.22	91
Pb	<0.1	0.67	20
V	27	21	150
Zn	39	13	240

Overall, the analyses showed that the soil was of acceptable chemical quality, however, for crop production, the soils were deficient in P and K, and N for non-leguminous crops. Amendments were, therefore, required to increase these nutrients.

3.4.2.1 Trial layout design

Due to the limited size of the trial site, a split-plot design was selected, with the different waters in separate blocks. Within each block, there were four cropping systems with four replicates, in a completely randomized design. The trial layout is presented in Figure 3-19. The main plots, which represent the different water treatments, each had an area approximately 449 m^2 (23 m x 19.5 m), with a spacing of 1.5 m between them. The subplots, which represent the different cropping systems, had an area of approximately 24 m^2 (5.25 m x 4.5 m), with a spacing of 0.5 m between them. The total area of the trial site was 1404 m^2 (72 m by 19.5 m) and each cropping system had a total area of 288 m^2 (24 m^2 times 3 treatments times 4 replicates).

The paths between the main plots and subplots were planted with *Cynodon dactylon,* a hardy low maintenance pasture crop, to minimise erosion and lateral flow of water into adjacent plots. A shallow trench was dug in the 1.5 m space between irrigation treatments to minimise the possibility of lateral surface flow of irrigation water between treatments. A barrier of galvanized wire with a dense shade net was placed between the different water treatments, to reduce the effects of wind drift. The net was rolled back after irrigation to avoid shading on edges of plots at certain times of the day.

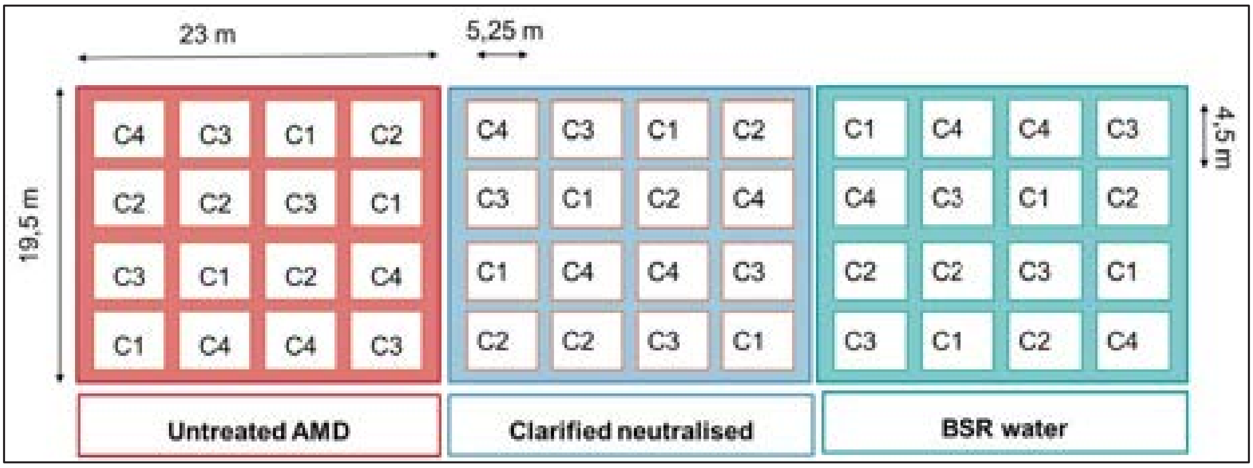


Figure 3-19: Trial layout design

3.4.2.2 Fertilizer Application Rates

As indicated in the previous sections, the P and K status of the soil was below optimum levels and had to be increased. To achieve this, P and K fertilizer was first applied to reach optimum levels, then additional fertilizer was applied to meet crop specific requirements. Fertilizer application rates were calculated according to the guidelines provided in the Fertilizer Handbook (FSSA, 2000). According to the handbook, 7 kg P/ha is required to increase P content of soil by 1 mg/kg, and 5kg K/ha is required to increase K-content of soil by 1mg/kg. The target P content to accommodate most of the selected crops was 30 mg/kg and for K it was 80 mg/kg. Therefore, the P-content of the deficient soil had to be increased by 28 mg/kg and the K-content had to be increased by 40 mg/kg, the application rates were calculated as follows:

P application rate= $\frac{7\ kg\ P}{ha} \times \frac{kg\ soil}{1\ mg\ P} \times \frac{28\ mg P}{kg\ soil}$ = 182 kg P/ha

K application rate= $\frac{5\ kg}{ha} \times \frac{1\ kg\ soil}{mg\ K} \times \frac{40\ mg K}{kg\ soil}$ = 200 kg K/ha

Crop-specific fertiliser application rates are presented in Table 3-18, together with seeding rates and row spacing requirements. Additional NPK was applied as top dressing.

Table 3-18: Planting densities and fertiliser requirements.[9]

Crop	Fertiliser rate	Seeding density	Row spacing
Soybean	150 kg N / ha, 15 kg P / ha and 45 kg K / ha	300000 seeds ha^{-1}	0.45 m
Wheat	60 kg N / ha,12 kg P / ha, 15 kg K / ha	40 kg ha^{-1}	0.3 m
Barley	60 kg N / ha, 30 kg P / ha, and 20 K kg/ha K	90 kg ha^{-1}	0.4 m
Tall fescue	90 kg N / ha, 30 kg P / ha, 60 kg K / ha	30 kg ha^{-1}	Broadcast
Ryegrass	300 kg N / ha	30 kg ha^{-1}	Broadcast
Teff	180 kg N / ha	15 kg ha^{-1}	Broadcast
Sorghum	100 kg N / ha 25 kg P / ha, 30 kg K / ha	5-20 kg ha^{-1}	0.2 m
Lucerne	30 kg N / ha, 30 kg P / ha and 120 kg K / ha	30 kg ha^{-1}	Broadcast

[9] Adapted from Barnard et al. (1998), Agricol (2016), and Pannar Product Catalogue (2013).

3.4.2.3 Irrigation system design

The irrigation system consisted of 3 blocks each fitted with 9 permanent sprinklers. One sprinkler covering a full circle was placed in the centre of the plot, with four sprinklers, covering quarter circles placed on each corner, and four sprinklers covering half circles placed at the centre of each side, as shown in Figure 3-20. The sprinklers were operated at 300 kPa, which provided approximately 5.4 mm/h at a 92% application uniformity for full circle application. Half- and quarter-circle applications delivered slightly more. To limit the spray from landing beyond the respective plot boundaries, a vertical shade net (80%) was erected as a barrier between main plots.

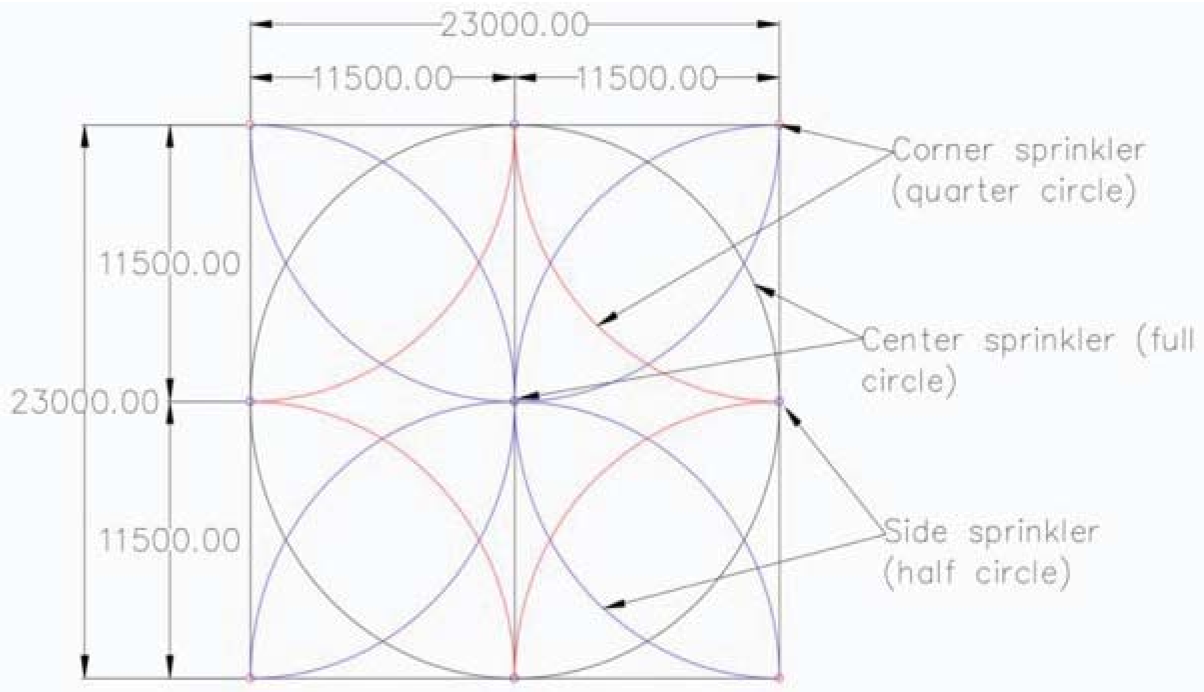


Figure 3-20: Schematic representation of the positions of the sprinklers on each main plot. Units for the values are mm.

Water was pumped from the different sources using centrifugal pumps. For the untreated and HDS treated waters, the water was first pumped into 15000-liter storage tanks placed near the plots (for storage capacity), then it was pumped from these tanks to the plots. The water from the BSR plant was pumped from an existing 20000 litre storage tank to the plot. The layout of the irrigation blocks is presented in Figure 3-21.

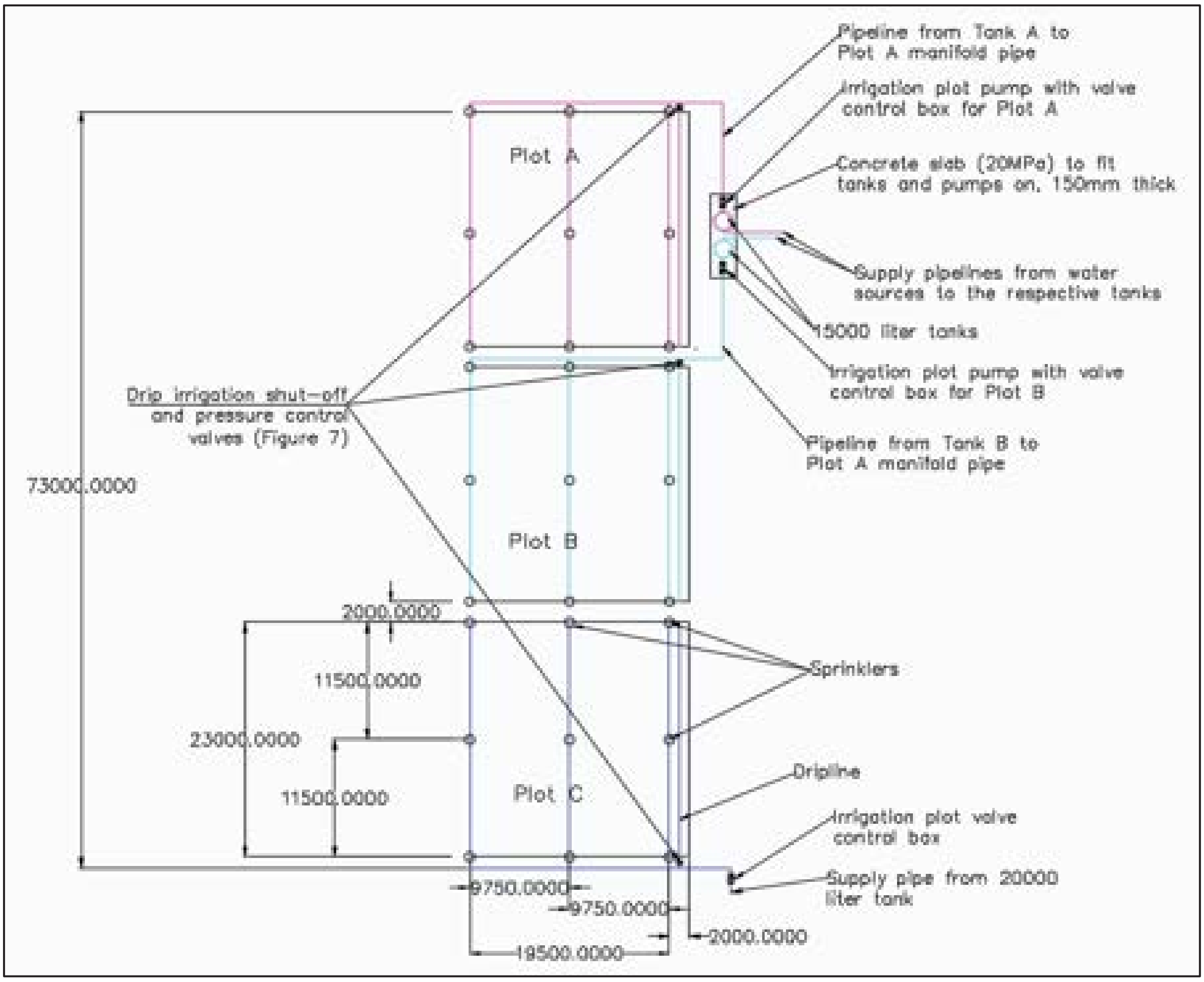


Figure 3-21: Schematic representation of the proposed irrigation system layout.

3.4.3 Site preparation

As previously indicated the area selected for crop establishment was not in suitable condition for cultivation and required a lot of work. First, the subsoil had to be levelled and reshaped to create a platform with a large enough area for the trial. This required the movement of rubble and other equipment from the site by a few metres as shown in Figure 3-22. Thereafter, topsoil had to be placed on the subsoil to get the platform to an irrigable condition. Fortunately, the team found a relatively small topsoil stockpile in close proximity to the proposed trial site (green outline in Figure 3-23). Once the earthworks were completed the site had to be levelled and cultivated to prepare for planting. A summary of these activities is provided below.

Figure 3-22: Trial site before earthworks commenced.

Figure 3-23: Location of the topsoil stockpile (outlined in green) relative to the subsoil stockpile (outlined in red) that has been shaped into a platform.

3.4.3.1 Earthworks: initial site levelling and topsoil replacement

The earthworks to prepare the site for cultivation commenced in January of 2023, however, there were several delays that set the project back by three months. Firstly, the company contracted to undertake the earthworks struggled to get their contractors pack signed off to begin work, then their work was stopped midway due to shortcomings with their contractors pack. Thereafter, the contractor experienced cashflow problems as they were about to complete their work. Eventually, the work was completed at the end of June in 2023. Figure 3-24 to Figure 3-26 show the progression of the site before, during, and after the earthwork activities.

