Crop and Environmental Response to Irrigation with Mine-Affected Waters: The Development of Technical Management Guidelines

By

SARAH NICOLE HEUER

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Supervisor: Prof. J. G. Annandale

Co-Supervisor: Dr. P. D. Tanner

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DECLARATION

I, Sarah Nicole Heuer, declare that this dissertation, which I hereby submit for the degree MSc (Agriculture) Soil Science at the University of Pretoria, is my own work, except where duly acknowledged, and has not previously been submitted by me for a degree at this or any other tertiary institution. I also certify that there was no plagiarism committed in writing this thesis.

Signed: Sarah Heuer

Date: 15 July 2023

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ABSTRACT

Decanting and illegal mine-affected water disposal are problems which have plagued South Africa's mining industry and have exacerbated the deterioration of the quality of water resources. Expensive and energy intensive mine water treatment has thus become normal practice for mine water management in most South African mines. The reuse of mine-affected waters in other industries allows for alternative mine water utilisation options and may partially alleviate mine water treatment costs.

Another of South Africa's largest water users is the agricultural industry. The mining industry in South Africa produces large volumes of mine-affected waters and the agricultural industry requires large water inputs to improve and maximize yields of crops. A noteworthy opportunity, therefore, arises for the use of mine-affected water for irrigation. If monitored and correctly managed, mine-affected water irrigation is a sustainable, consumptive, and alternative water utilization option. Due to the lack of concise guidance to facilitate regulatory approval of irrigation with mine-affected waters, it is not practiced on any meaningful commercial scale in South Africa.

Firstly, this study aimed at gaining a fundamental understanding of available literature on irrigation with mine-affected waters. Secondly, an established field trial at Mafube Colliery, (Middelburg, Mpumalanga, South Africa), provides a platform for the long-term quantification, monitoring and modelling of salt and water balances when irrigating with gypsiferous mine-affected waters. Finally, a technical management guideline is proposed as a standardised framework for site selection, constituents of concern identification, applicable environmental risk assessment, monitoring plans and action levels, when using mine-affected water for irrigation.

At the established field trial, white maize was irrigated for three seasons, 2017 to 2020, on unmined land. The quality of the grain produced was well above food and fodder safety standards, with the white maize producing reasonable to good yields with demonstrated profitability, under these irrigation conditions. Irrigation with gypsiferous mine water at this field site, has an acceptable and limited environmental impact, and with appropriate risk-based management, is a feasible and responsible practice. The routinely measured atmospheric, crop, soil, and water data obtained throughout this study were used as inputs for an irrigation water quality Decision Support System (DSS).

The technical management guideline developed here amalgamated the appropriate tools, practices, and guidelines specific to mine-affected water irrigation. The proposed comprehensive and site-specific risk assessment characterises a site's applicability,

susceptibility, and capacity to receive, conduct and function when irrigated with mine-affected water.

Keywords: Mine-Affected Water Irrigation, Gypsiferous Irrigation Water, Crop Growth Modelling, Decision Support System, Fitness-for-Use, Technical Guidelines, Environmental Risk Assessment.

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LIST OF ABBREVIATIONS

AMD	Acid Mine Drainage
DAP	Days After Planting
DM	Dry Matter (kg m^{-2} or kg ha^{-1})
DOY	Day of Year
DSS	Decision Support System
EC	Electrical Conductivity (mS m^{-1})
EC_e	Saturation paste extract EC (mS m^{-1})
ET	Evapotranspiration (mm day^{-1})
FC	Field Capacity (kPa or mm per m^{-1} of soil depth)
FI	Fractional Interception (photosynthetically active or incoming solar radiation)
GDD	Growing Degree Days (°C day)
GMWL	Global Meteoric Water Line
HDM	Harvestable Dry Mass (kg m^{-2} or kg ha^{-1})
HI	Harvest Index (% or fraction)
ICP-AES	Inductively Coupled Plasma - Atomic Emission Spectroscopy
LAI	Leaf Area Index (m^2 of leaf area per m^2 of soil surface area)
LF	Leaching Fraction
LR	Leaching requirement
MAW	Mine-Affected Water(s)
PAR	Photosynthetically Active Radiation
RH	Relative Humidity (%)
SAWQI	South African Water Quality Guidelines for Irrigation
SWB	Soil Water Balance model
TDM	Total Above-ground Dry Mass (kg m^{-2} or kg ha^{-1})
TDS	Total Dissolved Solids (ppm or mg L^{-1})
VWC	Volumetric Water Content (mm per m^{-1} of soil depth)
WRC	Water Research Commission

LIST OF CHEMICAL SYMBOLS

Al	Aluminium
As	Arsenic
B	Boron
Ca	Calcium
$CaSO_4.2H_2O$	Gypsum
Cd	Cadmium
Cl	Chloride
Cr	Chromium
Cu	Copper
F	Fluoride
Fe	Iron
Hg	Mercury
K	Potassium
Li	Lithium
Mg	Magnesium
Mn	Manganese
N	Nitrogen
Na	Sodium
Ni	Nickel
P	Phosphorus
Pb	Lead
SO_4	Sulphate
V	Vanadium
Zn	Zinc

CHAPTER 1: INTRODUCTION

With the exponential population growth into the new millennium and intensification in resource demand and use, there is an increased realisation that an “out-of-the-box” solution approach towards sustainable development is required (Avellan et al. 2018). The water-energy-food (WEF) nexus exemplifies the integration and interlinkages of multi-resource utilisation and practices, with a focus on the efficiency of the system rather than the productivity of the isolated sectors (Hoff, 2011). Water resources are central to the WEF nexus framework, and with increasing pressure on global freshwater systems, alternative water supplies are sought after (Stoakley, 2013; Donnenfield et al. 2018; Ally and Campbell, 2021). Being a water-scarce country, the topic of water is at the forefront of many decisions made by government and the private sector in South Africa (Webb, 2015).

One such water management problem is the production of large volumes of mine-affected waters (Tanner et al. 1999; Naicker et al. 2003; Adler & Rascher, 2007; DWA, 2010; Ochieng et al. 2010; McCarthy et al. 2011). This is especially prevalent in the coalfields of the Mpumalanga Province, where mining supports nearly 50% of South Africa’s power generation (Tshwete et al. 2006). Degradation of river water quality has been observed in the Mpumalanga Province and is at least partly attributed to mining activities and the release of mine-affected waters into the Crocodile and Olifants River Catchments (Ashton & Dabrowski, 2011; DWA, 2013a; Griffin, 2014; Mudaly and van der Laan, 2020). According to Ashton & Dabrowski (2011), there are over 650 active and abandoned mines in the Olifants River Catchment, and receiving water bodies are experiencing increased salinization, and degrading water quality due to the large salt and metal laden decants (Wamsley & Mazury, 1999; DWAF, 2004; Ochieng et al. 2010).

Mine waters that are of too poor a quality to discharge into the river systems, require costly water treatment (Durand, 2012; DWA, 2013a; Bobbins, 2015; Tong & Elimelech, 2016; Davenport et al. 2018; Grewar, 2019). Current water treatment technologies, such as high-density sludge plants and reverse osmosis, are energy intensive and expensive processes, with high carbon footprints (Ossa-Moreno et al. 2018). Many alternate physical, chemical, and biological mine water treatment options are available, but treatment technologies are resource intensive to develop, produce and use, thereby exacerbating required energy inputs and associated environmental issues (Ighalo et al. 2022).

In South Africa, the agricultural industry requires large water inputs to improve and maximise the yield of crops (Annandale et al. 2021), while the mining industry has large volumes of mine-affected waters available (Annandale et al. 2002; Annandale et al. 2006). Therefore, a noteworthy opportunity arises, providing a consumptive reuse of this water, irrigation with

mine-affected waters can sustainably produce a range of crops and reduce mine water salt loads to catchment water bodies through gypsum precipitation in the root zone (Du Plessis 1983a; Barnard et al. 1998; Tanner et al. 1999; Annandale et al. 2001, Jovanovic et al. 2001; Jovanovic et al. 2002, Annandale et al. 2006, Pulles, 2006; Annandale et al. 2007, Annandale et al. 2009, Idowu et al. 2010; GOWA, 2013; van der Laan et al. 2014; Datta et al. 2017; Madiseng, 2019).

As a result of Mpumalanga's erratic rainfall, this region is highly dependent on irrigation to produce crops economically (Van der Laan et al. 2014; Nieuwoudt et al. 2004). With increasing volumes of mine-affected waters being produced, as end of life of mines start to approach, and the availability of large areas of unfarmed land, an opportunity arises for utilising mine-affected waters for irrigation (Annandale et al. 2006). The application and reuse of mine-affected waters not only allows for an alternative mine water utilisation option, but can also reduce mine water treatment costs, and can contribute to food security amidst a growing demand, as well as assist in the reclamation of valuable agricultural lands and possibly provide much needed, direct or indirect employment opportunities (DAFF, 2015; Webb, 2015; LaRSSA, 2019).

1.1 Aim of study

This study has various general aims. Within each main aim, there are smaller objectives, and are stated within each relevant chapter.

The first was to monitor and quantify the water and salt balances of a commercial scale mine water irrigation field (19 ha unmined land pivot) in the Arnot area of Mpumalanga, South Africa.

The second aim of this study was to model field-scale water and salt balances for a commercial scale mine water irrigation field (19 ha unmined land pivot) in the Arnot area of Mpumalanga, South Africa.

The third and final aim of this study was to propose a technical guideline for the sustainable stewardship of irrigation with mine-affected waters in South Africa.

1.2 Objectives

1. To model and monitor the effect irrigation with untreated, circum-neutral gypsiferous mine water will have on white maize (*Zea mays* L.) crop performance, soil chemical properties and groundwater quality.
2. To establish a technical guideline for irrigating with mine-affected waters; using a risk-based assessment framework for the characterisation of an irrigation landscape capable of sustainably supporting a mine water irrigated cropping system.

1.3 Hypotheses

The main hypotheses that were formulated in this study were as follows:

1. Irrigation with untreated, circum-neutral gypsiferous mine waters will produce a viable crop and reduce mine water salt loading to catchment water bodies through gypsum precipitation in the soil profile.
2. Gypsiferous mine water irrigated crops will have a higher yield than dryland crops.
3. A technical guideline for irrigating with mine-affected waters will provide a standardised framework for evaluating the suitability and capability of irrigation landscapes for supporting a suitable mine water irrigated cropping system.