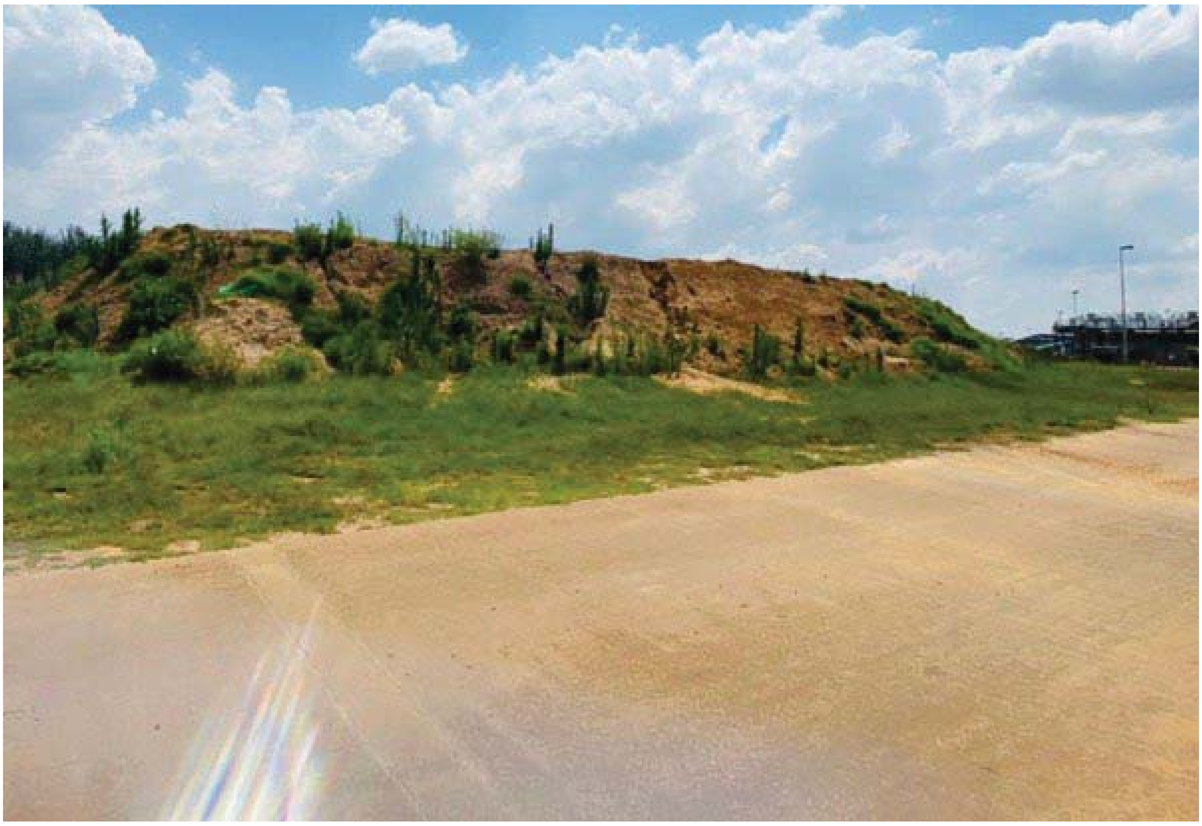


Figure 3-24: Subsoil stockpile before reshaping and topsoil placement.

a)

b)

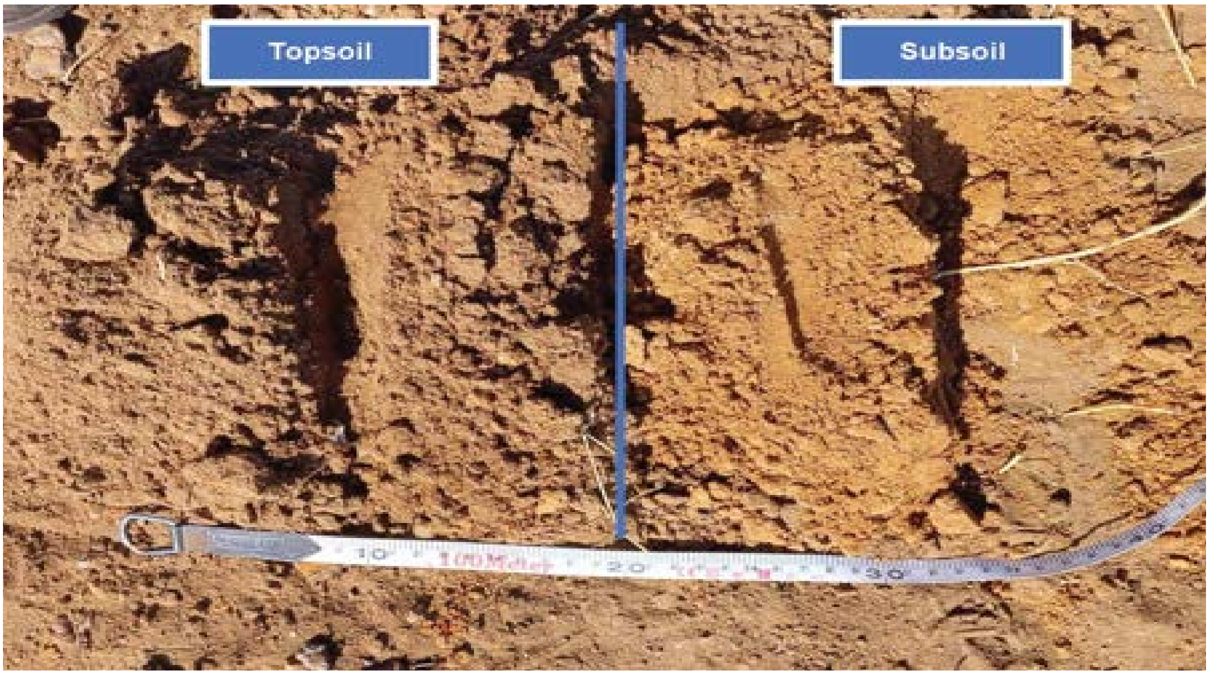
Figure 3-25: Subsoil stockpile during a) reshaping and b) topsoil placement.

Figure 3-26: Platform after earthworks were rectified by the team.

3.4.3.2 Final site levelling, decompaction, and topsoil thickness uniformity establishment

After the basic levelling earthworks were completed by the contractors, the research team undertook to complete the levelling of the site and to smooth the unevenness left by the earth moving machinery, as shown in Figure 3-27. However, as this final levelling work was underway the team noticed that topsoil was not evenly distributed, with some parts having a topsoil depth of up to 50cm while other parts had barely any topsoil. The variation in topsoil depth is illustrated in Figure 3-28. Upon further investigation, the team found that the subsoil was also not level.

Figure 3-27: Uneven surfaces created by earthmoving machinery.



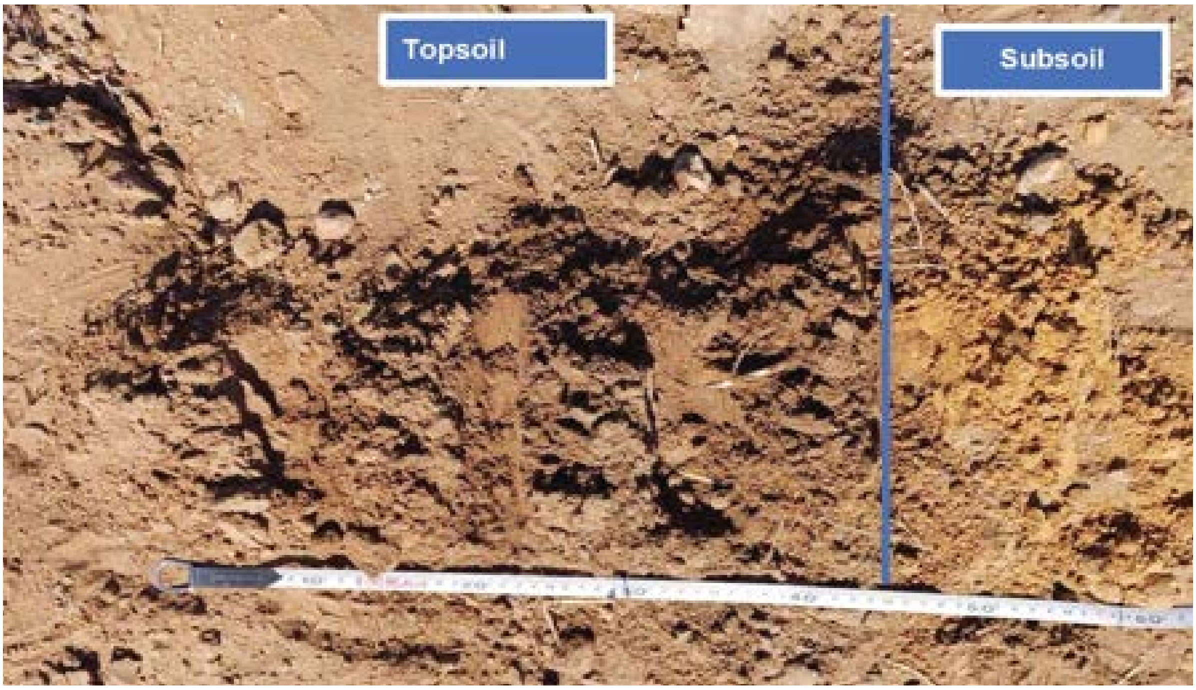


Figure 3-28: Variation in topsoil depth observed throughout the platform.

To level the site, the topsoil had to be removed, to allow for the subsoil to be levelled. Thereafter the topsoil was replaced evenly to a minimum depth of 15 cm. In addition, there were areas with rocks and rubble which had to be removed manually. Finally, there were highly compacted areas that had to be loosened manually.This exercise required more time than had been budgeted for, however, it was crucial to get the site into a suitable and uniform condition for planting. Figure 3-29 to 3-32 show the progression of the final site levelling activities.

Figure 3-29: Loosening of compacted soil with a pick.

Figure 3-30: Removal of topsoil and clearing of rocks and rubble to expose subsoil.

Figure 3-31: Levelling of subsoil.

Figure 3-32: Placement and levelling of subsoil

3.4.4 Irrigation system installation

3.4.4.1 Pipes and sprinkler installation

Work on the irrigation system installation commenced in the second week of September 2023. The work entailed digging trenches and laying out the pipes from the water sources to the tanks and from the tanks to the irrigation plots as shown in Figure 3-33 and Figure 3-34.

Figure 3-33: Piping for the passively treated water.

Figure 3-34: Lateral pipes during installation a) and sprinklers installed b).

3.4.4.2 Installation of pumps and electrical panels

Irrigation system installation was successfully completed at the end of 2023 (Figure 3-35). However, the commissioning of the untreated AMD and circumneutral water from the High-Density Sludge (HDS) plant was delayed due to an unfortunate incident where two pumps were submerged in sludge (Figure 3-36). This setback necessitated the purchase of new pumps and installation of stands to raise them, further delaying the commissioning process. Despite these challenges, the irrigation system was successfully commissioned and tested in the first week of July 2024.

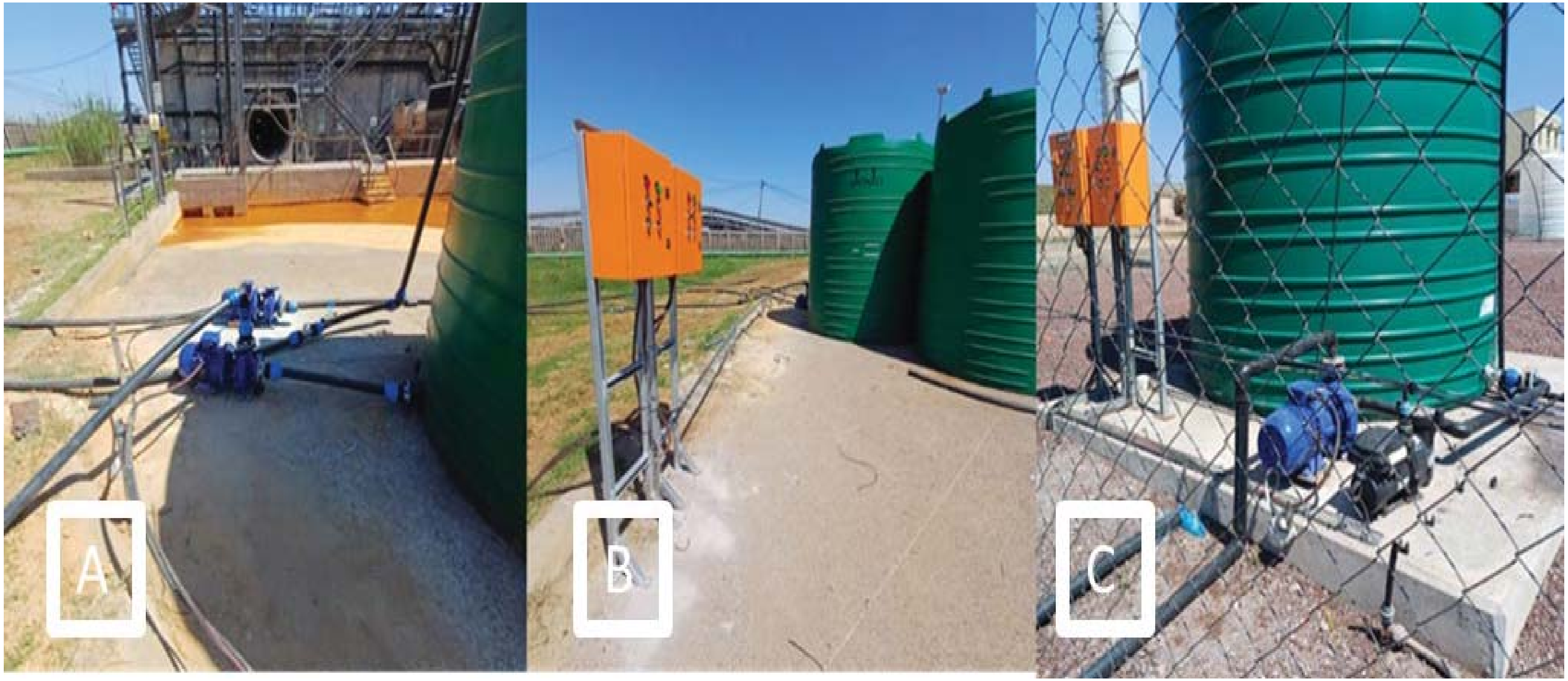


Figure 3-35: Pumps installed at the trial site a) with electrical panels b) and complete installed electric panel and pump at the passive plant c).

Figure 3-36: Pumps submerged in sludge a) and stands to raise new pumps b).

3.4.5 Summer crop trial

3.4.5.1 Seedbed preparation

The block irrigated with untreated AMD received calcitic lime to buffer the acidity of the water (Figure 3-37). All plots received inorganic fertilizers: Limestone Ammonium Nitrate (LAN), Potassium Chloride (KCl), and CalSiPhos. The application rates were recommended based on soil chemical analysis and crop requirements as discussed in Section 3.4.2.2. The lime and fertilizer were worked into the soil using a diesel powered tiller.

Figure 3-37: a) Lime and fertiliser application and b) soil tillage.

3.4.5.2 Planting

Following seedbed preparation, sorghum, soybean, teff, and lucerne were planted (Figure 3-38). Planting was done in the first week of December. Unfortunately, the irrigation system installation was not completed as planned, therefore the crops were rainfed for the entire growing season. Despite the challenges posed by the lack of irrigation water, this presented a unique opportunity to establish a baseline using these crops grown under dryland conditions. The crops were harvested in April, as shown in Figure 3-39. However, the soybeans did not reach maturity as they had to be replanted due to poor germination, caused by animals feeding on the seedlings. This challenge was later addressed by covering seedlings with shade nets to protect them.

Figure 3-38: Summer crops under dryland production at planting (a) and during the growing season (b).

Figure 3-39: Harvesting of plots.

3.4.5.3 Biomass accumulation

Biomass was measured at the end of the experiment to obtain the average production, and compared with expected biomass yields. The results showed that the biomass accumulated was lower than the expected yield for dryland production (Figure 3-40). This was due to late planting, which coincided with insufficient rainfall to support crop growth, and the higher temperatures experienced in the Highveld region in summer.

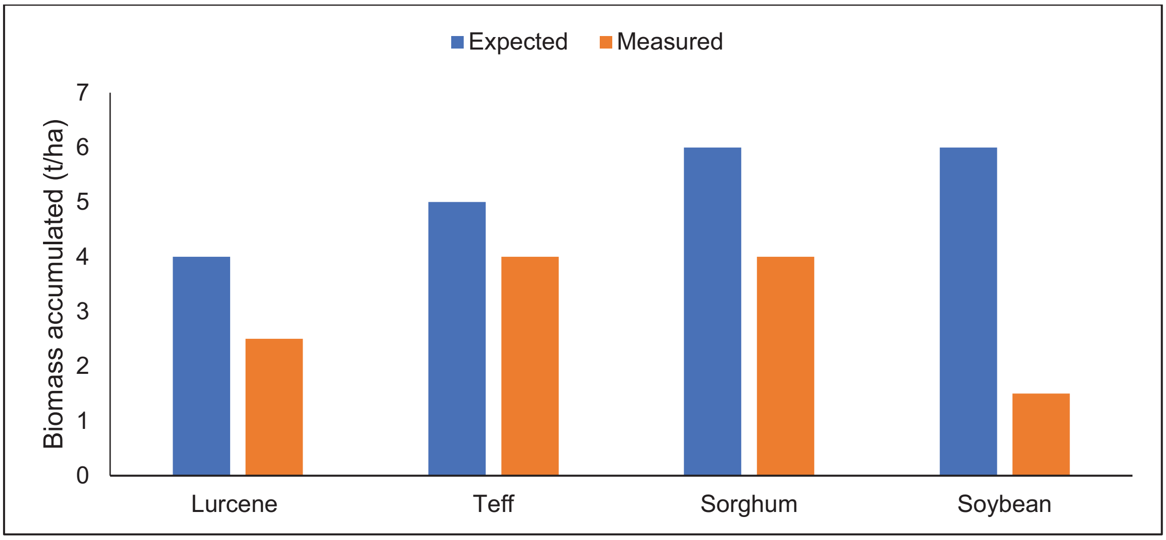


Figure 3-40: Biomass accumulated over the growing season under dryland production.

3.4.6 Winter crop trial

3.4.6.1 Soil preparation

The soil was prepared to ensure optimal conditions for winter crops, particularly in response to challenges experienced during the summer season. One of the key limitations identified was the crusting of the topsoil. To address this, compost was incorporated into the soil (Figure 3-41). The addition of compost was not only aimed at improving soil structure and reducing crusting, but also at enhancing soil fertility by increasing the organic matter content.

Figure 3-41: a) Compost application and b) soil tillage.

3.4.6.2 Planting

The winter crops were planted in July of 2024 (Figure 3-42a) and only irrigated using BSR-treated mine water, as the reinstallation of irrigation systems for untreated and circumneutral waters was still ongoing at this time. After planting, the plot was carefully covered with shade netting. The team continued to use shade netting even after the crops were established to prevent birds from feeding on them (Figure 3-42b). To limit the expected drift of irrigation waters beyond the designated plot boundaries of each water treatment, a vertical shade net (80%) was erected as a barrier between main plots (Figure 3-42a).

Figure 3-42: Shade netting at planting with vertical net separating main blocks (a) and shade net during growth period (b).

3.4.6.3 Crop management and monitoring.

Crop management involved weeding and top dressing, which was performed as required. These activities were carried out according to a management plan to ensure optimal crop growth and health. Weekly monitoring was conducted to check the amount of irrigation water applied, and plant growth, specifically by monitoring canopy cover and plant height.

3.4.6.4 Crop growth and productivity

Plant heights are presented in Figure 3-43. As there are no reference values for comparison, the plant heights are shown as unique data points. Crops established very well, as illustrated by Figure 3-44This depicts a healthy, well-developed crop, indicating the potential to use BSR-treated water for irrigation. The crops had to be harvested 5 weeks after planting to prepare the site for summer cropping; therefore, conclusions about the suitability of these waters for irrigation could not be drawn at this stage.

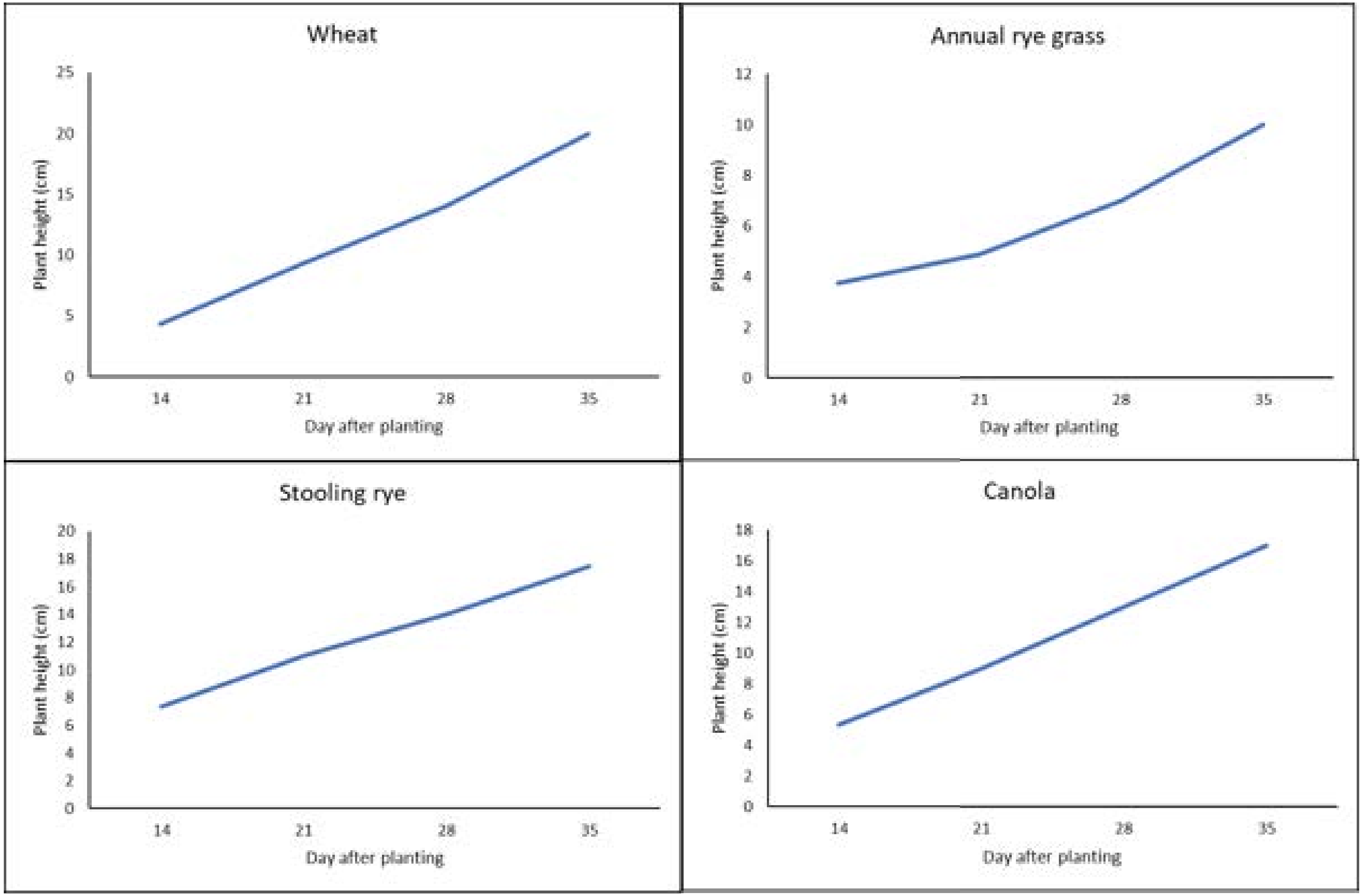


Figure 3-43: Wheat, stooling rye, annual rye grass and canola plant height.

Figure 3-44: a) Canola and stooling rye b) at five weeks after planting.

The above-ground dry mass of the plants is presented in Figure 3-45, the red bars show standard deviation. Since the crops were harvested in the early vegetative growth stage and there were no other water treatments for comparison, no solid conclusions could be made at this stage of the project. However, irrigation with the BSR water indicated some promise that crops could indeed be produced with this water source.

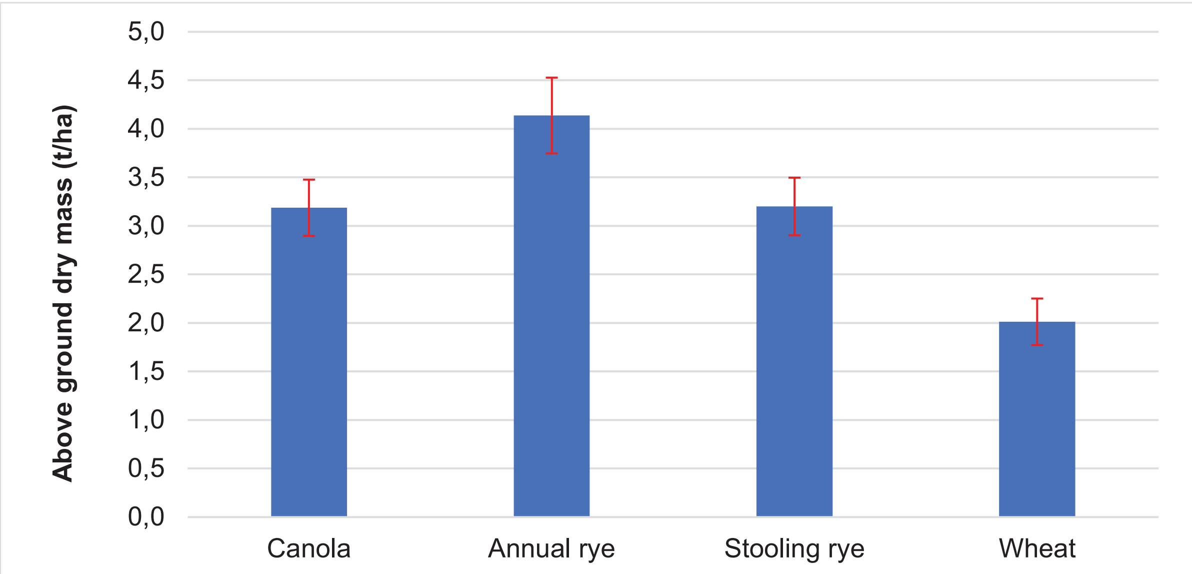


Figure 3-45: Above-ground dry mass of winter crops.

3.5 Conclusion

This component of the study evaluated the use of untreated and partially treated AMD for irrigation. The fitness for use assessments predicted, however, that long-term irrigation with untreated AMD would result in yield penalties. It was also predicted that irrigation with these waters would lead to rapid accumulation of trace elements, posing significant risks to food and fodder safety. However, it was hypothesized that liming soil would increase the soil pH, thereby reducing the solubility of toxic metals and preventing their excessive uptake by plants. This process serves as an alternative to using untreated water, with limed soil acting as an acid water treatment reactor. The BSR treatment process successfully reduced sulphates and most trace elements of concern and was expected to be suitable for irrigation.

The glasshouse experiments provided great insights into crop and soil responses to irrigation with untreated and partially treated AMD. The productivity of crops irrigated with partially treated AMD indicated that irrigation with these waters is feasible, at least in the short term. However, this becomes more feasible if a high leaching fraction is permitted, which helps remove surplus salts from the soil profile, lowering root zone salinity, and eventual salt stress. This could potentially unlock an alternative water source for agricultural production, benefiting local communities and saving costs and energy on water treatment by eliminating the need for expensive RO processes.

The pot experiments further demonstrated high accumulation of elements in soils irrigated with untreated acidic mine waters in just two seasons. In addition, a large yield penalty was paid when these waters were used for irrigation. Therefore, the liming strategy should be revised in an attempt to productively utilize such acidic waters and ensure the production of safe-to-consume produce. If food safety becomes a real or perceived concern, production of fibre or biofuel crops not destined for human or animal consumption should be considered, provided the environmental impacts of such irrigation are acceptable.

Although irrigation with unclarified mine waters was successful in the short term, the sludge loading experiments raised concerns about the sustainability of irrigating with these waters in the long term. Further studies are needed to investigate the feasibility of irrigating with these waters. The establishment of the small plot trials presents a great opportunity to evaluate the productivity of irrigation with untreated and partially treated AMD. However, due to circumstances outside the Project Team’s control, there were extensive delays in establishing these trials. As a result, the research team was not able to collect sufficient data to draw firm conclusions on the feasibility of irrigation with these waters in the field.

CHAPTER 4: SCALE OF OPPORTUNITY FOR MINE WATER IRRIGATION IN THE UPPER OLIFANTS CATCHMENT

4.1 Introduction

In Mpumalanga, mining activities were identified as a major contributor to the deterioration of water quality in the Upper Olifants Catchment, making it a priority catchment for managing mine water impacts (DWS, 2018a). The discharge of excess water from the mines, as well as the discharge of treated water high in salts, were highlighted as activities that require management actions to improve water quality in the catchment.

The use of mining-influenced waters for irrigation is likely to become a suitable technology that can be implemented on a broader scale in the Upper Olifants Catchment. However, the scale of opportunity for establishing such mine water irrigation schemes needs to be investigated. In this chapter, the prospects for mine water irrigation in the Mpumalanga region are explored, with a specific focus on water quality and quantity, as well as land availability.

4.2 Data collation

High-level desktop studies were conducted with the assistance of geohydrologists from Delta H. One of the major constraints in conducting this study was the limited access to information. Water quality and quantity data was obtained for 30 mines; 28 mines had water quantity data and 26 had water quality data. According to data obtained from the DMRE website, there are 101 operational mines in the Upper Olifants Catchment; therefore, the results obtained from the analyses discussed below are likely a gross underestimation of the actual situation. Figure 4-1 shows all the mines for which water quantity and or quality data was obtained within each management unit. Figure 4-2 shows mining rights areas of operational mines taken from the Department of Mineral Resources and Energy (DMRE) website(DMRE, 2017).

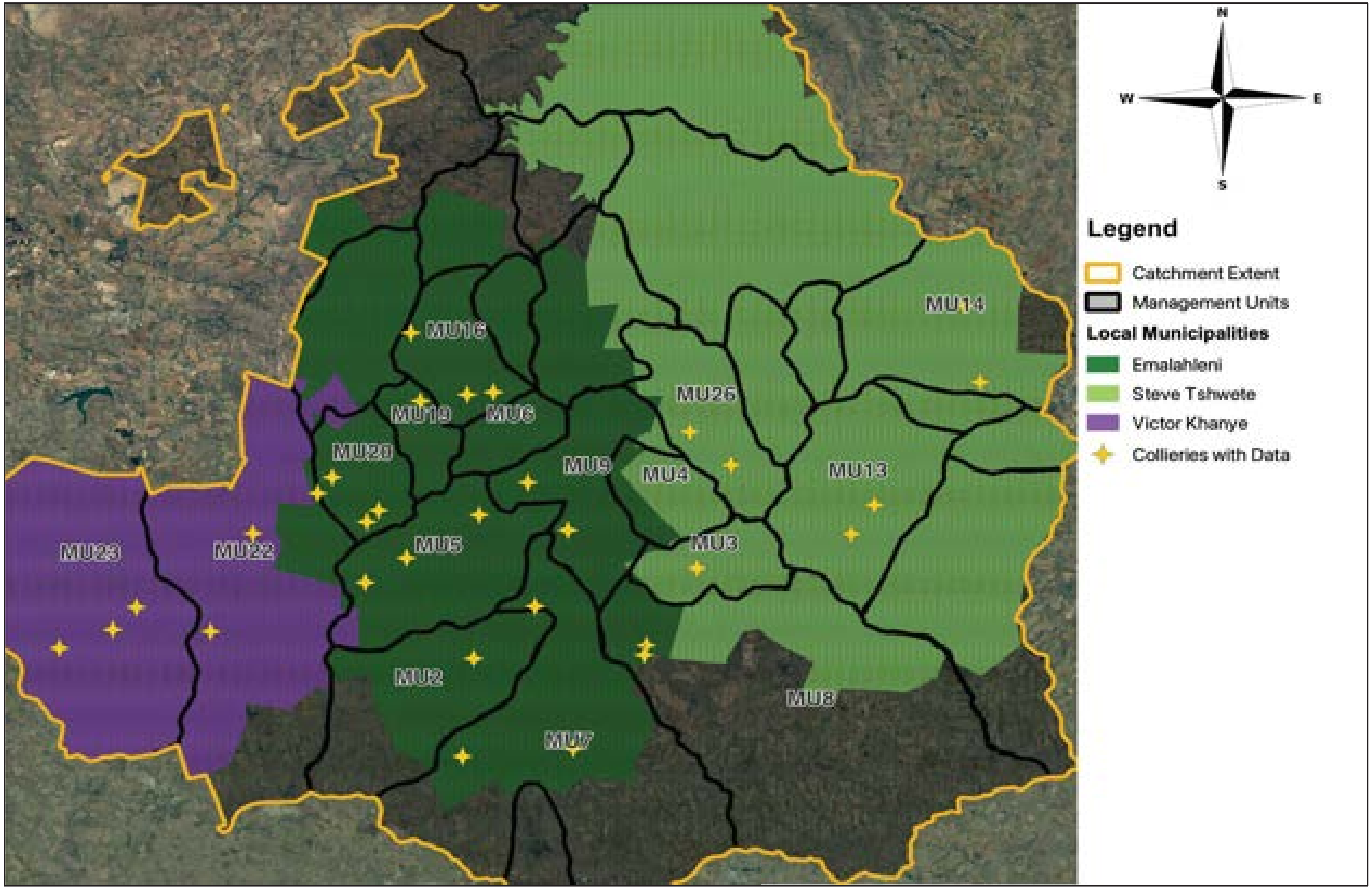


Figure 4-1: Collieries with water quality and quantity data within each management unit.

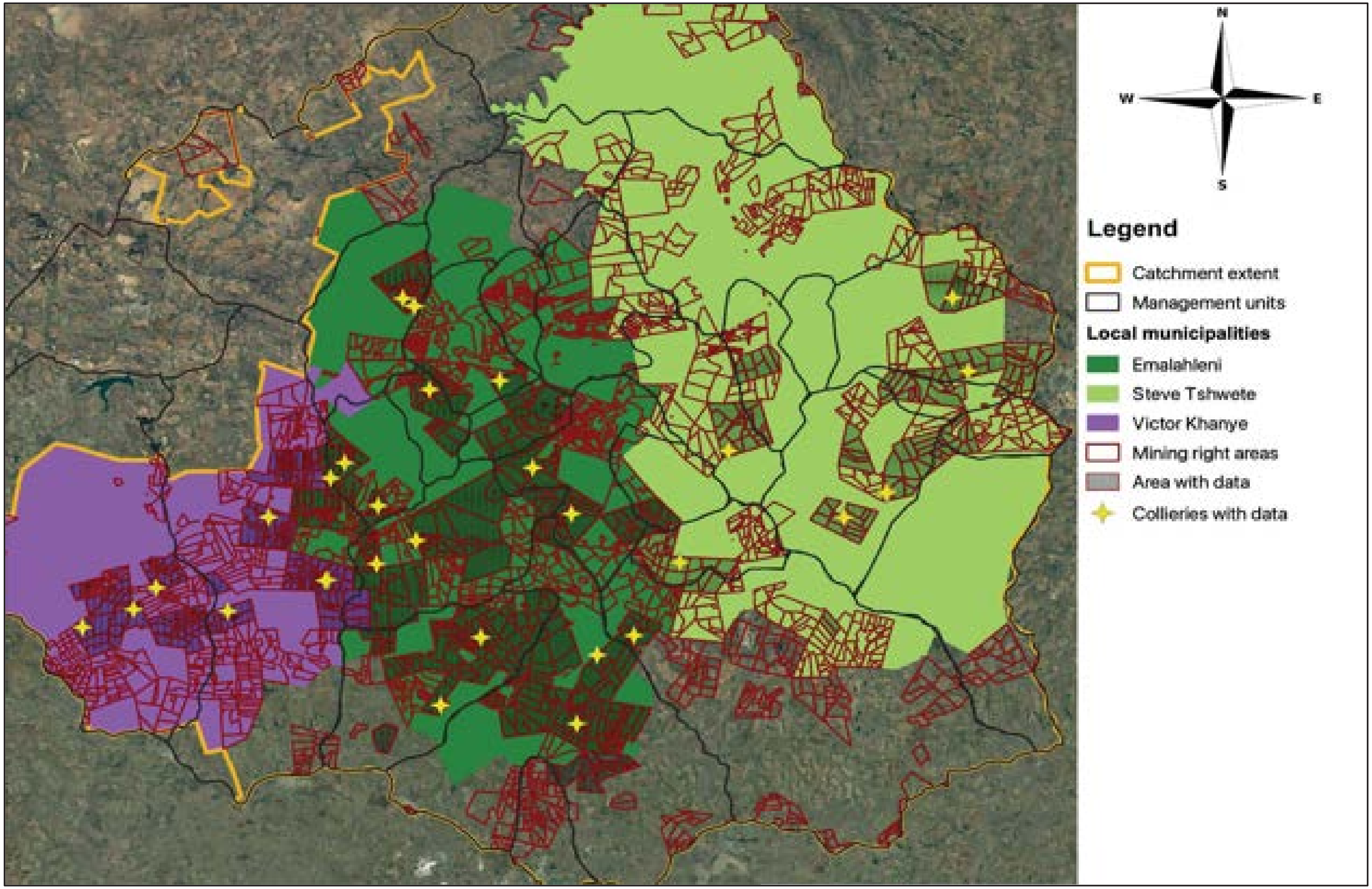


Figure 4-2: Mining right areas of operational collieries in the Upper Olifants Catchment.