1.4 Dissertation structure

This dissertation is structured into six chapters. Chapter 1 is an introduction to irrigation with mine-affected waters. It outlines the significance of the research, the problem statement, research questions and objectives.

Chapter 2 identifies relevant and key available literature, specific to irrigation with various mine-affected waters.

Chapter 3 details the quantification and monitoring of the water and salt balances of a small scale mine water irrigation field (19 ha unmined land pivot) in the Arnot area of Mpumalanga, South Africa.

Chapter 4 includes long- and short- term modelling of irrigating with gypsiferous mine water on soil and groundwater resources and various crop production responses.

Chapter 5 describes the proposed standardised framework for the establishment and stewardship of irrigation with certain mine-affected waters in South Africa. Details of a site-specific, risk-based approach to site irrigability, identifying constituents of potential concern and adaptive management strategies to be employed when irrigating with mine-affected waters.

Chapter 6 provides an integrated and concise summary of this dissertation's results of irrigating with mine-affected waters.

CHAPTER 2: LITERATURE REVIEW

This literature review aims to examine currently available mine-affected water irrigation research, relevant both within an international and within a South African context. It further

aims to examine salinity and irrigation modelling, and guidelines used to govern mine-affected water irrigation.

2.1 Introduction

The effects of population growth and the increasing pressure on the natural environment is well documented. Yearly, water scarcity and the demand on freshwater resources is increasing globally, and there is a compounding and cascading effect on water resources as well as the livelihoods of the nation's currently facing these water crises (Filho et al. 2022; Simpson et al. 2021a). By 2030, the global water demand is predicted to be 40% higher than the global supplies of water currently available, and the unsustainable usage of water resources will increase in water stressed nations (Deemer 2022). South Africa has been classified as a water scarce country (DWAF, 2004; Reinders, 2010), and water is at the forefront of decisions made by major governmental bodies and private sector industries of the South African economy (Webb, 2015).

There are various mineral resources mined globally, both historically and currently. Some commonly mined minerals are: coal, metals, oil and gas, gemstones, aggregates, and dimension stone. Just as there are many types of mined natural resources in different geologies, there are many mining types, methods of extraction, and resource management strategies (Mey & van Niekerk, 2009; Johnson & Hallberg, 2005). These listed factors are resource and site-specific, and consequently, on-site water management, both quantity and quality aspects, are affected by the combination of them. With the assortment of mineral resources present, there are also numerous mine water types, levels of mineralisation, and chemistries, which result from the infiltration of ground and surface waters into mining tunnels, voids, and excavations (Simate & Ndlovu, 2014; Durand et al. 2012).

Globally, mining is also known to intensify the problems of water availability and quality (Younger et al. 2005; Pretorius et al. 1999; Pulles et al. 1995). Coal and gold mining specifically, are infamously known to produce acid mine drainage (AMD) and allow untreated AMD, usually with high concentrations of sulphate and potentially toxic levels of trace elements, to enter into and degrade natural environments (Feng et al. 2019; van der Laan et al. 2014; Johnson and Hallberg, 2005). Some risks usually documented with AMD pollution are the health and environmental risks: human ailments; bioaccumulation; water and soil contamination and acidification (Ochieng et al. 2017; Pourrut et al. 2011; Naicker et al. 2003). The origin, formation, development, and movement of mine waters throughout environmental systems has long been researched and is well documented in literature (Verburg et al. 2009; Blowes et al. 2003; Johnson et al. 2002, Schippers et al. 1996; Pitchel & Dick 1991). There are extensive water treatment technologies which exist to rectify the impact mines have on

water resources, but it is noted that these technologies come at a great cost (Acharya & Kharel 2020; Davenport et al, 2018; Tong and Elimelech, 2016; Bobbins et al. 2015).

South Africa has significant reserves of mineral resources and has for long diversified and sustained its economy from the exploitation of these commodities (Davenport 2013). Gold and coal mining are the two largest mining sectors within South Africa and contribute upward of R90 billion to South Africa's Gross Domestic Product (GDP) (Statistics SA, 2022). With over 120 gold mines in the east, west and central Witwatersrand basin, the province of Gauteng and its development is attributed to these mining activities (Mujuru 2014). The largest coalfields are the Witbank and Highveld Coalfields, in the north-eastern part of South Africa, where it is reported that hundreds of active and abandoned mines exist (Hancox and Götz 2014; Frost and Sullivan 2014). South Africa has a complex geology, and both the gold and coal deposits have minor pyrite constituents (±8.5%) in their mineral structure (Buhmann 1991), and during the various stages of mining, large quantities of acidic water are often released (McCarthy 2011). The environmental legacy of these two mining industries are notorious, with numerous incidences of environmental negligence as a result of mine-affected spills having been reported (Coetzee et al. 2003; DWAF, 2004; Sakoane, 2005; CFG et al. 2010; Ashton & Dabrowski 2011). Past and current mining activities, and the associated mine-affected water production, are one of the serious water issues South Africa does and will continue to face (Morgan, 2012; Coetzee, 2006).

One of the objectives set out in the Irrigation Strategy for South Africa, is to increase the contribution of irrigated agriculture to food production (DAFF, 2015). The Irrigation Strategy sets out to support initiatives that revitalise irrigation schemes as well as develop new irrigation schemes, but this is constrained by the availability of scarce water resources. Simpson et al. (2019) has stated that in the Mpumalanga province, due to increased mining activity and expansion, the loss of arable land will have a lasting, long-term effect on food security and food prices in South Africa. With the competition for arable land increasing, and land capability classes decreasing due to mining and erosion, there is a great need for the implementation of alternate water use strategies.

Over exploitation of groundwater (Burger 2008) and increased limitation of surface water abstraction (Van Niekerk et al. 2018), makes investing in the use of potential alternate water resources critical for the expansion of irrigated agriculture in South Africa. The total land area of South Africa is 122.5 million hectares. Of this, the area used for commercial agriculture is 46.4 million hectares, approximately 38% of the total (CCA, 2008), with around 7.6 million hectares of arable land. The estimated actively irrigated area is 1.4 million hectares, comprising 18% of the total arable land, with the rest, 6.2 million hectares being rainfed (Van

der Stoep & Tylcoat, 2014) (Figure 2.1). It is estimated that two thirds of South Africa do not have sufficient rainfall to support dryland agricultural practices (WWFN, 2018). South Africa thus has major scope for irrigated land expansion. Yet, with increasing pressure on South Africa's freshwater, alternatives are sought.

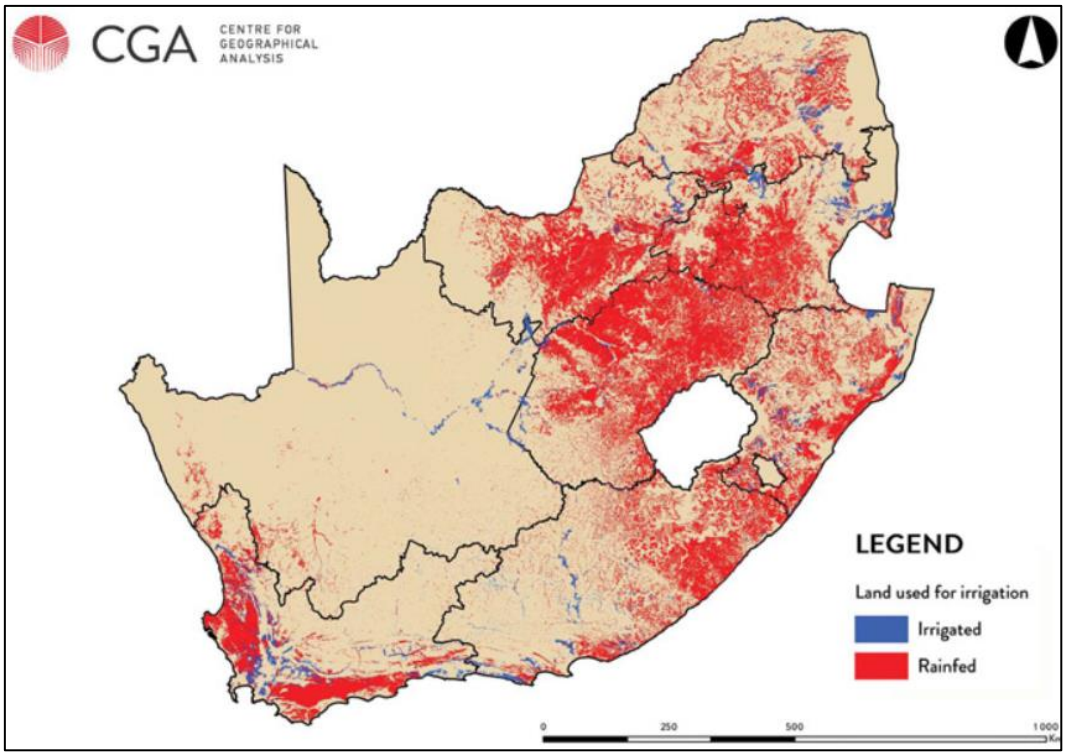


Figure 2.1: Irrigated and rainfed areas in South Africa (Van Niekerk et al. 2018).

The mining industry produces large volumes of affected waters (Table 2.1), and the agricultural industry requires large water inputs to improve and maximise yield of crops, a possible noteworthy synergy (Datta et al. 2017; Annandale et al. 2001; Tanner et al. 1999). Using mine impacted water for irrigation may alleviate water treatment costs post mine closure, and an additional and supplemented water supply may assist in the reclamation of valuable agricultural lands (Surber and Simonton, 2017; Rodda et al. 2011). According to Annandale et al. (2006), irrigation with mine-affected waters offers a plausible solution to the environmental and economic problem mine impacted waters usually pose, as long as it is effectively implemented, monitored, and managed. Irrigation with mine-affected waters can also be included in a mine's closure and rehabilitation plans, and along with the relevant post-mining rehabilitation processes, landscapes and legislation, the consumptive use of water can be added as a sustainable alternative (Kabir et al. 2015).

The 'maize belt' in South Africa consists of three major maize producing areas, the Free State, Mpumalanga, and the North West province (Greyling 2019). In South Africa, 70 percent of all grain production is maize and 60 percent of the total cropping area in South Africa is planted

to maize (Durand 2006; Oduniyi 2013). As seen in Greyling (2019) and SAGIS (2018), in 2015, the Mpumalanga Province had an average of 0.2 million hectares of land planted with maize (white and yellow) and gave an average yield of 5 - 6 tons per hectare. Within the Olifants River Catchment > 50 ML of mine-affected waters are produced daily (Table 2.1). This supplemented water supply could potentially increase the Mpumalanga average maize yield (tons/ha) and national food production and security (Jovanovic et al. 2002; Annandale et al. 2001).