4.3 Current and expected water quantities

Volumes of available mine water were estimated using groundwater flow models obtained from hydrogeological reports or data directly provided by various mining companies for life-of-mine operations and post-closure scenarios. Excess mine water volumes are reported in cubic metres per day (m^3/d). The volumes of available mine water were determined for each management unit using data from the 28 collieries, and the results are presented in Figure 4-3 and mapped in Figure 4-4. The data presented shows predicted volumes for the years 2025 and 2035. Management Units 13, 5 and 16 are expected to have the highest volumes of excess mine water, ranging from 17000 to 35000 m^3. This indicates a higher potential for mine water irrigation in these areas, provided there is sufficient irrigable land, and the water quality is suitable for irrigation.

The total volume of available mine water in the Upper Olifants Catchment is predicted to be at least 130 000 m^3/day in 2025 and at least 145 000 m^3/day in 2035 according to the assessed dataset. Since this dataset only represents 30 out of 101 mines, the volumes of water presented in the report are likely to be an underestimation of the actual volumes that will potentially be available. In a study conducted by Grobbelaar, et al. (2004), it was estimated that excess mine waters would exceed 170 000 m^3/day in the Olifants Catchment Area. Grobbelaar, et al. (2004) also highlighted access to data as a limitation in their study; however, they were able to assess 95% (by surface area) of the collieries present in the Mpumalanga Coalfields at that time and estimated that the total drainage volumes would be 360 000 m^3/day.

If available water volumes change at a particular site where irrigation is implemented as part of a mine water management strategy, then this will have implications for the way water is managed. In instances where water quantities increase over time, adjustments in management practices, such as expanding the irrigated area or switching to a cropping system with higher water demands, may be necessary. In instances where water quantities decrease over time, the opposite approach may need to be adopted.

There are currently five water reclamation plants (WRP) in Mpumalanga, treating mine waters to potable standards using reverse osmosis, namely Tweefontein WRP, Matla WRP, eMalahleni WRP, Optimum WRP and Middelburg Water Reclamation Plant. These water reclamation plants treat at least 100 000 m^3/day of mine water. Although reverse osmosis is an effective treatment that would allow for the beneficial use of mine water, the process has high capital and operating costs and is energy-intensive. In 2010, the treatment cost at the eMalahleni WRP was reported as R11/m^3 (R21/m^3 in today's value), and the water was sold to the municipality for R4.85/m³ (R9.26/m³), which meant there was no return on investment (Golder, 2012).

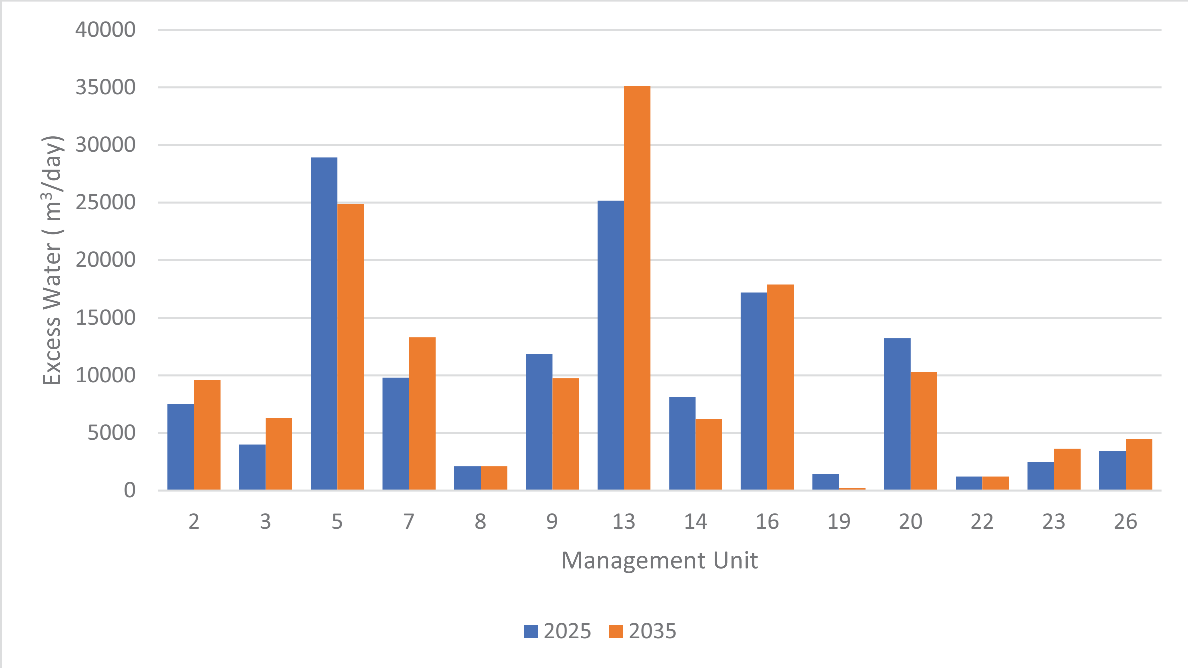


Figure 4-3: Volumes of excess mine water from assessed mines within each management unit.

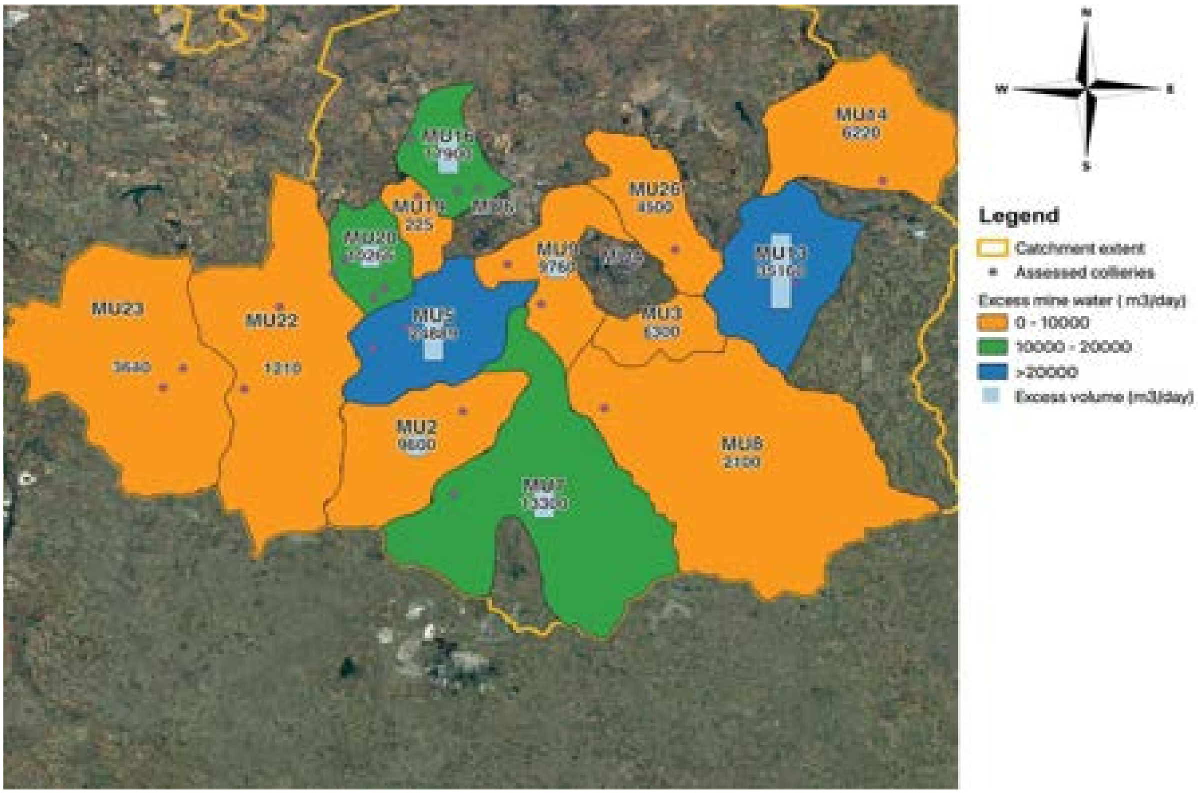


Figure 4-4: Map showing the distribution of excess mine water within the management units in 2035.

4.4 Water quality

One of the major concerns with the discharge of mine water into river systems is that the water is typically of poor quality, compromising the fitness for use of the receiving water bodies. In the Upper Olifants Catchment, salinization, sulphate loading, acidification, and nutrient enrichment (N and P loading) have been identified as major threats to water quality (DWS, 2018). Mining activities were highlighted as contributing significantly to the water quality impacts, specifically due to the high salt loads. Other water quality issues associated with mine water are the presence of potentially toxic trace elements and alkalinity.

The rationale behind the proposed use of mine water for irrigation is that mine waters considered unacceptable for domestic or other uses may be suitable for crop irrigation. With crop irrigation, the soil acts as a reactor, and there are management practices that can mitigate some potentially negative effects of water constituents. These include, for example, the addition of lime (to counter acidity and reduce mobility of trace elements), the use of gypsum (to counter high levels of sodium, reducing soil permeability), crop selection (considering crop tolerance to water constituents such as salinity) and irrigation system selection (to avoid scorching of leaves or damage to irrigation equipment).

Mine water qualities were estimated either according to available groundwater data based on sampled groundwater analyses (targeted at the seepage plumes emanating from open-cast pits and underground mining operations) or derived from geochemical models. Where no such information was available, water qualities from other potential source terms, such as seepage concentrations from waste rock dumps, were used as estimates. If more than one water quality sample was available, the median values of the different parameters were calculated as estimates for the expected mine excess water qualities. The water qualities obtained are presented in Table 4-1.

Table 4-1: Expected water quality of assessed collieries within the management units (MU).

Colliery ID	MU	Volume (m^3/day)	pH	EC (mS/m)	Na (mg/L)	Ca (mg/L)	Mg (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)	Al (mg/L)	Fe (mg/L)	K (mg/L)	Mn (mg/L)
1	2	3800	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2	2	3700	7.5	270	54	434	235	15	1761	6.00	25	134	3.08
3	3	4000	4.3	340	50	290	287	19	3700	1.40	2.4	10	7.80
4	5	1440	7.3	167	30	157	178	8	989	0.005	2.1	11	0.29
5	5	375	7	272	116	246	271	11	1670	0.060	0.4	9	4.20
6	5	27123	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
7	7	2800	7.1	320	205	397	209	25	1527	0.085	0.085	12	0.67
8	7	7000	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
9	8	2100	6.5	ND	150	750	350	ND	2500	1.00	1.0	ND	1.00
10	8	ND	7.1	308	21	337	316	31	1785	0.10	0.05	7.8	0.03
11	9	7100	7.3	410	47	520	451	10	3057	0.08	0.10	22	2.00
12	9	4760	6.8	488	97	477	621	26	4043	0.10	6.17	29	18.0
13	13	25000	7	525	110	550	570	35	3500	0.02	0.01	50	0.20
14	13	160	9.1	123	55	75	83	25	555	0.01	0.01	13	0.01
15	14	5900	6.9	194	177	149	90	70	691	0.20	1.52	12	0.11
16	14	2230	6.7	31	20	11	7	21	9	0.05	0.09	5.5	0.07

Colliery ID	MU	Volume (m^3/day)	pH	EC (mS/m)	Na (mg/L)	Ca (mg/L)	Mg (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)	Al (mg/L)	Fe (mg/L)	K (mg/L)	Mn (mg/L)
17	16	6900	6.9	307	94	469	188	28	1939	0.07	ND	11	5.60
18	16	7000	2.9	333	14	209	184	4	2356	101	167	9	71.0
19	16	3300	2.7	458	44	410	213	10	3424	115	494	6.5	27.6
20	19	1451	6.0	319	71	525	169	62	2223	0.01	29.8	25	11.2
21	20	6730	7.9	92	15	128	52	11	480	ND	ND	12	ND
22	20	2100	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
23	20	4400	7.8	331	80	467	259	9	2138	0.070	ND	20	0.020
24	22	640	8.0	25	8	17.5	14	10	11.6	0.005	0.009	2.4	0.001
25	22	70	7.9	56	52	19.6	22	53	11	0.009	0.001	8.3	0.001
26	22	500	4.6	428	12	368	272	20	4082	7.460	272	17	71.30
27	23	ND	8.19	53.6	0	53.2	33.3	18.8	31.9	0.37	ND	1.7	BDL
28	23	1800	7.7	270	45	440	174	15	1760	0.04	0.14	13	0.22
29	23	687	3.9	308	32	537	166	8	2014	1	1.02	7	6.00
30	26	3400	6.4	350	139	417	341	28	2357	0.02	0.02	17	0.02

An assessment of the major water constituents indicates that sulphate is the dominant cation in all the assessed waters (Figure 4-5). Most of the waters were dominated by Mg, on a molar basis, however, most also contain high levels of Ca, indicating the potential for gypsum precipitation in the soil profile. Precipitating salts, such as gypsum, are removed from the water system as root water uptake concentrates the soil solution(du Plessis, 1983). Gypsum precipitation is not harmful to the soil and is widely used in agriculture as a soil ameliorant, found to improve chemical and physical properties of acidic and sodic soils(Ilyas, et al., 1993, Toma, et al., 1999, Chen and Dick, 2011). Should irrigation cease, gypsum will be very slowly remobilised (over centuries to millennia according to other similar simulations) and should therefore be of no concern.

A map showing pH and EC of assessed waters is presented in Figure 4-6. On a volume basis, more than 80% of the waters assessed have a pH over 6.5 and could be considered for use without prior neutralization. The waters with a pH less than 6.5 could be considered for use if they are partially treated to be fit for irrigation purposes. At least 41% of the waters had an EC below 200 mS/m, indicating that these untreated waters would likely be suitable to irrigate most crops, even those that are salt sensitive. Only 30% of the waters have an EC above 400 mS/m, which means they are likely to be more suitable for irrigating salt tolerant crops. It should be noted that pH an EC are only partial indicators of water quality and cannot be the only factors considered when assessing the suitability of these waters for irrigation. A detailed analysis of water suitability for each water type is required to assess their fitness for irrigation use and account for other water quality parameters that can affect soil and crop quality when applied through irrigation water.

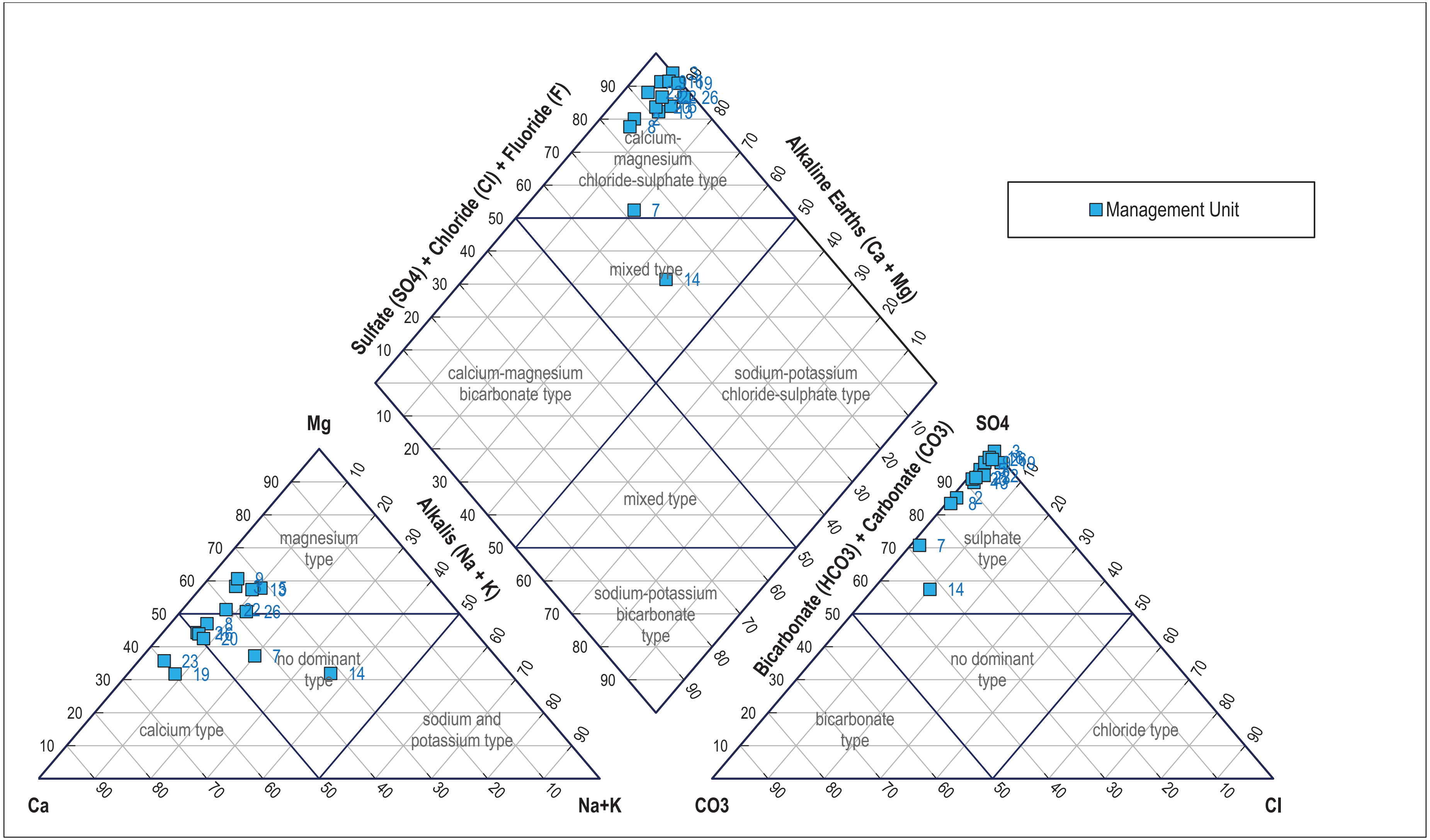


Figure 4-5: Piper Diagram showing major mine water constituents within the management units.

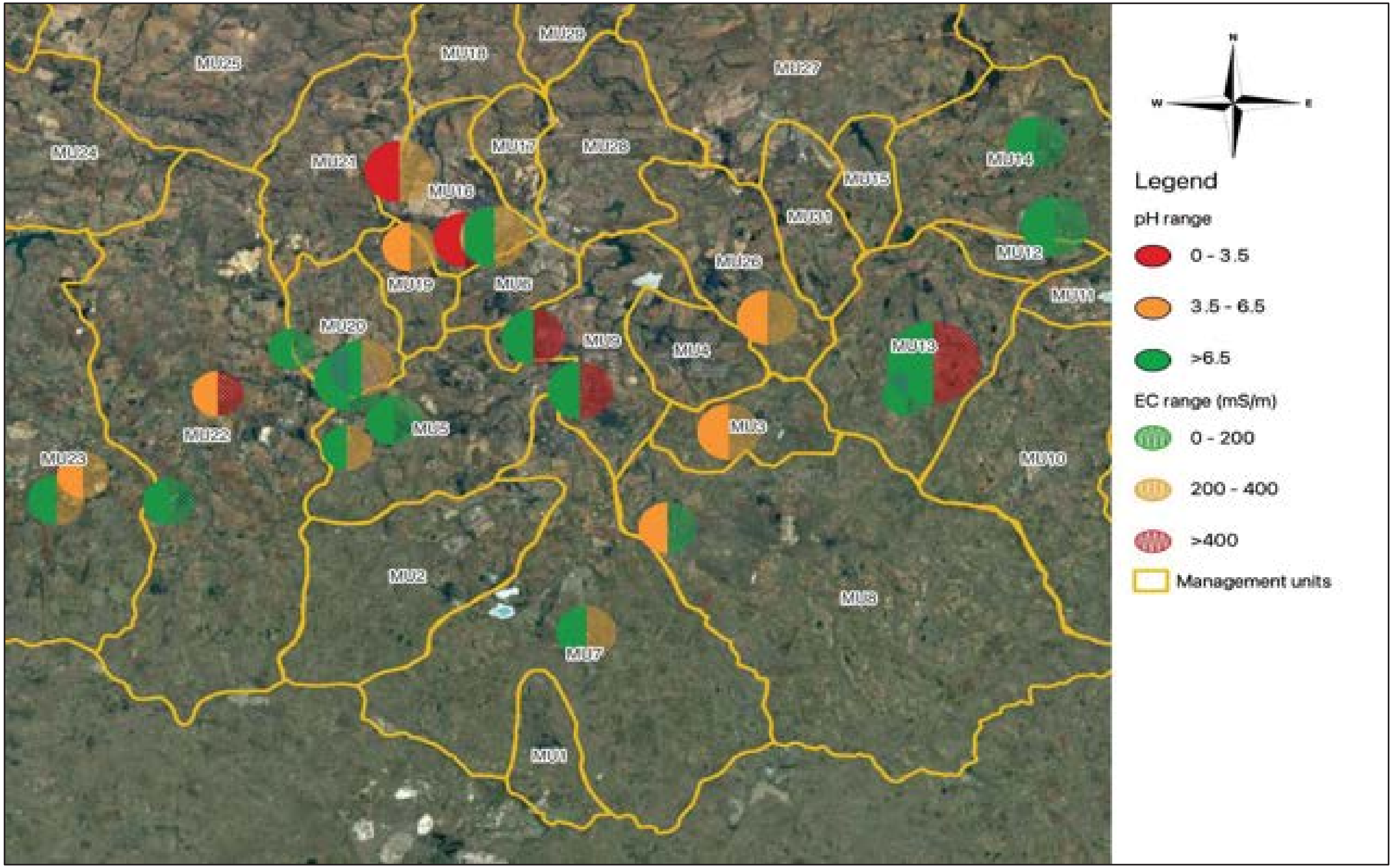


Figure 4-6: Map showing the representative quality of water from assessed mines using pH and EC as indicators of water quality.

4.5 Fitness for use of mine waters for irrigation

A site-specific, risk-based irrigation water quality Decision Support System (DSS), developed by (du Plessis, et al., 2023), was used to determine the suitability of mine waters from the Upper Olifants Catchment for irrigation. The DSS is able to assess the implications of irrigating with a range of waters, including mining-influenced waters, on soil and crop resources, as well as on irrigation equipment (not included in this analysis). This is done through the assessment of Suitability Indicators, with each divided into one of four Fitness-For-Use (FFU) classes, which are colour coded to make output intuitive, and is presented as being 'ideal', 'acceptable', 'tolerable', or 'unacceptable'.

Waters of varying qualities from different collieries within the Olifants River Catchment were assessed for their suitability for irrigation. Mine waters are difficult to irrigate with, therefore, it is recommended that these types of water only be considered for irrigating agronomic field crops such as grains, pulses and pasture with a high market demand, rather than niche crops. Two cropping systems were modelled based on agricultural practices common to the area: a maize monocrop and a soybean-oat rotation. A 1.0 m deep sandy loam soil profile was selected.

The model was set to irrigate when at least 15 mm was depleted from the profile, and this was then refilled to field capacity. With this irrigation management strategy, no purposeful leaching was simulated, and rainfall would be responsible for leaching soluble salts from the profile. An overhead irrigation system was selected to assess the risk of crop scorching. Weather stations closest to the water sources considered, were selected (Table 4-2). It should be noted that only a limited set of trace elements were considered. The results of the simulations are presented and discussed in the following sections.

Table 4-2: Weather data summary from representative weather stations used in the simulations

Weather Station	Latitude	Longitude	Elevation (m)	Avg Tmin (ºC)	Avg Tmax (ºC)	Cumulative Precipitation (mm)
Bethal-Wildebeesfonten	-26.1667	29.51667	1653	7.2	22.4	700
Delmas-Witklip	-26.15	28.6833	1560	8.2	23.5	681
Gemsbokfontein (805)	-25.7533	29.68333	1670	6.5	22.2	731
Kanhym-Investments	-25.95	29.5667	1569	7.6	22.8	686
Secunda	-26.5	29.1833	1597	8.8	22.9	694

4.5.1.1 Effect on soil profile salinity

More than 90% of the waters were in the ideal/acceptable FFU category when assessed for effects on profile salinity, indicating that most of these waters are not expected to result in excessive increases in salinity in these regions. Salinity is, however, predicted to be a tolerable problem associated with 6% of the waters on a volume basis. Leaching in higher rainfall areas and during high rainfall seasons influences accumulation of salts, therefore some variability is expected between the different cropping systems and between the different management units.

4.5.1.2 Effect on soil permeability

All assessed mine waters were in the ideal/acceptable categories when assessed for effects on surface infiltrability and about 90% (on a volume basis) of the waters are predicted to not present any significant soil hydraulic conductivity problems. Reduction in soil hydraulic conductivity was, however, predicted to be a tolerable/unacceptable problem for irrigation with 8% of the waters (on a volume basis). The application of gypsum should be able to address any problems associated with sodium and any soil compaction problems can be alleviated by cultivation.

4.5.1.3 Trace element accumulation

Most of the assessed waters were in the ideal category for the number of years to reach international soil threshold levels of Al, Mn and Fe. These elements are predicted to accumulate threshold values after more than 200 years of irrigation.

4.5.1.4 Effect on crop yield and quality

It is predicted that at least 90% of the waters assessed will be in the ideal/acceptable FFU categories for crop yield for all modelled crops. This suggests that irrigating with most of these waters is unlikely to result in significant yield reductions, even when irrigating relatively salt sensitive crops such as maize. It is also predicted that irrigation with these mine waters is unlikely to cause foliar injury when applied overhead.

4.6 Area required to utilize available mine water

In order for irrigation to serve as mine water management strategy, sufficient irrigable land is required to utilize the available water. To assess if sufficient land would be available to support mine water irrigation schemes, the area of land required to fully utilize the available mine water was calculated. This was done using the available water volume within each management unit and the irrigation requirement of each crop determined using the DSS model, assuming unlimited storage.

The area required to utilize the available mine water with maize irrigation ranged from 22 to 2 436 ha per management unit, with the total area required for maize irrigation amounting to about 14 000 ha (Figure 4-7). The Area required to utilize the available mine water with a soybean-oat rotation ranged from 8 to 900 ha per management unit, with the total area required for soybean/oats irrigation amounting to about 5 000 ha Figure 4-8). Management units 5, 13 and 16 have the highest land requirements, each having available volumes of water to irrigate at least 1 500 ha of single crop maize or to irrigate 600 ha of a soybean-oat rotation system. For a mine water irrigation scheme to be worthwhile, it is recommended that only management units that can support the irrigation of at least 100 ha be considered.

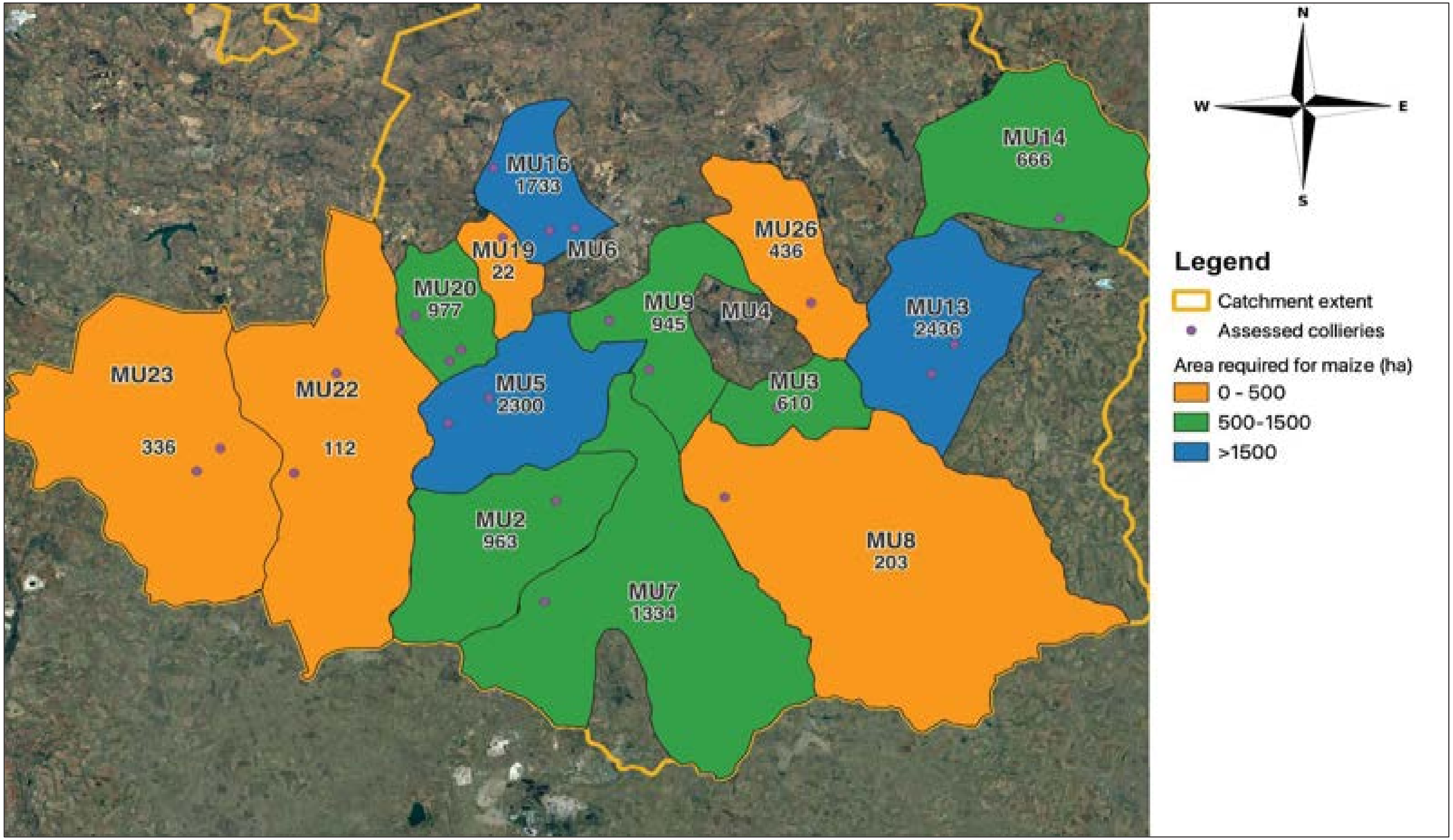


Figure 4-7: Map showing the area required to utilize excess mine water with maize irrigation.