Table 2.1: Estimated mine water discharge into the Olifants River Catchment.

Reference	Estimated mine water discharge, Olifants River Catchment
Van Zyl et al. (2001)	44 ML/day mine water discharge into Upper Olifants Catchment
DWAF (2004)	62 ML/day post-closure decant from defunct coal mines
Maree et al. (2004)	50 ML/day mine water discharge into Upper Olifants Catchment
Grobbelaar et al. (2004)	After closure, generation of up to 360 ML/day untreated water
	A volume of 170 ML/d is suggested for the Olifants Catchment
Golder (2012)	The mining sector in the Highveld area has excess water estimated to range from 60 to 100 ML/d for the period 2007 to 2027
MWCB (2020)	173 ML/day estimated excess water from mining operations

Various researchers and articles have reported estimated mine water discharge values (Table 2.1) that are predicted to have entered and will in future enter the Olifants River Catchment. Within the Mpumalanga Province, there are highly productive soils, and the majority of the grain crop is under dryland production. Mine-affected water for irrigation can stabilise and improve dryland crop production as well as enable dry season crop production (Frost & Sullivan, 2011). An alternative irrigation strategy in this wider Mpumalanga area, is thus theoretically possible (Annandale et al. 2002).

It is noted that large areas of South Africa have both unsuitable mine waters to be used for irrigation as well as acidic soils not ideal for agriculture (Venter et al. 2001; Jovanovic et al. 1998). However, not all mine waters are ‘dangerous’ and unusable, there are some mine waters that are suitable for irrigation and some soils that are able to support such irrigation practices (Banks et al. 1996). With the correct identification of water sources, site selection procedures, and adaptive management approaches, irrigation with mine-affected water is possible. Section 2.2 provides a summary of both local and global research on irrigation with mine-affected waters.

2.2 Irrigation with mine-affected waters

As stated by Ma et al. 2015, there are many relevant studies focused on the harmful effects of mine-affected waters on human health and the ecology, industrial waste and saline water irrigation, the bioavailability of heavy metal elements in mining areas, and mine water suitability for irrigation. Seldom are there studies focused on field trials using mine-affected waters for irrigation and their effects on soil and water properties, crop growth and quality and economic viability and sustainability.

Table 2.2 summarises mine water irrigation field trials conducted between 1983 and 2021, both in South Africa, and internationally. These studies were all either conducted on unmined or rehabilitated land, and all irrigation waters were directly sourced from mining activities, either stated as untreated, partially, or fully treated waters. For each study the crop that was irrigated is stated and the summary findings of each research trial presented. The chapter concludes with a final summary of all general findings of these studies.

Table 2.2: A summary of mine-affected water irrigation research, in South Africa and Internationally.

Reference	Location	Water source	Unmined land	Rehabilitated land	Offsite monitoring	Onsite monitoring	Alternate	Crops	Conclusion
Annandale et al. 2021	Mafube, Middelberg, South Africa	Coal mine water	√	x	√	√Plant, soil & water monitoring	-	White maize	→Irrigated maize safe for food and fodder consumption →No influence of irrigation water on groundwater →Small quantities of gypsum precipitation in soil's top 90cm →Economically viable use of gypsiferous mine water
Kondash et al. 2020	Central Valley, California, USA	Oilfield Produced water (OPW) & blends	√	x	x	√Plant, soil & water sampling	-	Pistacios	→OPW irrigation water not systematically different from low-saline groundwater →Higher B & Na in irrigated OPW soils →228Ra & 226Ra in OPW & groundwater irrigated soils not systematically different → raw brackish OPW had increased soil organic matter accumulation →No metals accumulation - pistachio nuts
Mafuyai et al. 2020	Jos South Plateau State, Nigeria	Tin mine water	√	x	x	√Plant, soil & water monitoring	-	Tomato, Eggplant, Pepper, Cabbage, Carrot, Spinach	→Cadmium transfer factor highest in all vegetable fruits and lead the lowest →No bioaccumulation present in any vegetable crops & all safe for human consumption →Long-term use of tin mine water for irrigation needs to be determined
Nevhulaud-zi et al. 2020	Randfontein South Africa	Gold mine water	√	x	x	√Plant, soil & water sampling	Glass house experiment	Cowpeas	→Cowpea seeds inoculated with *B. subtilis* sequester heavy metals from AMD best; have highest growth nodulation & yield compared to other treatments

Reference	Location	Water source	Unmined land	Rehabilitated land	Offsite monitoring	Onsite monitoring	Alternative	Crops	Conclusion
Oliveira et al. 2019	Serra da Ibiapaba, e Pedra Verde, Brazil	Copper mine water	√	x	x	√Plant, soil & water sampling	-	Bananas	→Banana leaves don't concentrate copper, the fruit and roots Cu concentration are sevenfold higher than established reference values →Soil organic matter increased Cu-inner sphere complexes and Cu retention
Ronquest 2019	Mafube, Middelberg, South Africa	Coal mine water	√	x	x	√Plant, soil & water monitoring	-	White maize	→Irrigated maize more profitable than dryland production → Minimal environmental impacts in short term →Grain safe for human consumption
Li et al. 2018	Qinshui Basin, Shanxi Province, China	Coal bed methane (CBM) water	√	x	x	√Plant, soil & water monitoring	-	Maize	→Soils metal concentration did not significantly increase → Higher pH and SAR values were obtained in the irrigated soils →Maize crop growth not adversely affected →Dry season irrigation using CBM water with an appropriate salt content increases crop yield
Mahato et al. 2017	Damodar Valley, India	Coal mine water	√	x	x	√Plant, soil & water monitoring	Glass house experiment	Maize	→Maize seed germination and seedling can establish in soils irrigated with mine water →Total chlorophyll, a and b, and soil enzyme activity were not affected by mine water irrigation →No adverse effects on plant or soil quality

Reference	Location	Water source	Unmined land	Rehabl and	Offsite monitoring	Onsite monitoring	Alternative	Crops	Conclusion
DPIRD 2017	Woodie Woodie, Western Australia	Manganese mine water	√	x	√	√Plant, soil & water monitoring	-	Screening Trial: Grasses (Rhodes grass, sorghum), Legumes (Lucerne, cowpeas, cavalcade, burgundy bean)	→Germination and establishment generally good →High quality crops with good yields achieved: Sorghum and Oats →Pilot project successfully demonstrated the potential for irrigated pasture and fodder production in the Pilbara area →Stressed importance of reliable water supply →Economics of irrigation for further expansion need to be further investigated due to remoteness of sites
Huang et al. 2016	Yunfu, China	Pyrite mine water	√	x	x	√Plant, soil & water monitoring	-	Rice	→Paddy soils had highly elevated Thallium (Tl) concentrations →Tl increased with soil depth and subsequently rice root mass decreased with soil depth →No Tl guideline value established for agricultural soils in China →Tl bioaccumulation in roots, not translocation to leaves, stem or rice
Daniel et al. 2014	Barkin Ladi, Plateau state, Nigeria	Tin mine water	√	x	x	√Plant, soil & water monitoring	-	Cabbage	→Cabbage leaves accumulated Cr, Ni, Pb posing a potential health risk - Cd not detected →No abnormal amounts of any heavy metals detected in soil

Reference	Location	Water source	Unmined land	Rehab land	Offsite monitoring	Onsite monitoring	Alternative	Crops	Conclusion
Sun et al. 2014	Xingdong Mine area, China	Coal mine water	√	X	X	√Plant, soil & water monitoring	-	Yellow maize & wheat	→pH and soil heavy metal contents were not of toxic levels in the soil or water →High water-soluble and total fluorine levels caused a 50 – 100% loss of crop production
Field & Harold 2013	Tom Price, Pilbara, Australia	Iron ore mine water	√	X	√	√Plant, soil & water monitoring	-	Feed – Rhodes Grass	→The 850 ha (17 irrigation pivots) produces up to 30 000 tons/ yr for cattle fodder (safe for consumption) → Use of mines surplus water for irrigation increased regional development, economic diversification, and reduced grazing pressure on sensitive rangelands areas
Mulder 2013	Arizona, USA	Treated copper mine water	√	X	X	√Plant & soil monitoring	-	Alfalfa	→ $CaSO_4$ rich treated mine water had no bearing on quality (crude protein, neutral & acid detergent fibre content) of forage & suitable supplemental irrigation source
Dutta et al. 2012	Barapukuria Bangladesh	Coal mine water	√	X	X	√Plant, soil & water monitoring	-	Rice	→No deleterious effects found on soil chemistry and rice plant tissues
Abubaker et al. 2011	Al-Quwayrah, Jordan	Phosphate mine water	√	X	X	√Plant, soil & water monitoring	-	Potatoes	→Higher salinity mine water produced lower potato yields by ±2-4 tons/ha → Low metal concentrations found in tubers →Slight increase in soil salinity after irrigation

Reference	Location	Water source		Unmined land	Rehab land	Offsite monitoring	Onsite monitoring	Alternative	Crops	Conclusion
Rimawi et al. 2009	Al-Abyad area, Jordan	Phosphate mine wastewater		√	x	x	√Plant, soil & water	-	Maize & Black medic	→ Mine wastewater irrigation increased soil salinity & decreased crop yield →Crops safe for fodder consumption
Vermeulen & Usher, 2008	Witbank South Africa	Aim: Investigate parameters affecting irrigation plume for mine-affected water on local and regional groundwater (field & laboratory experiments).								→Deeper aquifers indicate no significant water quality deterioration →Constituents in irrigation water show slow movement within soil profile - attenuated by different mechanisms between surface & aquifers (clay layers) →Soil type & morphology important for vertical movement of constituents →Short to medium term - mine water irrigation shows no significant threats to regional groundwater quality
		Coal mine water	Kleinkopje 1, Witbank	√	x	√	√Soil & ground-water monitoring	-	-	→Groundwater quality not deteriorated over time (salts attenuated in soil)
			Kleinkopje 4, Witbank	√	x	√				→ exceptionally high rainfall possible cause of profile leaching (further monitoring required to assess trend) → build-up of salts in soils above & within clayey layers
			Syferfontein Colliery	√	x	√				→irrigation shown a minimal impact on the groundwater (very slow movement of the constituents) → shallow zones prevent salt migration & salt strongly in upper profile -due to clay & soil type onsite