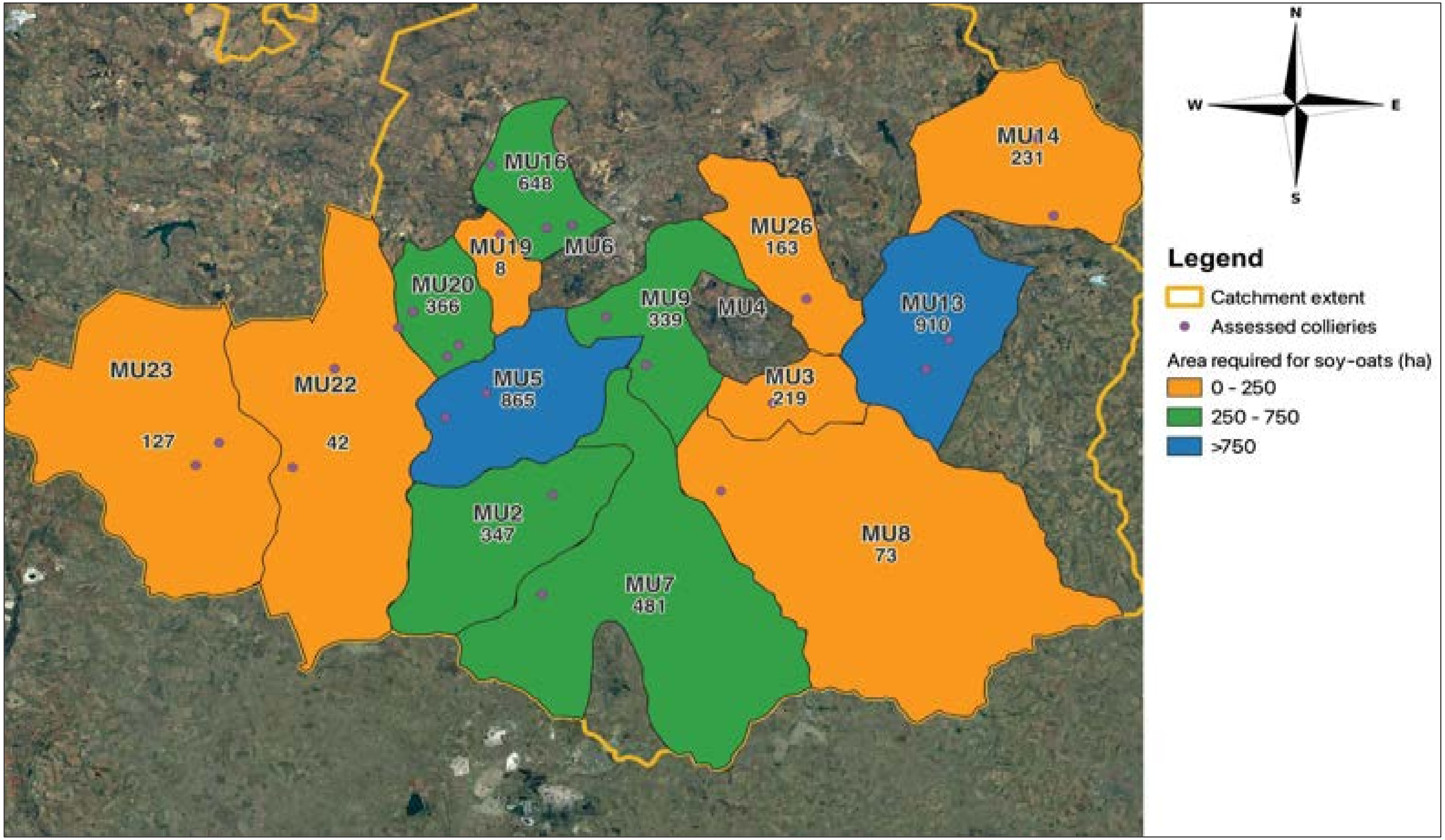


Figure 4-8: Map showing the area required to utilize excess mine water with soy-oats irrigation.

4.7 Technical considerations and regulatory aspects of mine water irrigation

Several technical considerations must be addressed when establishing mine water irrigation schemes. These include identifying suitable sites for establishing mine water irrigation schemes, identifying key unwanted events that may occur as a result of irrigation with mine water, ensuring that the qualities of soils, waters, and crops fall within acceptable environmental thresholds, and implementing adaptive management strategies when thresholds are exceeded. To assist with this process, Heuer et al. (2021) developed guidelines for site selection, water-quality evaluation, selection of cropping systems, and identification of potential constituents of concern. These guidelines include recommendations for establishing monitoring requirements and action thresholds.

The current regulations governing the management of mine water during operation and after closure do not prohibit irrigation with mining-impacted water; however, there is a lack of prescriptive guidance to facilitate informed decision-making regarding the use of mine water for irrigation in the post-mining landscape. A review of the current policies and regulatory frameworks, conducted by Pocock and Coetzee (2021), indicated there is allowance for the beneficial use of mine water for irrigation under the right conditions. An important outcome of their research was the development of guidelines for the large-scale, sustainable use of mine water for the irrigation of agricultural land during mine operations and post-closure.

Both guidelines emphasise the importance of closely monitoring and controlling large-scale mine water irrigation schemes to ensure that off-site impacts are acceptable and that such schemes are not used as disposal mechanisms for surplus mine waters, particularly during periods of excessive rainfall. Irrigation with mine waters is a technically challenging undertaking; therefore, if inexperienced emerging farmers are settled on mine water irrigation schemes, they will require sufficient technical support to help them maintain safe and sustainable use of the water. Additionally, the successful rolling out of mine water irrigation schemes will depend on the availability of current and future water quality and quantity. If the water is only going to be available for a short period, less than 20 years, and the quality is expected to deteriorate significantly over time, it is recommended that mine water irrigation not be considered in that area.

4.8 Conclusion

The assessment of the scale of opportunity for irrigating with mine waters in the Upper Olifants Catchment was performed using water quantity data for 28 mines and water quality data from 26 mines. The assessment indicated that the amount of excess water available could irrigate approximately 5 000 ha of land in a double-cropping system, such as soybeans and oats, and 14 000 ha of land in a single-cropping system, such as maize. Although most of the waters assessed were of a reasonable quality and would likely be suitable for irrigation without prior treatment, a few issues were identified with some of the waters. In this regard, irrigating mine-owned land with mine water will likely prove challenging for inexperienced farmers with little technical experience.

CHAPTER 5: SOCIO-ECONOMIC ASPECTS OF ESTABLISHING MINE WATER IRRIGATION SCHEMES IN MPUMALANGA

Irrigation with mine-impacted waters provides a platform for responsible mine water management, community upliftment and land and water stewardship. However, the socio-economic feasibility of establishing mine water irrigation schemes in the Mpumalanga region has not been widely investigated.

In this chapter, the socio-economic aspects of irrigation using mine water in Mpumalanga are explored, with a specific focus on the Upper Olifants Catchment. The potential for cost offsetting, job creation, and incorporating irrigation with mine water schemes into social development plans, as well as transferring projects to emerging commercial farmers, is discussed.

5.1 Description of the regional context

5.1.1 Locality

The Upper Olifants Catchment is one of five sub-catchments that form the Olifants River System in the Highveld Region of South Africa. The area includes the eMalahleni, Goven Mbeki, Msukaligwa, Thembisile, Victor Kanye and Steve Tshwete Local Municipalities. Three main rivers flow through the catchment: the Olifants River, Klein Olifants River and Wilge River. Figure 5-1 shows the location and extent of the Upper Olifants Catchment within Mpumalanga, with the rivers and local municipalities that fall within the catchment highlighted.

5.1.2 Land uses and land availability

The Upper Olifants Catchment covers an area of 1 053 515 ha within Mpumalanga, of which 47% (492 041 ha) is cultivated land, according to the 2020 South African National Land Cover (SANLC) Survey (DFFE, 2020). The cultivated land includes commercial annual crops, commercial orchards, fallow land and subsistence farm land. More than 90% of the land cultivated with commercial annual crops (366 571 ha) is dryland/rain-fed and only 5% (22492 ha) is irrigated. The remaining cultivated land (102 735 ha) is fallow land that was previously used for dryland/rain-fed production. The second most dominant land cover is grassland, which makes up 33% of the catchment area. Mines and quarries account for 4% of the area, and only 3% is built-up. A map showing the different land uses is presented in Figure 5-2.

Assuming that approximately 20% of existing rainfed cropland can be converted to irrigation, at least 70 000 ha of land would potentially be available in the Upper Olifants Catchment. In the context of the three municipalities that make up most of the catchment, the area available would be at least 50 000 ha, which would be adequate to fully utilize the available mine water. In addition to the available cultivated land, it is expected that there will be large tracts of rehabilitated mining-influenced land that will be available to establish mine water irrigated cropping systems. Detailed studies will be required to determine if the available land is suitable for irrigation before establishing mine water irrigation schemes.

5.1.3 Agricultural activity

A census of commercial agriculture conducted by StatsSA in 2017 (StatsSA, 2020), showed that micro farms (defined as those with an annual turnover of less than R1 million) made up the most substantial proportion (40%) of the total number of farms in Mpumalanga and accounted for 1% of the total income and 5% of the total employment in agriculture. When measured by farm size, small farming units ranked second in terms of the total number of farming units, income and employment.

Mixed farming was identified as the most dominant type of farming in Mpumalanga, making up 43% of the total farming units. Mixed farming also had the highest share of income. Farming of animals ranked second in the context of the total number of farms (661 out of 2823 farms), and income (30% of total revenue). Farming with cereals and other crops ranked third in terms of the number of farms (22%), income (14%), and employment (18%).

5.1.4 Socio-economic profile

The distribution of land uses shown in Figure 5-2 indicates that most mining activity is concentrated in three of the five local municipalities that fall within the Upper Olifants Catchment. These are the eMalahleni, Victor Kanye and Steve Tshwete local municipalities. Most of the mine water is expected to emanate from these three municipalities. These municipalities are also expected to have the greatest potential for establishing mine water irrigation schemes; therefore, the socio-economic profiling will focus on them. The three municipalities occupy a total area of 788 148 ha, which is approximately 75% of the catchment area.

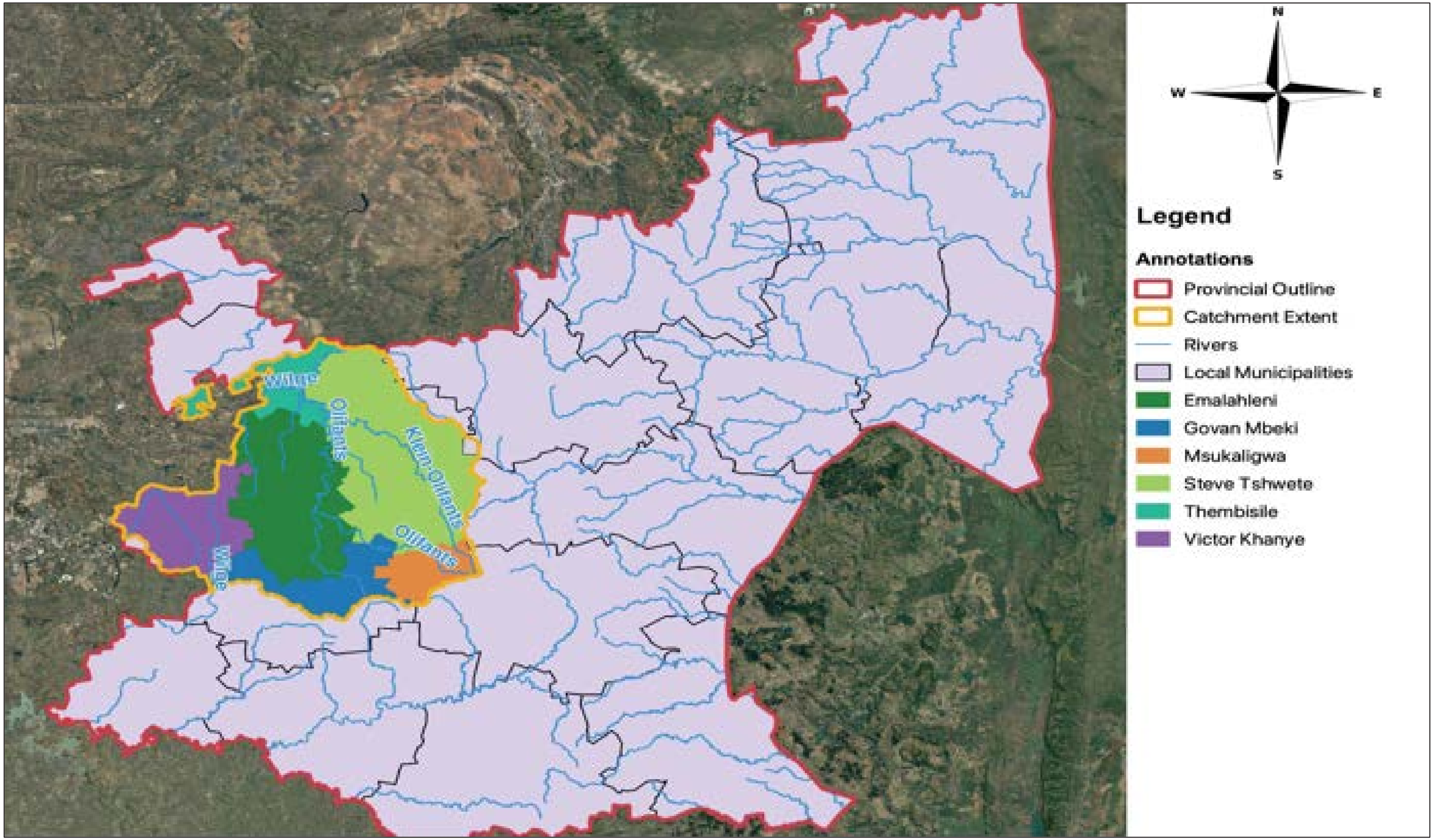


Figure 5-1: Location of the Upper Olifants Catchment in the Mpumalanga Province.

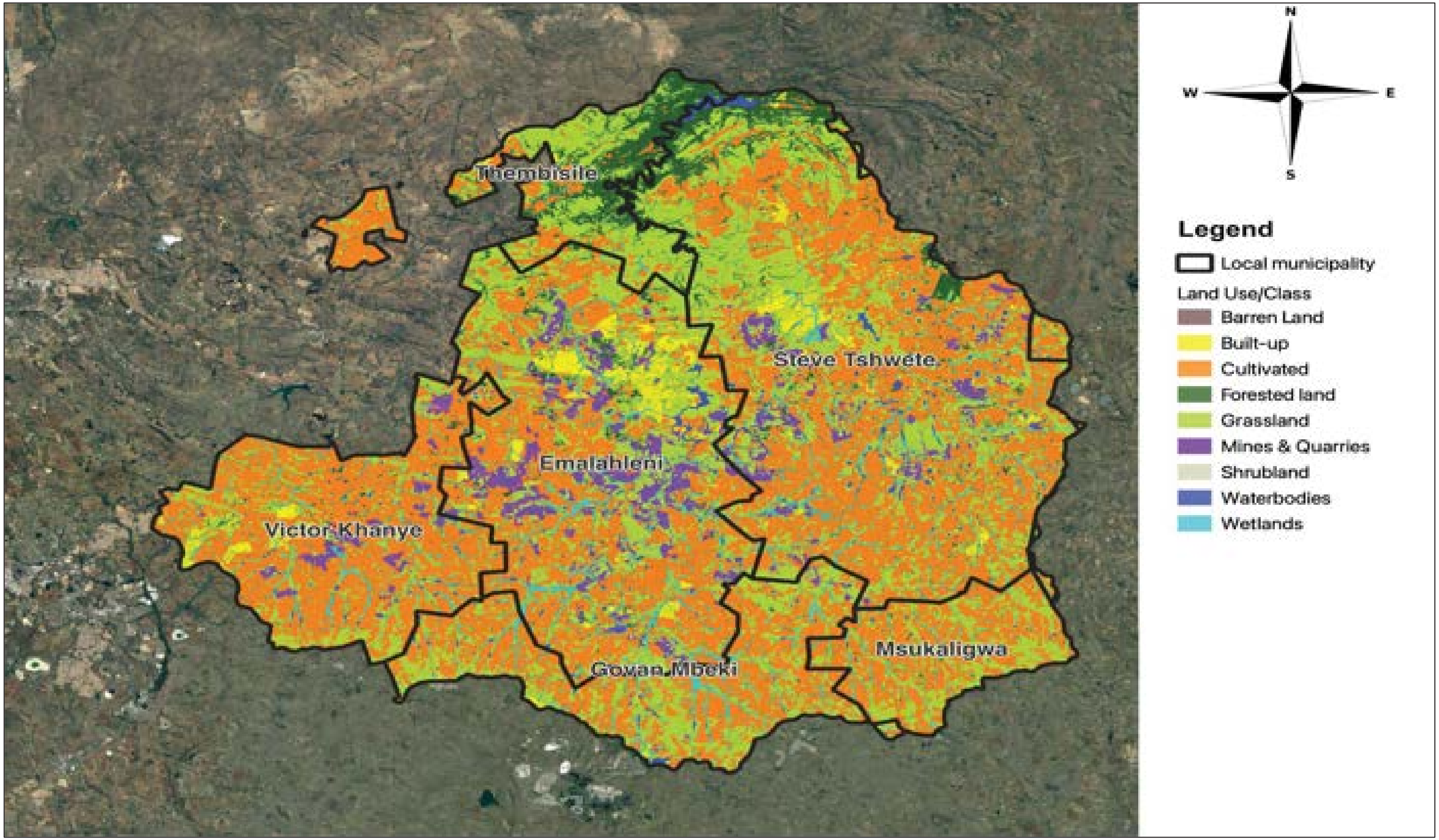


Figure 5-2: Land use/cover in the Upper Olifants Catchment

5.1.4.1 Demography

The total population in the three municipalities is approximately 940 000, based on an average population growth rate of 3% as determined in the 2016 Community Survey (StatsSA, 2016). The municipalities have a high percentage of young people, with 67% of the population under 35. Although more than 60% of these households have access to safe drinking water, less than 40% reported not having access to it. Approximately 4% of the households rely on groundwater and 0.4% on surface water for domestic purposes. At the time of the 2016 Community Survey, 20% of households reported running out of money to buy food, and 13% reported skipping a meal in the past 12 months. This indicates the threat of food insecurity in the region.

5.1.4.2 Economic activity

Approximately 70% of the population is of working age, and 70% of this group is economically active. The region has an unemployment rate of roughly 30% (StatsSA, 2011). The primary economic activity in the study region is mining, which accounts for approximately 38% of the region's economy and 20% of its employment (StatsSA, 2011). Although a large portion of the area is covered by agricultural land, agriculture only contributes 5% to the region's economy and employs 5% of the working-age population.

5.2 Economic feasibility of mine water irrigated cropping systems

Economic modelling performed by OABS Development (Pty) Ltd in a previous project suggested that establishing mine water-irrigated cropping systems for specific crops under specific conditions would be financially feasible(Heuer, et al., 2021). However, the analysis showed that the highest projected debt ratio in some modelled scenarios exceeded financing norms, and that some capital contribution would be required.

Sensitivity analyses indicated that a decrease in water quality resulting from an increase in salinity would have a negative impact on the economic viability of a mine water-irrigated cropping system (Heuer, et al., 2021). However, positive financial returns were predicted for mine-water-irrigated cropping systems. Even scenarios with the lowest net present value per cubic meter (m^3) of irrigation water were expected to yield a positive return on investment compared to the estimated cost of around R26 per m^3 for alternative mine water treatment.

It was noted that although large-scale crop production utilises excessive amounts of mine water and maximises economies of scale, it is not an efficient means of creating jobs (Heuer. Nonetheless, the economic analyses indicated that settling emerging commercial farmers on mine water irrigation schemes would be beneficial from a social perspective (increased job creation and improved livelihoods of more people compared to the large commercial farm option).

5.3 Mine water irrigation schemes as social development projects and implications for mine closure

5.3.1 Incorporation of mine water irrigation schemes into social development plans

The Mineral and Petroleum Resources Development Act, 2002 (Act No. 28 of 2002) (MPRDA) requires every mining rights holder to have a Social and Labour Plan (SLP). The SLP is a crucial tool for ensuring that holders of mining rights contribute to the socio-economic development of the areas in which they operate, promote employment, and advance the social and economic welfare of communities. According to Regulation 46 of the MPRDA, the SLP must include the following:

- A human resources development programme
- A local economic development programme
- Processes pertaining to the management of downscaling and retrenchment
- Financial provisioning for the implementation of the social and labour plan

Irrigation with mine water could significantly contribute to the economic development of mining communities by empowering emerging commercial farmers. In the context of the social labour plan, mine water irrigation schemes could be incorporated into the local economic development programme as an infrastructure and/or poverty eradication project. Establishing mine water irrigation schemes would require infrastructure for the distribution, storage, and application of mine water. Depending on the topographical location of the mine water source, pumping equipment may also be necessary. On this basis, the development of mine water irrigation schemes would be an infrastructure project. However, establishing these schemes specifically for emerging commercial farmers would also help alleviate poverty by creating jobs and improving livelihoods.

Additionally, existing mining infrastructure can be repurposed by farmers for various uses, including storage, office space, farm worker accommodation, and other purposes, depending on the type of infrastructure available. This would also reduce costs associated with demolition and rehabilitation. This, of course, will be subject to the NEMA regulations governing the rehabilitation of mine infrastructure.

5.3.2 Project transfer to emerging commercial farmers

The transfer of mine water irrigation schemes is of a complex nature, as mining-influenced waters could be considered an environmental liability according to Regulations Pertaining to the Financial Provision for Prospecting, Exploration, Mining or Production Operations (GNR 1147) of the National Environmental Management Act, 1998 (Act No. 107 of 1998) (NEMA). In such a case, the transfer of mine water irrigation schemes could be seen as a transfer of liability. It would need to comply with the MPRDA regulation for the transfer of environmental liability. According to the MPRDA regulations, the person to whom such a transfer is made must meet the following criteria:

a) have the expertise, resources and organisational abilities to integrate risk assessment, risk management and risk financing to ascertain the cost of environmental management;
b) have the expertise, financial and other resources to meet his or her obligations to carry out actions necessary to fulfil the environmental obligations as set out in the environmental management plan or the environmental management programme or any closure plan concerned;
c) have appropriate experience in environmental management, prospecting or mining operations and mine health and safety matters;
d) have direct access to insurance products and alternative risk financing services appropriate to financing of exposure to risks;
e) have the ability to manage trusts set up in terms of section 10(1)(cH) of the Income Tax Act, 1962 (Act No 58 of 1962); and have expertise and experience or proven access thereto to interpret and manage the findings of an environmental risk assessment.

Based on the criteria above, it is reasonable to expect that most farmers would not qualify as custodians of mine water irrigation schemes if the mine water is considered an environmental liability. GNR 1147 requires financial provisions for the pumping and treatment of polluted or extraneous water. If mine water is viewed as a resource and mine water irrigation is accepted as a suitable technology for mine water management, which effectively replaces treatment, transferring mine water irrigation projects to emerging farmers would be feasible.

According to the regulations, where financial provision is made for the remediation of latent or residual environmental impacts which may become known in the future, including the pumping and treatment of polluted or extraneous water, as contemplated in regulations 5(c) and 6(c), the financial vehicle used for that purpose must, on issuance of a closure certificate in terms of the Mineral and Petroleum Resources Development Act, 2002, be ceded to the Minister responsible for mineral resources, or, if the financial vehicle contemplated in regulation 8(1)(c) is used, the trustees must authorise payment to the Minister responsible for mineral resources. In such a case, the Minister could be the custodian for any mine water irrigation scheme established by the former mineral right holder upon closure.

Alternatively, the mineral right holder could retain the responsibility of managing the mine water and administering the mine water irrigation schemes. In this case, the funds allocated to post-closure treatment could be used to establish the schemes as determined by the Minister. A potential challenge may arise if a closure certificate is issued and irrigation is not considered an acceptable mine water management option.

According to the MPRDA, no closure certificate may be issued unless the Chief Inspector of Mines and each government department charged with the administration of any law that relates to any matter affecting the environment have confirmed in writing that the provisions pertaining to health and safety, and pollution management of water resources, the pumping and treatment of extraneous water and compliance to the conditions of the environmental authorisation have been addressed.

If irrigation is accepted as a long-term mine water management option, there is room for the mineral right holder to retain responsibility for the mine water irrigation scheme even after obtaining a closure certificate. According to the MPRDA, the Minister may retain any portion of such financial provision for latent and residual safety, health or environmental impact that may become known in the future. On this basis, one could argue that the mineral rights holder would have fulfilled their obligations, and funds would be available to remediate unexpected impacts should the need arise.

5.4 Conclusion

The use of mine water for irrigation in the Upper Olifants Catchment presents an opportunity to sustainably manage mining-influenced waters while contributing to agricultural production and socio-economic development. This study component investigated the socio-economic feasibility of establishing mine water irrigation schemes in the Upper Olifants Catchment. An analysis of the region revealed that commercial agriculture is a significant activity, with a substantial portion dedicated to annual crops, primarily grown under dryland conditions. The dryland areas could be developed for irrigated crop production using mine water if they are irrigable.

Previous work undertaken to assess the economic viability and feasibility of mine-water irrigated cropping systems indicates that mine-water irrigated crop production systems are financially feasible if capital contributions are made to such schemes. A review of policy and legislation indicated that mine water irrigation can be incorporated into social labour plans as infrastructure and/or poverty eradication projects within an economic development programme. Incorporating mine water irrigation schemes into social labour plans could significantly contribute to the economic development of mining communities by empowering emerging commercial farmers. If irrigation with mine waters becomes accepted as a suitable technology for mine water management, the transfer of mine water irrigation schemes could be facilitated by or through the Ministry responsible for mineral resources, or the mineral right holders could retain the responsibility if it does not interfere with their ability to obtain a closure certificate.

There is potential for establishing mine water irrigation schemes in the Upper Olifants Catchment. However, the practicality of such schemes would need careful planning and management. Given that these waters can be productively used for irrigation rather than incurring high treatment costs, it is prudent to consider irrigation as a serious long-term water management option and address any potential concerns.

The following recommendations are made if the roll-out of mine water irrigation schemes is considered:

- The rolling out of mine water irrigation schemes needs to be trialled at a smaller scale to assess the feasibility before attempting large-scale roll-out, and to learn from experience
- Some economies of scale will be required when rolling out mine water irrigation schemes to make them viable; therefore, areas that are too small (less than 100 ha) should not be considered.
- Only areas that have a good chance of success should be selected for establishing mine water irrigation schemes.
- Only agronomic crops that maximise water use, are marketable and profitable, such as grains and pulses, should be considered for mine water irrigation schemes.
- Guidelines for establishing mine water irrigation schemes and obtaining regulatory approval need to be followed.

If such schemes are to be established to support inexperienced emerging commercial farmers, extensive technical support would be required to ensure they are operated responsibly.

- Intensive monitoring and management will be required to ensure environmental sustainability.
- Current policies and regulatory frameworks need to be revised to accommodate the use of mine water for irrigation as an alternative to treatment, as well as other rehabilitation options for mine closure.
- Detailed assessments of up-to-date volume and quality data will be required to ensure the sustainability of the irrigation schemes.
- For mine water irrigation schemes to be sustainable, the volume of water available must not decrease, and its quality must not deteriorate significantly over time. In addition, there should be sufficient water available for at least 20 years.

CONCLUSIONS AND RECOMMENDATIONS

Conclusion

Irrigation with untreated or partially treated mine-influenced waters is an innovative approach to mine water management that may facilitate the sustainable closure of many collieries by generating income from what is generally seenas a costly waste stream that requires careful, expensive, and continual management. A key aspect of the irrigation approach is the ability to create livelihoods through agricultural production businesses. This is especially important at closure, when communities are required to diversify their activities away from mining.

Additionally, tens of thousands of hectares of mine land have been rehabilitated, and these areas are in proximity to mine water sources that require management. These lands are also mostly underutilised, creating an ideal opportunity to, with support, establish a new generation of commercial farmers. This project aimed to demonstrate the productivity and sustainability of commercial-scale, medium-term irrigation with calcium- and sulphate-rich, circumneutral mine water; investigate irrigation of rehabilitated land with mine-influenced water; and explore opportunities for further cost savings by irrigating with untreated and partially treated AMD. Overall, the project successfully met most of its aims.

Medium-term monitoring undertaken at the Mafube commercial-scale site demonstrated that calcium– and sulphate-rich, circumneutral, untreated mine waters can be used productively for irrigation with minimal environmental impacts and produce crops that are safe for consumption. Although the project team is fairly confident that commercial-scale irrigation with circumneutral calcium and sulphate-rich waters is sustainable in the long term, it would be valuable to continue monitoring this site to strengthen the argument. This is also a site that regulators or others interested in mine water irrigation can visit to see proof of concept.

Extensive work was undertaken at the rehabilitated site to characterise rehabilitated land by irrigability rather than conventional arability, and to identify factors that influence its irrigability. The work undertaken suggests that irrigation of rehabilitated land can be productive. Soil physical conditions and hydrological position in the landscape were identified as crucial factors for the successful irrigation of rehabilitated land. The work undertaken culminated in the development of draft guidelines for the irrigation of rehabilitated land, which will be published as a standalone document. These guidelines are a valuable output and would benefit significantly from critical evaluation and revision where necessary.

Due to challenges in establishing small-plot field trials, the data obtained were insufficient to adequately assess the productivity of irrigating untreated and partially treated AMD. Nonetheless, the extensive glasshouse work conducted provides excellent insights into crop and soil responses to irrigation with this water. The productivity of crops irrigated with partially treated AMD indicates that irrigation with these waters is feasible, at least in the short term. There are concerns about irrigating with untreated AMD, particularly regarding the productivity and accumulation of selected trace elements. However, it is hypothesised that there are conditions under which irrigation with these waters would be successful. Additionally, concerns, whether real or perceived, regarding the safety of the produce for consumption could be addressed by producing industrial biofuel crops.

The assessment of the scale of opportunity for irrigating with mine waters in the Upper Olifants Catchment indicated that the amount of excess water available could irrigate 5 000 to 14 000 ha of land, depending on the cropping system. The socio-economic assessment of establishing mine water irrigation schemes in the Upper Olifants Catchment indicates that sufficient land is available for their establishment within the catchment. However, the practicality of rolling out such schemes would need careful planning and management. Considering that these waters can be productively used for irrigation rather than incurring high treatment costs, it is prudent to seriously consider irrigation as a potential long-term water management option and to address any potential concerns.

Overall, this project demonstrated that irrigation can be a sustainable solution for managing most mine-influenced waters, with important socioeconomic benefits, especially if rehabilitated land can be utilised.

Recommendations

A considerable investment has been made in establishing the trial sites discussed in this report, and the project team considers them valuable in facilitating the acceptance of irrigation as an option for managing mine waters in the Mpumalanga Coalfields. It’s recommended that further work be undertaken to better understand the irrigation of rehabilitated land and the use of untreated and partially treated AMD. A valuable demonstration site has been established at Mafube, and it would be beneficial to maintain this site’s activity. Possible future studies for consideration include the following:

- Continued monitoring of productivity and environmental impact (crop growth and yield, profitability, food safety, soil quality, surface and ground water quality) of medium to long-term irrigation with circumneutral waters on unmined land

- Evaluation and revision of the draft guidelines on rehabilitation for irrigation, and development of an electronic decision support system to make the guidelines user-friendly.
- Establishment and management of small plot and/or glasshouse pot trials to screen food, fodder and industrial crops for their productivity and quality when produced with untreated and partially treated mine-influenced waters.

REFERENCES

ADNAN M, SHAH Z, FAHAD S, ARIF M, ALAM M, KHAN IA, MIAN IA, BASIR A, ULLAH H, ARSHAD M, INAYAT-UR-REHMAN, SAUD S, IHSAN MZ, JAMAL Y, AMANULLAH, HAMMAD HM and NASIM W (2017) Phosphate-Solubilizing Bacteria Nullify the Antagonistic Effect of Soil Calcification on Bioavailability of Phosphorus in Alkaline Soils. *Scientific Reports* **7**. https://doi.org/ARTN 1613110.1038/s41598-017-16537-5.

AKCIL A and KOLDAS S (2006) Acid Mine Drainage (AMD): causes, treatment and case studies. *Journal of Cleaner Production* **14**(12) 1139-1145.

ALMEIDA IA, DE SOUSA PEREIRA DJ, DE OLIVEIRA COSTA J, QUILOANGO-CHIMARRO CA and COELHO RD (2022) Dripper clogging: emphasis on the problem and how to minimize impact. *Revista Brasileira de Engenharia de Biossistemas* **16**.

AMY SW, DANI U, NU'MAN H, MUSLIM D, NASRUDDIN D, NURYAHYA H, NURHASAN R and AGUSTIN DS (2023) The Forming of Acid Mine Drainage Based on Characteristics of Coal East Indonesia. *Journal of Ecological Engineering* **24**(7) 301-310. https://doi.org/10.12911/22998993/162551.

ANNANDALE J, DU PLESSIS M, TANNER P, HEUER S and MADISENG L (2023) Irrigation Should be Explored as a Sustainable Management Solution to the Acid Mine Drainage Legacy of the Witwatersrand Goldfields. *Mine Water and the Environment*. https://doi.org/10.1007/s10230-023-00961-3.

ANNANDALE J, JOVANOVIC N and CLAASSENS A (2002) The influence of irrigation with calcium and sulphate-rich mine water on soil properties and drainage water. Pretoria: Water Research Commission; 2002. Report No.: 858/1/02.

ANNANDALE J, JOVANOVIC N, BENADE N and TANNER P (1999) Modelling the long-term effect of irrigation with calcium and sulphate-rich water on soil and water resources. *Agriculture, Ecosystems & Environment* **76**(2-3) 109-119. https://doi.org/10.1016/s0167-8809(99)00079-1.

ANNANDALE J, JOVANOVIC N, HODGSON F, USHER B, AKEN M, VAN DER WESTHUIZEN A, BRISTOW K and STEYN J (2006) Prediction of the environmental impact and sustainability of large-scale irrigation with calcium and sulphate-rich mine-water on groundwater resources. *Water SA* **32**(1). https://doi.org/10.4314/wsa.v32i1.5235.

ANNANDALE J, JOVANOVIC N, PRETORIUS J, LORENTZ S, RETHMAN N and TANNER P (2001) Calcium and sulphate-rich mine water use in irrigation on rehabilitated open-cast mine land: Crop Production, soil water and salt balance. *Ecological Engineering* **17**(2-3) 153-164. https://doi.org/10.1016/s0925-8574(00)00155-5.

ANNANDALE J, TANNER P and HEUER S(2021) Irrigation with poor-quality mine water in Mpumalanga. Research Report. Pretoria: Water Research Commision; 2021. Report No.: TT 855/1/21.https://wrcwebsite.azurewebsites.net/wp-content/uploads/mdocs/TT%20855-1-21_with%20appendices%20final%20web.pdf.

ANNANDALE JG, TANNER PD, DU PLESSIS HM, BURGESS J, RONQUEST ZD and HEUER S (Year) Irrigation with mining-influenced waters: a demonstration with untreated colliery water in South Africa. In: Proc, IMWA Conf, Session, pp.71-76.

AYERS RS and WESTCOT DW (1985) *Water quality for agriculture*. Food and Agriculture Organization of the United Nations Rome, pp.