Reference	Location	Water source		Unmined land	Rehab land	Offsite monitoring	Onsite monitoring			Alternative
Vermeulen & Usher, 2008 (continued)	Witbank South Africa	Coal mine water	Optimum Colliery	x	√	√	√Soil & ground-water monitoring	-	-	→SWB simulations →Water containing enough buffering potential be used for irrigation on spoils
			New Vaal Colliery, Vereeniging	√	x	√		-	-	→ no significant deterioration within underlying aquifer due to irrigation (possible dilution due to high lateral flow & high natural recharge of sandy layers) → Thick, shallow clay layer impedes downward migration of water & salts
Beletse 2008	Waterberg Lephalale, South Africa	Coal bed methane (CBM) water		√	x	x	√Plant, soil & water monitoring	-	Italian ryegrass, stooling rye cotton, Bermuda grass	→ Barley, Italian ryegrass & Bermuda grass had no leaf burn & toxicity problems, cotton foliage was scorched → SWB gave a good estimation of suitability of NaHCO3 rich irrigation water → Feasible to grow crops with this water if high leaching fraction applied, gypsum application required (Ca can displace adsorbed Na)
Idowu et al. 2008	Syferfontein Secunda, South Africa	Coal mine water		√	x	√	√Plant, soil & water monitoring	Hydrological modelling	Maize	→Salt movement and amounts are controlled by whether or not land is unmined or rehabilitated → A thicker, low-resistivity, near-surface layer near the exit of each pivot indicated an increased salt content of subsurface in the direction of surface water flow →Modelling indicated barley, cotton, sugar beet, sorghum, and wheat, have 100% yield potential with irrigation waters
	Kleinkopje, Witbank, South Africa	Coal mine water		x	√	x			Pasture	

Reference	Location	Water source	Unmined land	Rehabilitated land	Offsite monitoring	Onsite monitoring	Alternative	Crops	Conclusion
Annandale et al. 2007	Kleinkopje, Witbank, South Africa (2005/ 2006)	Coal mine water	√	√	X	√Plant, soil & water monitoring	-	Maize, wheat, sugar beans, potatoes	→Irrigated maize yield lower than dryland yield – due to rapid EC increase due to drainage limitations →Wheat had no yield reduction effects
	New Vaal, Vereeniging South Africa	Coal mine water	X	√	√	√Plant, soil & water monitoring	-	Wheat, maize, peas, sweetcorn soybean, pumpkin	→Natural soil clay lenses and close proximity dam caused large amounts of water logging and subsequent crop losses →Poor yields obtained for Maize, wheat, soybean, and vegetable crops due to poor irrigation
	Syferfontein Secunda, South Africa	Coal mine water	√	X	√	√Plant, soil & water monitoring	-	Perennial, temperate, subtropical pasture	→Very heavy clay soils- naturally limits drainage- non-ideal site for irrigation →Annual and perennial pasture crops had adequate yields
									→Poor irrigation site selection was identified as the main factor for yield reduction for all sites stated in this study
Lin et al. 2005	Guangdong Dabaoshan Mine, China	Poly-metallic (Mo-W, Cu-Pb-Zn, Fe) mine water	√	X	X	√Plant, soil & water monitoring	-	Rice	→Heavy metal soil fractionation pattern: Zn + Cu bound to organic matter, Pb bound to oxides →Cadmium exceeded limits in edible portions of crop – exceeds Chinese national standards →High transfer rate of Cd from soil to crops

Reference	Location	Water source	Unmined land	Rehabilitated land	Offsite monitoring	Onsite monitoring	Alternative	Crops	Conclusion
Mercuri et al. 2005	Upper Hunter Valley, Australia	Coal mine water	x	√	x	√Crop growth response	-	Spotted Gum tree, Bangalah, Swamp yate, Red gum Eucalyptus trees	→Tree survival after 24 months improved with irrigation (89.8%) compared to the rain-fed treatment (78.6%) → Saline mine water irrigation can establish plantations without impacting deleteriously on tree growth and substrate EC
Beletse 2004	Syferfontein South Africa	Na_2SO_4 rich mine effluent	√	x	x	√Plant, soil & water monitoring	-	Fescue, Lucerne	→ Negligible influence on foliage quality & yield → Require a well-drained profile & large leaching fraction to prevent unsustainable build-up of salt in soil →Certain tropical pasture species are not tolerant to high sodium amounts & not suitable

Reference	Location	Water source		Unmined land	Rehabilitated land	Offsite monitoring	Onsite monitoring	Alternative	Crops	Conclusion
Annandale et al. 2001; Jovanovic et al. 2002	Witbank, South Africa	Coal mine water	Pivot Major (1997–2000)	√	x	√	√Crop growth response	-	Sugar-beans, maize, wheat	→ Good yields- maize & wheat →Groundwater chemistry indicates irrigation salts applied trapped in soil →Longer irrigation period required to determine long term aquifer impacts if any
			Pivot Tweefontein (1997–2000)	x	√	x	√Crop growth response			→Naturally acidic soils can be reclaimed through irrigation of water rich in Ca →Low yields of sugar beans, but higher than dryland yields →Good yields- maize & wheat
			Pivot Jacuzzi (1997-1999)	x	√	x	√Crop growth response			→ Good yields- maize & wheat →Proper preparation of rehabilitated land critical → Waterlogging, soil profile drainage plays great role in yield reductions & soil salinization
			Pivot Fourth (1999-2000)	√	x	√	√Crop growth response			→ Good yields- maize & wheat →Soil chemical analyses indicated soil salinity increased over trial duration → Exchangeable Ca^{2+} and Mg^{2+} increased with time, K^{+} decreased at all four sites

Reference	Location	Water source	Unmined land	Rehabilitated land	Offsite monitoring	Onsite monitoring	Alternative	Crops	Conclusion
Jovanovic et al. 2001	Selebi Phikwe, Botswana	Nickel mine water	√	x	x	x	Agro-hydrological model (SWB & CLIMGEN)	Lucerne, maize-oats rotation, soybean-wheat rotation, sorghum-swiss chard rotation	Depending on cropping system: →Lucerne most suitable (limited leaching and maximum precipitation) → Between 18 and 32% of total salts added are predicted to leach out of the soil profile after 11 years of irrigation.
Annandale et al. 1999b	Kleinkopje, Witbank, South Africa	Coal mine water	√	x	x	x	Agro-hydrological model (SWB & CLIMGEN)	Wheat, soybeans, maize, ryegrass, oats, babala, lucerne, fescue, beans	→Soil acts as an effective salt sink →Over 30 years, salt precipitation was modelled between 252 – 500 tons/ha (depending on crop rotation) →Depending on irrigation strategy, between 418 - 636 tons/ha of leached salt →Year-round, high frequency irrigation, with winter leaching fraction, is effective utilization of large gypsiferous water volumes

Reference	Location	Water source	Unmined land	Rehabilitated land	Offsite monitoring	Onsite monitoring	Alternative	Crops	Conclusion
Barnard et al. 1998	Kromdraai Colliery, Witbank, South Africa	Coal mine water	x	x	x	√Plant, soil & water monitoring	Glass house pot trials	Screening: Maize, Soybean, Sorghum, Pearl millet; Cowpea; Rye; Oats; Triticale; Wheat; Rye Grass; Lucerne, Fescue, Crown vetch, Cocksfoot, Milkvetch, Weeping lovegrass, Smuts finger, Kikuyu, Panicum, Rhodes	→Foliar damage noted on some crops due to high Na & Cl contents →Soil solutions of high sulphate contents provoked nutritional imbalances → Soil salinity increased compared to non-irrigated soil →Excellent yields: subtropical pastures →Moderate yields: Soybean, pearl millet, cowpeas, winter cereals →Temperate pastures: Lucerne &Fescue yielded better than cocksfoot → Deep cultivation with deep placement of lime and phosphorus is essential for irrigation on sandy acid soils → High frequency irrigation and application of fertilisers several times during the growing season in small amounts are recommended
Du Plessis 1983a	South Africa	Lime treated acid mine waters	√	x	x	x	Steady state chemical equil. model	Maize, Lucerne, Beans	→Gypsum precipitation has a moderating effect on the average profile conductivity (chloride waters 1.4 times that of sulphate waters) → Relatively high yields achievable for widely grown crops (maize & lucerne) under low leaching fractions with sulphate water

Reference	Location	Water source	Unmined land	Rehabilitated land	Offsite monitoring	Onsite monitoring	Alternative	Crops	Conclusion
Cronce et al. 1980	United States of America	Acid mine waters	√	x	x	x	-	Fescue, Ryegrass	→Both limed and unlimed soils neutralised the applied flood irrigated acid waters (525cm) →With time lower pH's and higher levels of acidity were observed with depth on the unlimed soils →The growth of ryegrass and tall fescue was not adversely affected by acid water irrigation →Tall fescue yielded significantly more with increased levels of acid water irrigation

The conclusions drawn from all the pilot trials is that in the short term (< 5 years of irrigation), irrigation with mine-affected waters shows promise as an alternative use of mine water, in that smaller volumes of mine water would need to be treated and reduced salt loads would be discharged into river systems. Many of the studies conducted in South Africa have concluded that mine-affected waters can be used as an additional and alternative water resource for agriculture in mining areas, especially during periods of prolonged drought.

In general, little to no adverse effects were observed on the yield and performance of the trialled crops, with the mine water irrigated crops outperforming dryland crop production. It was noted that the success of the trial is determined by site selection. On waterlogged and on rehabilitated sites, crop yield was significantly decreased due to increased soil salinity and reducing soil root conditions.

Of the trials that monitored on- and off-site groundwater conditions, no measurable change in groundwater quality was present. The unaccounted-for salts are seemingly located in the deeper saprolite and did not enter the deeper aquifers and affect groundwater quality.

Constituent partitioning into the edible portions of the selected irrigated crops were below the selected countries' thresholds and standards and were deemed safe for consumption. Grain crops were in general the crops of choice for the trials, with very little research done on the irrigation of horticultural, plantation and cash crops with mine-affected waters. The perceived risk of the irrigation water source and associated crop effects is thought to prevent research into crops with greater establishment costs and greater economic losses if any damage in the trial occurs. Another possible perceived risk is the higher constituent partitioning into the fruits of fleshy crops in comparison to grain. If any harmful constituents are present in the irrigation water, there is supposedly a greater risk that fleshy fruits will have a greater uptake compared with of grain, resulting in a loss of fruit quality.

The research that used Na-Cl rich water had increased levels of crop scorching and higher levels of salinity in the irrigated soil profile. Conclusions of these trials were that salt-tolerant crops are preferably used with these types of waters, and particular attention should be given to land preparations to ensure free draining soil profiles exist and no waterlogging occurs. The gypsiferous mine water studies had no adverse effects on crop establishment, growth, yield, or qualities. No measurable amounts of gypsum precipitated out in any of the trial's soils. All studies concluded that with longer term irrigation, an improved and more accurate conclusion of long-term impacts of mine water irrigation can be determined.

The trials were conducted over a wide variety of water qualities, climates, soils, and cropping systems. Successful irrigation with mine-affected waters was determined possible, with the underlying conclusion being greater insight is required when considering regulating this type of water use. From the literature review, it appears that irrigation with mine-affected waters have been successfully tested on both a small, large, and commercial scale projects. An empirical foundation of both global and local data is present, and regulatory frameworks can under the correct decision support, be established from these results.

2.3 Irrigation and Salinity Modelling

Salts occur naturally in soils and waters and are usually as a result of the chemical and physical weathering of parent material. A soil's temporal and spatial salt variation are usually an expression of the hydrological landscape, and environmental drivers resulting in the unique salt concentration patterns (Dagar et al. 2019). Anthropogenic activities, such as the intensive use of fertilisers, irrigation with salt-rich water, land use changes, and the improper management of these activities, results in increased salt loads to water bodies and soils (Singh et al. 2018).

Salinity is a term to describe the amalgamated measure of the concentration of major ions, namely Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, SO_4^{2-} , CO_3^{2-} and HCO_3^- (van Dam et al. 2014). Soil salinity is the total salt concentration in the soil solution, comprising of soluble and readily dissolvable salts (Corwin 2003). According to Hoffman (2004), salt affected soils are soils that generally have a high salt content and a low crop yield. Hoffman (2004) stated that if there is too little soil leaching then the amount of salt removal is also low, and salts start to accumulate within the soil profile.

The accumulation of soil salinity, and increased salinization occurs as a consequence of a variety of processes, namely, insufficient rainfall for adequate salt leaching, high evaporative conditions, poor internal soil profile drainage, the presence of shallow water tables, and possible waterlogging conditions (Corwin & Scudiero 2019). An in-depth assessment of salt accumulation in soil can be found in Corwin et al. (2012).

The management of salinity throughout global agriculture, has been critical to minimising crop yield losses, ensuring that soil fertility, soil structure and crop nutrition is maintained, and in sustaining the integrity of the agricultural environment in the long term (Heuperman et al. 2002). Increased salinization and degradation of once fertile soils has been reported to affect more than five hundred million hectares throughout the world, as a result of mismanaged irrigated soils, especially in arid and semi-arid areas (Wicke et al. 2011; FAO, 2021).

The modelling of soil salinity and salt balances has long been researched, and has guided and aided global soil salinity management, ensuring agricultural environments are preserved and restored (FAO, 2021). Crop models are one of the mechanistic models and tools used for determining theoretical salt balances, salt movement and interactions within the soil-water-atmosphere-plant system, and predicting effects of salinity on crop yield, and soil and water properties within an irrigated environment (Hassanli et al. 2016).

As summarised by Yu et al. (2021), the following are some commonly used crop models for simulating the response of crops to salinity: SWAGMAN (Robbins et al. 1995); SWB-Sci (Annandale et al. 1996); SWAMP (Bennie et al. 1998); WAVES (Zhang et al. 1999a); Hydrus (Ramos et al. 2011); AquaCrop (Tan et al. 2018); APSIM (Radanielson et al. 2018) and SALTMED (Chauhdary et al. 2020). As stated by Ragab et al. (2015), each model simulates the effect of salinity and the subsequent crop responses. The assumptions, processes, and structures of each model may differ, and the limitations of simulation results should always be noted when interpreting the results (Addiscott & Wagenet, 1985).

The chosen crop model for this study, SWB-Sci (Benadé et al. 1995; Annandale et al. 1996), was specifically developed with mine-affected water irrigation in mind. Using various mine water qualities, water management regimes and cropping systems, projections of the potential temporal salt movement as well as gypsum precipitation in the soil profile can be made. Long term simulations of salt balances and crop performance can be modelled, and the effects of changes in irrigation water quality on crop yield predicted. Monitoring soil, crop, and water parameters on-site, enables the parameterisation of the SWB model, allowing for increased accuracy in long-term simulations of crop growth (biomass accumulation, grain yield response), water use (irrigation scheduling) and soil water balances (Pereira et al. 2015).

2.4 Irrigation Guidelines

Many countries have policies and legislative level strategies for the use of wastewater and excreta in agriculture, these are mostly adopted the WHO (2006) wastewater for agriculture guidelines, and these are mainly the basis on which most of the technical standards are set globally. The five-volume guideline of wastewater sludge usage in South Africa, provides both a technical and legislative framework for water users wanting to beneficially use sludge as an alternative water source (Herselman & Snyman, 2009). This guideline was updated and aligned with internationally acceptable practices and with local studies and guidelines. The same approach adopted for the sewerage sludge guidelines can be followed in developing a comprehensive technical guideline for irrigation of mine-affected water, and should summarise key studies and national and international guidelines, in order to create one coherent source of technical information for irrigating with mine-affected waters.

Volume number four of the eight-part South African Water Quality Guidelines is the primary source of information for irrigation water uses (DWAF, 1996). DWAF's mandate states specifically that water uses, and their water quality requirements, are determined on the basis of maintaining the protection of aquatic ecosystems and water use on a sustained basis. According to DWAF (2006), the irrigation guideline used the following international publications as basis for its development: ASCE Publication on Agricultural Salinity Assessment and Management (Tanjii,1990); Australian Water Quality Guidelines for Irrigation Water Supplies (Hart, 1974; Hart et al, 1992); Canadian Irrigation Water Guidelines (Canadian Guidelines, 1987); FAO's Guide for Evaluating the Suitability of Water for Irrigation (Ayers and Westcott, 1985); USA Quality Criteria for Irrigation Water (US EPA, 1973), and the USDA Handbook on Diagnosis and Improvement of Saline and Alkali Soils (US Salinity Laboratory Staff, 1954). Although the final guidelines are very general in terms of fitness-for-use of waters for irrigation, it is stated that there are site- and case- specific scenarios where the thresholds can be adjusted to suit the receiving environment's capacity to receive constituents from irrigation waters. This DWAF (1996) guideline forms the basis of most regulatory decisions made for irrigation in South Africa.

After a review of several years of mine-affected water studies within South Africa, as well as their own field and laboratory trials, Vermeulen et al. (2008) proposed an operations and monitoring guideline for groundwater, for water users irrigating with mine-affected waters. Their findings were that appropriate groundwater monitoring be implemented, and that boreholes be sited and developed correctly to best monitor different flow zones and aquifers, beneath and around these irrigation sites. The findings suggested that short- and medium-term impacts of irrigation with mine-affected water on regional groundwater quality were negligible, and that the long-term sustainability of such practices should be further investigated. Irrigation of mined land or spoils was also investigated, and optimal irrigation should be on small spoil areas that should not consist of acid generating materials. Although this guideline did not fully address the cropping aspect of this water use, it provided a good basis for which groundwater monitoring specifically can be incorporated into a bigger technical management guideline for mine-affected water irrigation.

The software-based decision support system (DSS) developed by du Plessis et al. (2017), is a revised tool using the 1996 South African Water Quality Guidelines as its basis. The DSS is a risk-based, site-specific modelling system, which evaluates the fitness-for-use of a given water quality. The three-tiered approach used in this tool amalgamates current crop-soil-climate models and guidelines to categorise water qualities into four colour coded categories, each with its own implied risk. Tier 1 is a generic assessment of the irrigation water quality, with potential constituents highlighted, as stated in the DWS (1996) guidelines. A Tier 2

assessment is an in-depth evaluation of the irrigation water quality using site-specific factors such as climatic conditions, irrigation management, soil type, and cropping selections. This user-defined tier permits a detailed overview of the fitness-for-use of the water quality on crop performance, soil chemical and physical quality, and irrigation equipment. Tier 2 of this DSS is a simplified version of the Soil Water Balance (SWB) crop growth model, which uses the crop evapotranspiration estimations from the FAO56 Penman Monteith crop water requirements approach (Allen, 1996). For each parameter, either a time value (in years) or a percentage is calculated, providing the fraction of time a certain constituent would fall into each specific fitness-for-use category. Tier 3 is not stipulated in the DSS and is used on an ad-hoc basis. The use of the DSS model is ideal when looking at the suitability of a mine water for irrigation, and its potential interactions within the soil-water-plant continuum.

Pocock & Coetzee (2021) published a WRC report reviewing the regulatory policies and frameworks in place that currently allow for the licencing of mine-affected water irrigation in South Africa. Their study concluded that the current legislative framework in South Africa allows for the beneficial use of mine water for irrigation under the right conditions. If there is a surplus of water, after all other re—use possibilities have been considered, this irrigation practice is both allowable and licensable (WUL Authorization). The study concluded that the locally developed DSS is ideal for thorough fitness-for-use and water quality indicator assessments. In accordance with site-specificities, specialist studies may be required by the various licensing departments to support license applications.

Table 2.3 summarises some international and local guidelines and legislation currently available (reference and legislative documents), for irrigation with different water sources. This is by no means a complete list of all available documents, but a brief summary showing some sources and guidelines available when looking to irrigate with different water sources. The summary table highlights some currently available guidance documents for alternative irrigation water sources. No single, comprehensive document is available providing guidance for irrigating with mine-affected water. This contrasts with the guideline for irrigation with greywater, wastewaters, and sludges, which also includes site -specific criteria for crops, soils, and water.

Table 2.3: Summary of some legistlative, international and local, South African, guidelines pertinent for irrigation with various water sources.