BAUDER JW and BROCK TA (2001) Irrigation water quality, soil amendment, and crop effects on sodium leaching. *Arid Land Research and Management* **15**(2) 101-113. https://doi.org/Doi 10.1080/15324980151062724.

BELL F, BULLOCK S, HäLBICH T and LINDSAY P (2001) Environmental impacts associated with an abandoned mine in the Witbank Coalfield, South Africa. *International Journal of Coal Geology* **45**(2) 195-216.

BIAN Z, INYANG HI, DANIELS JL, OTTO F and STRUTHERS S (2010) Environmental issues from coal mining and their solutions. *Mining Science and Technology (China)* **20**(2) 215-223. https://doi.org/https://doi.org/10.1016/S1674-5264(09)60187-3.

CHEN L and DICK WA (2011) *Gypsum as an agricultural amendment: General use guidelines*. Ohio State University Extension, pp.

DE MORAES MT, DA SILVA VR, ZWIRTES AL and CARLESSO R (2014) Use of Penetrometers in Agriculture: A Review. *Engenharia Agricola* **34**(1) 179-193. https://doi.org/Doi 10.1590/S0100-69162014000100019.

DEPARTMENT OF MINERAL RESOURCES AND ENERGY(DMRE)(2017) Operating mines. URL: https://www.dmr.gov.za/mineral-policy-promotion/operating-mines/mpumalanga?search=Coal#14753.

DEPARTMENT OF WATER AND SANITATION(DWS). (2018a). Development of an Integrated Water Quality Management Plan for the Olifants River System: Upper Olifants Sub-catchment Plan. (P WMA 04/B50/00/8916/8). Pretoria.

DEPARTMENT OF WATER AND SANITATION(DWS). (2018b). Development of an Integrated Water Quality Management Plan for the Olifants River System: Water Quality Status Assessment and International Obligations Report. (Report No: P WMA 04/B50/00/8916/3).

DU PLESSIS H (1983) Using lime treated acid mine water for irrigation. Water Science and Technology 15(2) 145-154.

DU PLESSIS H, ANNANDALE J, BENADÉ N, VAN DER LAAN M, JOOSTE S, DU PREEZ C, BARNARD J, RODDA N, DABROWSKI J, GENTHE B and NELL P). (2017). Risk Based, Site-Specific, Irrigation Water Quality Guidelines: Volume 1 Description of Decision Support System. (WRC Report no. TT 727/17). Water Research Commission.

DU PLESSIS MH, ANNANDALE JG and BENADé N (2023) A Decision Support System That Considers Risk and Site Specificity in the Assessment of Irrigation Water Quality (IrrigWQ). *Applied Sciences* **13**(23) 12625. https://doi.org/10.3390/app132312625.

DU PREEZ K (2021) Mintek's integrated cloSURE^{TM} technology for treatment of acid mine drainage. *International Mine Water Association* 10-12.

EDWARDS KJ, GIHRING TM and BANFIELD JF (1999) Seasonal variations in microbial populations and environmental conditions in an extreme acid mine drainage environment. *Applied and Environmental Microbiology* **65**(8) 3627-3632.

EQUEENUDDIN SM, TRIPATHY S, SAHOO PK and PANIGRAHI MK (2010) Hydrogeochemical characteristics of acid mine drainage and water pollution at Makum Coalfield, India. *Journal of Geochemical Exploration* **105**(3) 75-82. https://doi.org/10.1016/j.gexplo.2010.04.006.

EYNARD A, LAL R and WIEBE K (2005) Crop response in salt-affected soils. *Journal of Sustainable Agriculture* **27**(1) 5-50. https://doi.org/10.1300/J064v27n01_03.

FENG D, ALDRICH C and TAN H (2000) Treatment of acid mine water by use of heavy metal precipitation and ion exchange. *Minerals Engineering* **13**(6) 623-642. https://doi.org/Doi 10.1016/S0892-6875(00)00045-5.

FERIS L and KOTZE LJ (2014) The regulation of acid mine drainage in South Africa: law and governance perspectives. *Potchefstroom Electronic Law Journal* **17**(5) 2105-2163.

FRANCOIS LE, DONOVAN TJ, LORENZ K and MAAS EV (1989) Salinity Effects on Rye Grain-Yield, Quality, Vegetative Growth, and Emergence. *Agronomy Journal* **81**(5) 707-712. https://doi.org/DOI 10.2134/agronj1989.00021962008100050001x.

GOLDER(2012) eMalahleni Mine Water Reclamation Expansion Project: public Participation report. 2012.

GROBBELAAR R, USHER B, CRUYWAGEN L, DE NECKER E and HODGSON F(2004) Long-term impact of intermine flow from collieries in the Mpumalanga Coalfields. Pretoria: Water Research Commission; 2004. Contract No.: 1056/1/04.

GUAN RX, QU Y, GUO Y, YU LL, LIU Y, JIANG JH, CHEN JG, REN YL, LIU GY, TIAN L, JIN LG, LIU ZX, HONG HL, CHANG RZ, GILLIHAM M and QIU LJ (2014) Salinity tolerance in soybean is modulated by natural variation in. *Plant Journal* **80**(6) 937-950. https://doi.org/10.1111/tpj.12695.

HARTEMINK AE and BARROW NJ (2023) Soil pH - nutrient relationships: the diagram. *Plant and Soil* **486**(1-2) 209-215. https://doi.org/10.1007/s11104-022-05861-z.

HE QL, BERG A, LI Y, VALLEJOS CE and WU RL (2010) Mapping genes for plant structure, development and evolution: functional mapping meets ontology. *Trends in Genetics* **26**(1) 39-46. https://doi.org/10.1016/j.tig.2009.11.004.

HEUER S, ANNANDALE J, TANNER P and DU PLESSIS H(2021) Technical Guidelines for Irrigation with Mining-influenced Waters. Pretoria: Water Reserch Commision; 2021. Report No.: TT 855/2/21.https://wrcwebsite.azurewebsites.net/wp-content/uploads/mdocs/TT%20855-2-21%20final%20web.pdf.

HU JL, WU FY, WU SC, SUN XL, LIN XG and WONG MH (2013) Phytoavailability and phytovariety codetermine the bioaccumulation risk of heavy metal from soils, SA DEPARTMENT OF WATER AFFAIRS AND FORESTRY(DWAF). (1996). South African Water Quality Guidelines (second edition).

HUSSAIN S, SHAUKAT M, ASHRAF M, ZHU C, JIN Q and ZHANG J (2019) Salinity stress in arid and semi-arid climates: Effects and management in field crops. *Climate change and agriculture*. IntechOpen,

IDOWU O, LORENTZ SA, ANNANDALE JG, AKEN M, MCCARTNEY M, THORNTON-DIBB S and WESTHUIZEN A (2010) Comparative assessment of widespread irrigation with low quality mine-water in undisturbed and rehabilitated mine-lands in the upper Olifants using the ACRU2000 model. *Water SA* **36**(5) 543-552. https://doi.org/10.4314/wsa.v36i5.61988.

ILYAS M, MILLER RW and QURESHI RH (1993) Hydraulic Conductivity of Saline-Sodic Soil after Gypsum Application and Cropping. *Soil Science Society of America Journal* **57**(6) 1580-1585. https://doi.org/https://doi.org/10.2136/sssaj1993.03615995005700060031x.

JARVIS AP and YOUNGER PL (2001) Passive treatment of ferruginous mine waters using high surface area media. *Water Research* **35**(15) 3643-3648. https://doi.org/Doi 10.1016/S0043-1354(01)00089-6.

JEONG H, KIM H and JANG T (2016) Irrigation water quality standards for indirect wastewater reuse in agriculture: a contribution toward sustainable wastewater reuse in South Korea. *Water* **8**(4) 169.

JONES JD (2020) Iron availability and management considerations: A 4R approach. *Crops & Soils* **53**(2) 32-37

JOVANOVIC N, BARNARD R, RETHMAN N and ANNANDALE J (1998) Crops can be irrigated with lime-treated acid mine drainage. *WATER SA-PRETORIA-* **24** 113-122. https://www.wrc.org.za/wp-content/uploads/mdocs/WaterSA_1998_02_apr98_p113.pdf

KATERJI N, VAN HOORN JW, HAMDY A and MASTRORILLI M (2003) Salinity effect on crop development and yield, analysis of salt tolerance according to several classification methods. *Agricultural Water Management* **62**(1) 37-66. https://doi.org/10.1016/S0378-3774(03)00005-2.

KHAN A, KHAN S, KHAN MA, QAMAR Z and WAQAS M (2015) The uptake and bioaccumulation of heavy metals by food plants, their effects on plants nutrients, and associated health risk: a review. *Environmental Science and Pollution Research* **22**(18) 13772-13799. https://doi.org/10.1007/s11356-015-4881-0.

KHAN S, HESHAM AEL, QIAO M, REHMAN S and HE JZ (2010) Effects of Cd and Pb on soil microbial community structure and activities. *Environmental Science and Pollution Research* **17**(2) 288-296. https://doi.org/10.1007/s11356-009-0134-4.

KRISHNAN S, ZULKAPLI NS, KAMYAB H, TAIB SM, DIN MFB, ABD MAJID Z, CHAIPRAPAT S, KENZO I, ICHIKAWA Y, NASRULLAH M, CHELLIAPAN S and OTHMAN N (2021) Current technologies for recovery of metals from industrial wastes: An overview. *Environmental Technology & Innovation* **22**. https://doi.org/ARTN 101525

LE ROUX, S.G., DU PLESSIS, A. & CLARKE, C.E. 2019. MicroCT-based bulk density measurement method for soils. Journal of the South African Institution of Civil Engineering: 6: 2-9.

LI QS, CAI SS, MO CH, CHU B, PENG LH and YANG FB (2010) Toxic effects of heavy metals and their accumulation in vegetables grown in a saline soil. *Ecotoxicology and Environmental Safety* **73**(1) 84-88. https://doi.org/10.1016/j.ecoenv.2009.09.002.

LIN C, WU L and WU Y (2005) Agricultural soils irrigated with acidic mine water: acidity, heavy metals, and crop contamination. *Australian Journal of Soil Research* **43**(7) 819-826. https://doi.org/10.1071/Sr04148.

LIU L, NIU WQ, GUAN YH, WU ZG and AYANTOBO OO (2019) Effects of Urea Fertigation on Emitter Clogging in Drip Irrigation System with Muddy Water. *Journal of Irrigation and Drainage Engineering* **145**(9). https://doi.org/Artn10.1061/(Asce)Ir.1943-4774.0001416.

LUO CL, LIU CP, WANG Y, LIU XA, LI FB, ZHANG G and LI XD (2011) Heavy metal contamination in soils and vegetables near an e-waste processing site, south China. *Journal of Hazardous Materials* **186**(1) 481-490. https://doi.org/10.1016/j.jhazmat.2010.11.024.

MAAS EV and HOFFMAN GJ (1977) Crop salt tolerance—current assessment. *Journal of the irrigation and drainage division* **103**(2) 115-134.

MASINDI V and MUEDI KL (2018) Environmental contamination by heavy metals. *Heavy metals* **10**(4) 115-133.

MCCARTHY TS (2011) The impact of acid mine drainage in South Africa. *South African Journal of Science* **107**(5-6) 01-07.

MCGLADDERY C (2019) Evaluation of irrigation water quality guidelines for arsenic and lead, with implications for food safety. MSc Dissertation, University of Pretoria, Pretoria.

MCLEAN JE (1992) *Behavior of metals in soils*. Technology Innovation Office, Office of Solid Waste and Emergency Response, pp.

MOGOTSI K and VAN DER MERWE F (2017) Can one use the dynamic cone penetrometer to predict the allowable bearing pressure. *Proceedings of the 9th South African Geotechnical Engineers Cconference*.

MOLWANTWA J, MOLIPANE N and ROSE P (Year) Biological sulfate reduction utilizing algal extracellular products as a carbon source. In: WISA 2000 Biennial Conference, Sun City, South Africa, Session.

NORTJé GP and LAKER MC (2021) Factors That Determine the Sorption of Mineral Elements in Soils and Their Impact on Soil and Water Pollution. *Minerals* **11**(8). https://doi.org/ARTN 821

NUKPEZAH D, RAHMAN FA and KORANTENG S (2017) The impact of small scale mining on irrigation water quality in Asante Akim Central Municipality of Ghana. *West African Journal of Applied Ecology* **25**(2) 49-67.

PAGE KL, DANG YP, MARTINEZ C, DALAL RC, WEHR JB, KOPITTKE PM, ORTON TG and MENZIES NW (2021) Review of crop-specific tolerance limits to acidity, salinity, and sodicity for seventeen cereal, pulse, and oilseed crops common to rainfed subtropical cropping systems. *Land Degradation & Development* **32**(8) 2459-2480. https://doi.org/10.1002/ldr.3915.

PAIGE-GREEN P and DU PLESSIS L (2009) Use and interpretation of the dynamic cone penetrometer (DCP) test. CSIR.

PARIHAR P, SINGH S, SINGH R, SINGH VP and PRASAD SM (2015) Effect of salinity stress on plants and its tolerance strategies: a review. *Environmental Science and Pollution Research* **22**(6) 4056-4075. https://doi.org/10.1007/s11356-014-3739-1.

PATOUSSIAS P, ANNANDALE J and TANNER P (2024) Guidelines for rehabilitating mined land to irrigable standard. Water Research Commission.

POCOCK G and COETZEE L(2021) Guidance for attaining regulatory approval of Irrigation as a large-scale, sustainable use of mine water. Pretoria: Water Reserch Commision; 2021. Report No.: TT 837/20.

REZAIE B and ANDERSON A (2020) Sustainable resolutions for environmental threat of the acid mine drainage. *Science of the Total Environment* **717**. https://doi.org/10.1016/j.scitotenv.2020.137211

RHOADES J and MERRILL S (1976) Man-made factors: assessing the suitability of water for irrigation: theoretical and empirical approaches. *FAO Soils Bulletins (FAO). no. 31.*,

SAVIOUR MN (2012) Environmental impact of soil and sand mining: a review. *International Journal of Science, Environment and Technology* **1**(3) 125-134.

SAYEGH AH, KHAN NA, KHAN P and RYAN J (1978) Factors Affecting Gypsum and Cation-Exchange Capacity Determinations in Calcium and sulphate-rich Soils. *Soil Science* **125**(5) 294-300. https://doi.org/Doi 10.1097/00010694-197805000-00004.

SHELDON AR, DALAL RC, KIRCHHOF G, KOPITTKE PM and MENZIES NW (2017) The effect of salinity on plant-available water. *Plant and Soil* **418**(1-2) 477-491. https://doi.org/10.1007/s11104-017-3309-7.

SKOUSEN J, ZIPPER CE, ROSE A, ZIEMKIEWICZ PF, NAIRN R, MCDONALD LM and KLEINMANN RL (2017) Review of Passive Systems for Acid Mine Drainage Treatment. *Mine Water and the Environment* **36**(1) 133-153. https://doi.org/10.1007/s10230-016-0417-1.

SPOSITO G (2008) *The chemistry of soils*. Oxford university press, pp.

THISANI SK, KALLON DVV and BYRNE P (2020) Geochemical Classification of Global Mine Water Drainage. *Sustainability* **12**(24) 10244. https://doi.org/10.3390/su122410244.

TOMA M, SUMNER ME, WEEKS G and SAIGUSA M (1999) Long-term Effects of Gypsum on Crop Yield and Subsoil Chemical Properties. *Soil Science Society of America Journal* **63**(4) 891-895. https://doi.org/https://doi.org/10.2136/sssaj1999.634891x.

VAN DER LAAN M, FEY MV, VAN DER BURGH G, DE JAGER PC, ANNANDALE JG and DU PLESSIS HM(2014) Feasibility study on the use of irrigation as part of a long-term acid mine water management strategy in the Vaal Basin. Research Report; 2014. Report No.: 2233/1/14.https://wrcwebsite.azurewebsites.net/wp-content/uploads/mdocs/2233-1-14.pdf.

VAN HUYSSTEEN L (1983) Interpretation and Use of Penetrometer Data to describe Soil Compaction in Vineyards. *South African Journal of Enology and Viticulture* **4**(2) 59-65.

VAN RENSBURG LD, DE CLERCQ WP, BARNARD JH and DU PREEZ CC (2011) Salinity guidelines for irrigation: Case studies from Water Research Commission projects along the Lower Vaal, Riet, Berg and Breede Rivers. *Water Sa* **37**(5) 739-749. https://doi.org/10.4314/wsa.v37i5.11.

VAZQUEZ O (Year) Effect of Acid Mine Drainage on Aluminum Release from Clay Minerals. In: World Environmental and Water Resources Congress 2009: Great Rivers, Session, pp.1-8.

WANG W, ZHAO XQ, HU ZM, SHAO JF, CHE J, CHEN RF, DONG XY and SHEN RF (2015) Aluminium alleviates manganese toxicity to rice by decreasing root symplastic Mn uptake and reducing availability to shoots of Mn stored in roots. *Annals of botany* **116**(2) 237-246.