Reference	Water source	Aim	Site selection criteria	Monitoring requirements	Thresholds for constituents	Risk management procedures	Conclusion
FAO, 1992	Treated Wastewater	Encourage collection, treatment & use of wastewater in agriculture in a safe manner, maximum advantage taken of resource	√	√	√	√	→Technical criteria for field management practices with wastewater irrigation →Threshold constituent levels present, method of analysis stated →no on-site monitoring advised →Risk for pathogenic agents & Microbiology quality stated
DWAF, 1996	Water for irrigation purposes (Source unspecified)	Primary source of info in SA, for determining water quality requirements for water uses and protection & maintenance of the health of aquatic ecosystems	x	x	√ Generic guideline values of constituents provided	√	→Water quality guidelines for irrigation →irrigation water sources are varied (treated or not) →ideal water quality for water uses and fitness-for-use of water (Crop yield & quality, soil suitability, irrigation equipment) →Thresholds limit of each constituent present →Assumption that suitable soils will be irrigated
NWA, 1998	Part 5: Controlled activities: Disposal of waste or water containing waste	National Act for water resources. Sustainability and equity in the protection, use, development, conservation, management & control of water resources. Fundamental reform of the SA law relating to water resources	x	x	x	√ Quantify current & long-term risks pertaining to water management	→Rights and responsibilities of water management institutions and responsible authorities and water users →Definition of and listed water uses; pollution prevention, →Over arching governance of water resources and uses in SA → Authorisation of water use based on risk of impact on water resources

Reference	Water source	Aim	Site selection criteria	Monitoring requirements	Thresholds for constituents	Risk management procedures	Conclusion
FAO, 2003	Untreated or partially treated wastewater	A guide for use of treated effluent for irrigation and aquaculture	√	√	√	√	→ uses WHO Guidelines for health protection measures →Outlines selection of sites and cropping systems, irrigation techniques and resource planning →Global case studies under different conditions
DWAF, 2006	Water Reuse (unspecified)	Process or approach to be followed to establish Water Reuse & Reclamation Plan (H2+3)	x	√	x	√	→ Water from operating mines for irrigation need to be undertaken within framework of water conservation or water demand management requirements → Detailed data on water management activities on mines and water and salt balance data
WHO, 2006	Wastewater, Greywater & Excreta	Minimisation of human health risks when using greywater for irrigation	x	√	√	√	→ To guide rational use of wastewater & excreta in agriculture & aquaculture →Comprehensive and adaptable to local conditions globally
Snyman & Herselman, 2006	Wastewater Sludge	Appropriate use of sludge in agricultural practice	√	√	√	√	→ user-friendly document for regulatory authorities for beneficial sludge management and use →In detailed monitoring plan and threshold levels proposed → Upper limit of application is 10 tons/ha/yr

Reference	Water source	Aim	Site selection criteria	Monitoring requirements	Thresholds for action	Risk management procedures	Conclusion
Vermeulen et al. 2008	Mine water	Define conditions for mine-water irrigation & operational and monitoring guidelines for groundwater	√	√ Groundwater and soil only	x	√	→ Provide a screening tool for site selection, operation, and management →Soil suitability rating feasible and suitable for irrigation for undisturbed and spoil soils →Monitoring guidelines same as monitoring networks from DWAF Minimum Requirements for Monitoring at Waste Disposal facilities (2005) →user-friendly screening tool, called GIMI (Groundwater Impacts from Minewater Irrigation) developed →No crop or irrigation scheduling information provided
Rodda et al. 2010a	Greywater	Water-quality guidance for use of greywater for small-scale irrigation in South Africa	x	√	√	√	→Elements necessary to facilitate greywater irrigation use in South Africa →Conceptual framework for managing risks for greywater safe usage (probability of a defined adverse effect occurring in an exposed population) →Water quality criteria matched against risk categories
Du Plessis et al. 2017	Irrigation waters (Source unspecified)	Risk-based, site-specific water quality guidelines for irrigation	√	√ Identifies constituents of concern possibly requiring monitoring	x	√	→ Assessing the fitness of water for irrigation use →Setting water quality requirements for irrigation users →No on-site monitoring requirements are stated only constituents of potential concern

With the presence of these various irrigation guidelines, the established frameworks allow for water users to investigate, plan and implement scientifically proven methods to ensure irrigation practices are sustainable. Standard practices per sector or per water type for irrigation allows for more extensive contingency planning and more easily imposed ramification measures when irrigation practices negatively affect environmental integrity and are not deemed sustainable.

Each sector, industrial, domestic, agriculture and mining, produces unique water qualities and types. For example, a large portion of mining affected waters are rich in iron sulphate compounds, while agricultural waters may be rich in nitrogen. With each water type being sector specific, there are unique management requirements, and dedicated guidelines per sector are necessary if sustainable irrigation practices are to be implemented with these unique water sources.

As seen in many countries, the absence of a technical standard for mine-affected water irrigation is a shared, recurring, and global challenge (Zhang et al. 2021; Heuer et al. 2021; Hanjra et al. 2012). As a consequence, water users are less likely to invest into an irrigation project of this nature as there is no clarity on procedure, and the risks are therefore deemed higher. As part of the objectives of this study, a technical guideline will be proposed for irrigation with mine-affected waters in South Africa. The absence of formalised guidelines in South Africa and globally, and with the knowledge gained from the last 30 years' of published trial results, a framework for decision making and stewardship can be developed for irrigation with mine-affected waters.

2.5 Conclusion

Mining is pertinent to South Africa's economy, both as a revenue source and for crucial electricity generation. A middle ground between mining-induced degradation, resource sustainability and environmental safe-guarding needs to constantly be balanced. As increasing pressures on the environment become more prevalent, and water resource management becomes increasingly challenging, certain water users, i.e. domestic water use, will have to be given preference to safe and better-quality waters, and alternatIVE water sources for irrigation, mining and industrial uses, will be sought.

Mine-affected waters are water sources that can relieve the water shortages the agricultural sector may experience to some extent, as well as costly water treatment pressures and responsibilities mines currently face. Along with easing water supply and quality stresses, if governed correctly, irrigation with mine-affected waters can be implemented from a local (site-specific) to a regional (catchment or provincial) scale, and a substantial increase in sustainable crop production can be achieved.

As with all the stated studies in this literature review, mine-affected water irrigation is possible if well manage, and can generate produce that is safe for consumption. An important and valid theme throughout the studies was the selection of irrigation waters, the correct management of irrigation sites, and the appropriate monitoring strategy that should be implemented in order to sustainably irrigate with mine-affected waters.

Various comprehensive studies on mine-affected water irrigation in South Africa, as well as various tools such as the South African Water Quality for Irrigation (SAWQI) DSS exist (du Plessis et al. 2017) for guiding sustainable irrigation practices. Various guidelines for other water sources and types exist for irrigation or agricultural use, yet, no one guideline or procedural document specific for mine-affected waters exist. The proposed technical guideline for mine-affected water irrigation in this dissertation, has the main purpose of amalgamating relevant sources, and advancing standard practices required to use mine-affected waters economically and sustainably for irrigation.

CHAPTER 3: DEMONSTRATING THE SUSTAINABLE USE OF UNTREATED, CIRCUM-NEUTRAL MINE WATER FOR IRRIGATION: UNMINED LAND

The literature, reviewed in Chapter 2, demonstrates the extensive research into and success in practice, of mine water irrigation in both southern Africa and internationally. This chapter will add an additional irrigation site and accompanying monitoring details and data to the body of knowledge of research conducted on mine-affected water irrigation over the last 30 years.

3.1 Introduction

Du Plessis (1983a) first illustrated that crops can successfully be irrigated with gypsiferous mine waters, and that there are substantial quantities of calcium sulphate that precipitate out in soils, primarily as gypsum. It has also been shown that crop performance is not hindered by the presence of this precipitate in the soil. The past three decades of research on South African coal mines have shown that there is potential to produce crops by irrigating with gypsiferous mine waters, both economically and sustainably (Jovanovic et al., 1998; Annandale et al., 2001; Annandale et al., 2006). Due to the large scale at which irrigation with mine-impacted waters could be practised in Mpumalanga, there is a need for more detailed information regarding the fate of solutes and the impact on the larger environment due to such irrigation (Annandale et al. 2007; Vermeulen et al. 2008, van der Laan et al. 2014).

The aims of this study were to monitor field-scale water and salt balances for a commercial field-scale mine water irrigation scheme in Mpumalanga. The trial looked to successfully produce crops irrigated with an untreated circum-neutral, gypsiferous mine water, that are both economically viable and safe for consumption as food or fodder. This will assist in predicting the long-term impact and sustainability of gypsiferous mine water irrigation on the soil and groundwater environment.

The research can serve as a reference for potential mine water irrigators, and those needing to authorise such irrigation practices.

3.2 Methodology

3.2.1 Trial Overview

Site description

The unmined site, where the irrigation trial took place, is situated 30 kilometres east of Middelburg, Mpumalanga, South Africa, in the Arnot area (Figure 3.1). The experimental site is located at a latitude of 25°48'25" S and a longitude of 29°45'48" E and is 1 670 m above sea level, within the quaternary catchment B12C, and lies within the north-eastern portion of the South African inland plateau. The surrounding land uses are mainly agricultural and mining, with small pockets of residential areas present.

The Arnot area of Mpumalanga receives on average 660 mm of rainfall annually, has a mean annual evaporation of 1630 mm, with typical temperature ranges from a minimum of 8^{o}C to a maximum of 33^{o}C and average wind speeds are generally around 1.6 m/s (Schulze, 1997a).

The trial site consists of 30 ha of unmined land area, of which 19 ha was planted to white maize under irrigation and 11 ha was dryland maize. The cropping system was a long season white maize variety monocrop, which was selected to suit the collaborating, leading commercial farmer's needs and business plan.

Since 1985, this trial site has been used for dryland agriculture by the Kane-Berman farmers, and prior to this, the area was classed as natural grasslands. The neighbouring Mafube mine began in 2004 and borders the trial site on the western side. Although this trial site has been cultivated for the last 35 years without supplemented water sources, the mine provided the infrastructure and water supply for the irrigation trials. This study focuses on the monitoring of the trial site for the irrigation period between November 2016 to March 2020.

The coal mined in this area is from the Nooitgedacht coal reserves, within the Witbank coalfields. Mining has subsequently stopped at the Mafube mine, and efforts are now in place to rehabilitate the disturbed area. The mine's void water was used as the irrigation water for this trial. The water supply infrastructure and pumping costs were covered by the Mafube colliery.

The geology of this site is comprised of shallow primary aquifers, namely alluvium and weathered Karoo Supergroup rocks. The primary aquifer is underlain by the Vryheid formation of the Ecca Group, a part of the Karoo Supergroup. This secondary aquifer encompasses a suite of weathered and metamorphosed shales, mudstones and sandstones, forming an aquitard and aquiclude (Brink, 1983). This sequence overlies the rhyolite and intrusive dolerite dykes and sills of the Upper Transvaal Supergroup, which acts as an aquiclude. The hydraulic conductivity and porosity will be highest within the upper primary aquifer, and this is where the

majority of the lateral flow, and dilution and dispersion transport would occur. The lower secondary aquifers will have very low hydraulic conductivities and porosities and will not readily facilitate large volumes of water movement.

The study area and surrounds are made up of the Glencoe and Hutton soil forms, with isolated areas of waterlogged soils of the Longlands soil form. The soil profile is generally quite deep (±5 – 7m), as identified by the borehole logs provided by the neighbouring mine. The Glencoe and Hutton soil forms in this area, generally have a high clay percentage (15 - 25% kaolinitic clay) and high cation exchange capacity (~15 cmol(+)/kg), making them ideal for crop production by having a good water holding capacity and nutrient reserve storage and release ability.

Deep Glencoe soils can be found in the northern section of the irrigated field, and lateral subsurface flow, and possible perched water tables are expected to occur as water reaches the deeper hard Plinthic B horizon. There are little signs of wetness in the northern part of the field, as the soils are deep, and the west sloping gradient of the land allows for drainage to the wetland to the west of the field. The western parts of the field are partly waterlogged and show signs of wetness, indicated by the strong presence of iron and manganese oxides or mottling throughout the soil profile. The Longlands soil form predominates in this western area of the pivot. The southern and eastern parts of the field are deep Hutton soils, which are ideal for crop production under irrigation, as they have good drainage properties. The water movement in this area is more likely be through the vadose (unsaturated) zone, and less likely via the less permeable fractured rock system of the Ecca Group rocks.

Around 20% of the pivot footprint is situated in non-ideal cultivation conditions, and experiences intermittent waterlogging throughout the crop growing season. The recommendation to the farmer would be to move this pivot eastward, so there are less prominent effects on the germination, growth, and yield of the crop due to anoxic soil conditions, and with time, salinisation. This proposed move is supported by the results of the crop monitoring done during the trial period, showing a definite yield decline due to soil conditions.

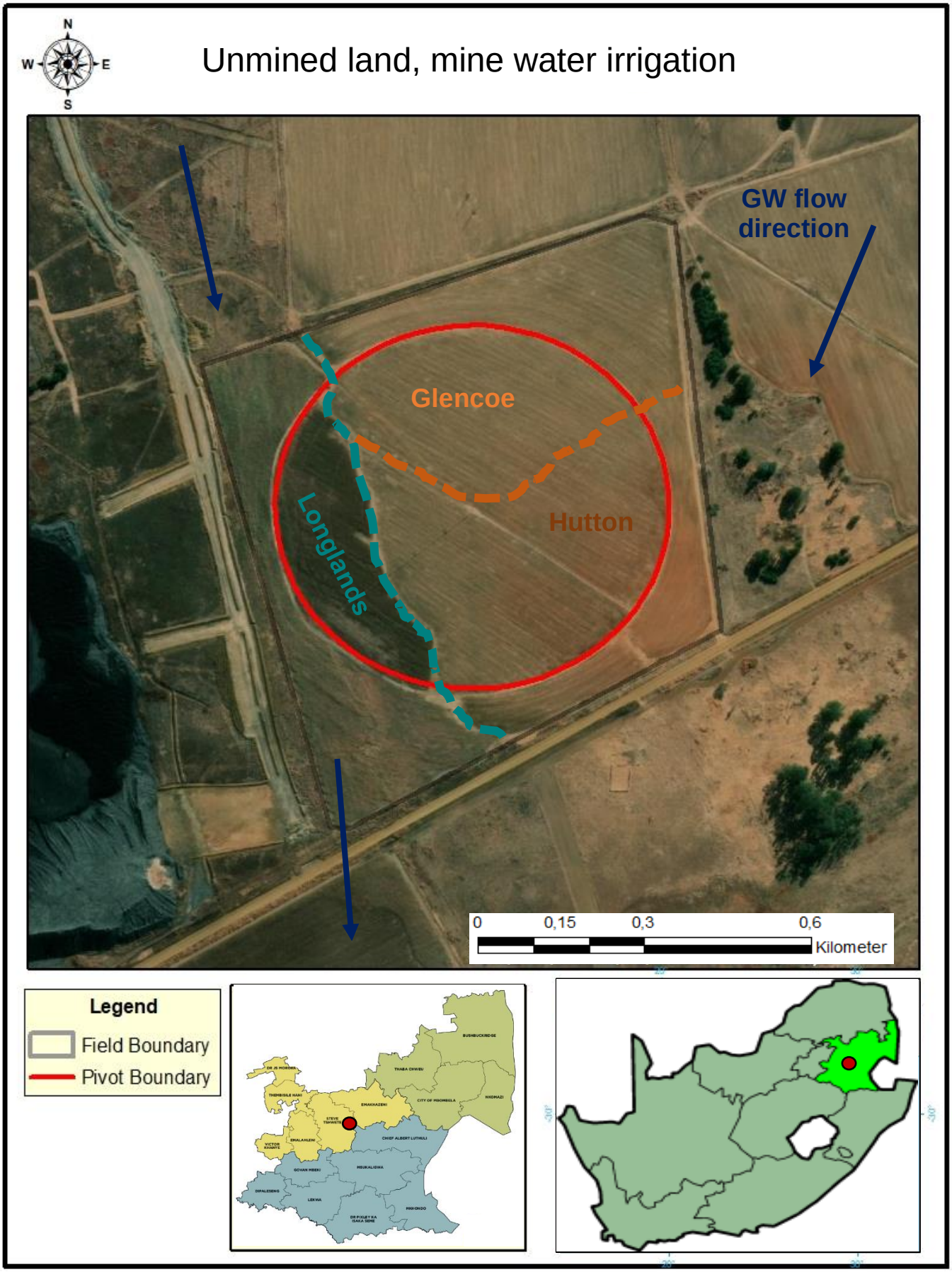


Figure 3.1: The trial location within South Africa (bottom-right), Mpumalanga (bottom-left), the trial boundary where irrigation with circum-neutral, gypsiferous mine water occurred, as well as the general soil forms found within the trial boundary.

Monitoring setup

The following parameters were monitored on the trial site: the weather conditions, soil chemical and physical status, shallow and deep groundwater, irrigation water quality, maize crop's performance, and associated changes over time. The monitoring equipment used was selected so as to accurately quantify any environmental changes and effects of mine-affected water on each measured parameter.

The 30-ha trial site's monitoring setup (Figure 3.2) consisted of an automatic weather station, four soil monitoring stations (2 within the dryland area and 2 within the irrigation area), four onsite boreholes [shallow (BH02 & 04 – 10m) and deep (BH01 & 03 – 30m)], two piezometers (3 m), two offsite boreholes (BH05 & 06), and a downstream surface water monitoring point (Beestepan Dam). Figure 3.3 provides a cross sectional view through the trial site indicating the monitoring setup within the water-soil-crop domains.

The first year on the trial site, 2016, was dryland production, as irrigation only commenced in September of 2017. The water quality data collected during the first season can be used as a baseline to compare the subsequent irrigated seasons to.

The four onsite boreholes were sited and drilled in 2016, before irrigation commenced. Borehole 01 and 02 are on the eastern border and are upslope of the trial site. If the mine-affected irrigation water percolates downward into groundwater, the lateral extent of the discharge plume would be identified by the changes in concentrations of the groundwater chemistry compared with the upslope site. Borehole 03 and 04 are on the western border and are downslope of the trial site. Changes in groundwater concentrations attributed to the irrigation discharge plume can then potentially be intercepted and carefully monitored.

Two shallow piezometers (3m deep) were installed in September 2017, on the far corner points of the western border of the trial site. These shallow water monitoring points are expected to be greatly influenced by meteoric water, mixed with irrigated runoff and percolation water. It is also noted that the piezometers are in partially waterlogged soils, with reducing conditions possible, specifically in the rainy season.

As part of the neighbouring mine's water use licence process, two offsite downstream boreholes were drilled, date unknown. The historic water quality data supplied by the mine for these offsite boreholes, provides insights as to any changes the trial's irrigation practices may have on the groundwater further away from the site. It is also noted the mines discard dump lies between the irrigation pivot and the offsite boreholes, BH 05 and BH 06.

The downstream surface water monitoring point (Beestepan Dam), an earthen dam, was built in 2003, by the collaborating commercial farmer. Communication with the farmer indicated

their dam's water quality was only monitored from 2016, on a quarterly basis. No historic data were therefore available to compare the trial's bi-monthly water data against.

Figure 3.2: The location of the monitoring stations for the unmined land irrigation trial.

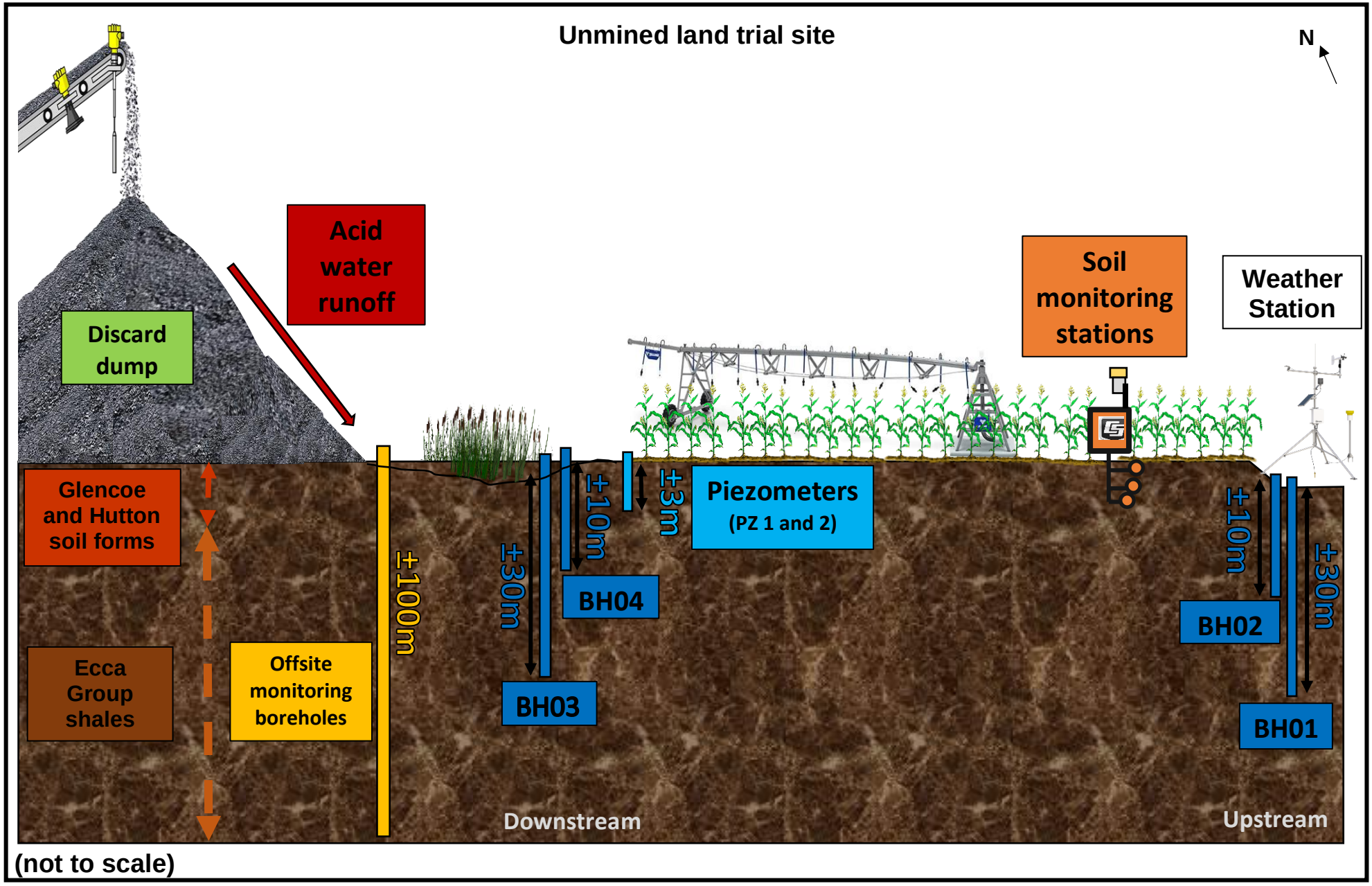


Figure 3.3: A west-to-east cross-section from the mine's discard dump through the adjacent wetland and across the unmined pivot indicating the various shallow and deep groundwater monitoring points.

The subsequent sections describe each monitored parameter and their setup.

3.2.2 Weather Monitoring

An automated Campbell Scientific weather station (Figure 3.4) was set up in an open area, with short grass beneath the station, near the unmined pivot (20 metres east of the pivot edge). This enabled accurate monitoring of changing weather conditions over the period of the growing season. The following components were mounted on the tripod:

- CR300 data logger and 12-volt battery
- TE525(WS) tipping bucket rain gauge
- RM Young three-cup anemometer and wind vane (wind speed (u) and wind direction)
- HMP60 sensor (air temperature (T_{air}) and relative humidity (R_h))
- Apogee CS301 sensor (solar radiation)

The data logger captured the measurements made with these sensors at 30-minute intervals over the period of three growing seasons (October 2017 – February 2020). Air vapour pressure deficit (VPD_{air}) was calculated from the T_{air} and R_h. Using the FAO Penman-Monteith equation for a short grass reference surface, a reference evapotranspiration (ETo) can be calculated (Allen et al. 1998).

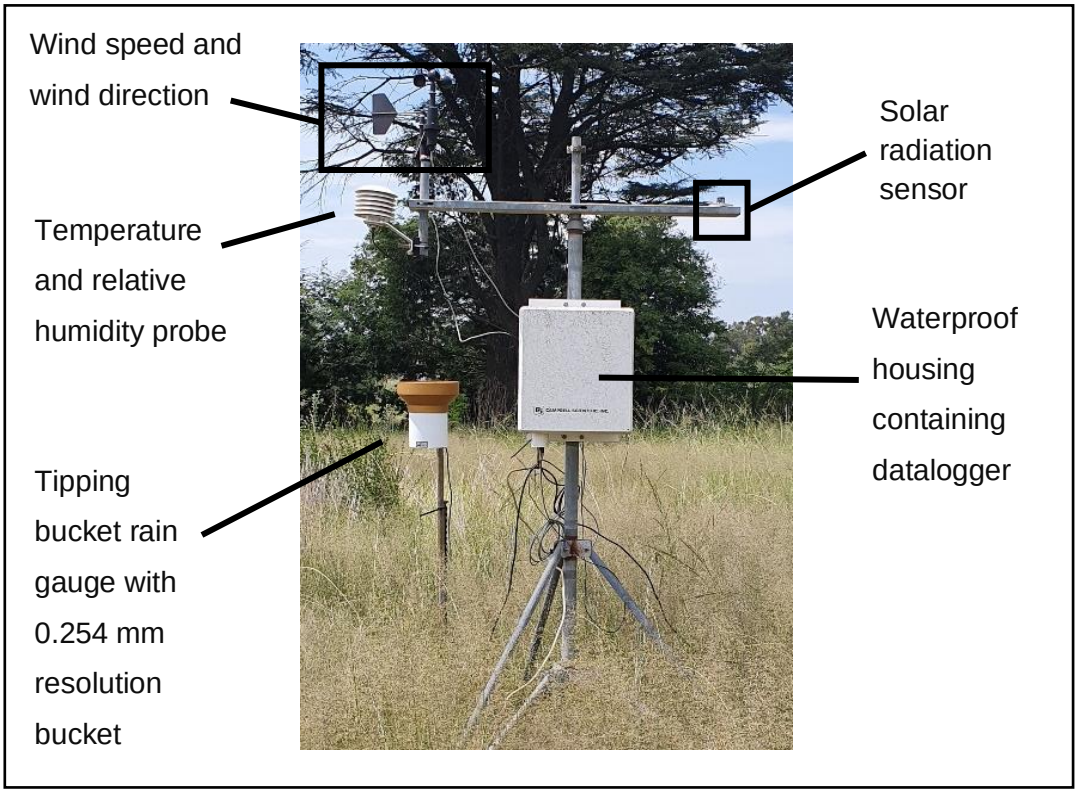


Figure 3.4: The weather station, and all labelled components, at the unmined land irrigation trial site.

Monitoring weather conditions provides insight into the growing conditions of the crop (Section 3.3.1). This is crucial when determining if there are any limiting climatic conditions which would negatively impact the crop growth and subsequent yield potential. A good example of this is noting periods of minimal rainfall or heavy precipitation (for example hail experienced in the 2018/2019 season), and how this coincides with the growth phases and performance of the crop. Irrigation amounts and timing can supplement periods of lower rainfall and in critical growth periods.

3.2.3 Water quality monitoring

The monitoring network established, facilitated representative samples (ground and surface water) being taken, in order to ascertain if any effects of irrigation could be observed in the catchment's downstream water resources. Soil and water monitoring points in closest proximity to the pivot, both upstream and downstream, were ideal for monitoring any direct runoff, downstream percolation, and base flow of the groundwater, as well as identifying and monitoring any changes in the irrigation environment's original state.

Irrigation water

The irrigation water is sourced from the neighbouring mine's void. This water is an untreated, circum-neutral gypsiferous mine water, and the changes in volume and quality are affected by both mine management and the weather. The volume (in mm) and the total amounts of salts (in kg/ha) applied to the trial site over the 28-month irrigated period was calculated. The commercial farmer should also consider nutrient loading rates through irrigation, and adjustments made to fertilizer application rates. The chemical signatures of ground, surface and irrigation water sources were compared to assist in determining if any correlations between sources exist.

A hydrogeologist from the Mpumamanzi Group, contracted by the mine, sampled the mine void water every two weeks. Waterlab (Pty) Ltd in Pretoria analysed all water samples submitted. The research team conducted spot checks of the irrigation water quality (Void water) throughout the season, sampled from the pivot sprayers, to corroborate the chemical analysis data provided by the mine.

Onsite groundwater piezometers and boreholes

Four boreholes were drilled in September 2017, before irrigation on the trial site began. Boreholes 1 and 2 are in the well-drained eastern side of the field, and boreholes 3 and 4 are in the poorly drained western side of the field, near the neighboring discard dump. The shallow boreholes (BH02 and BH04) are 10 m deep and the deep boreholes (BH02 and BH04) are 30 m deep. The objective of the staggered drilling and monitoring depths in close proximity to

the trial site enables the monitoring of changes in the natural groundwater quality once irrigation commenced.

Two shallow piezometers were installed at a depth of 3 metres. As seen in Figure 3.2, Piezometer one (Pz 1) was installed at the furthest north-western corner of the trial site, and Piezometer two (Pz 2) was installed at the furthest south-western corner of the trial site. The objective of the piezometers is to monitor the trial site's direct runoff and seepage, lateral flow, and changes in the chemistry of the shallow perched water table. These shallow groundwater monitoring points were ideally placed for interception, as they were both slightly downstream from the trial site.

The following procedure was used for sampling shallow (Piezometers) and the deep (Boreholes) groundwater monitoring points:

Samples were taken every two weeks for the shallow groundwater piezometers (Pz1 & Pz2) and quarterly for the deeper boreholes (BH 01 – 04). The sampling method followed was the procedure set out in Weaver et al. (2007), where plastic bottles from a certified water analysis laboratory were used. Before ICP-AES analysis, the samples were filtered through 11 µm filter paper. It is also noted that borehole purging was not done, as sampling was done regularly enough to ensure the borehole water did not become stagnant and was representative of the flux of water and salt interaction between the rainfall, runoff, shallow groundwater and irrigation water at the pivot (Nielsen, 2006). Samples were preserved physically, and once sampled were stored in a portable ice cooler, at temperatures of around 6^{o}C (DWAF, 2006).

Water levels were measured using an electronic groundwater level detector and samples retrieved using a bailer. Temporal graphs show the changes in chemical constituents for the different monitored water sources over the irrigation period. All water quality results are also plotted in Piper diagrams, to indicate the hydrofacies and evaluate the differences in water chemistries and signatures (Piper, 1994; USEPA, 2004; Chihi et al., 2015). A strong spatial coherence between hydrogeochemical facies clustering suggest all samples are from the same groundwater source.

Offsite groundwater boreholes

Hydrogeologists from the Mpumamanzi Group, contracted by the mine, sampled the water of the offsite boreholes (BH5 & BH6) every quarter, since September 2018. Waterlab (Pty) Ltd in Pretoria analysed all water samples submitted.

Downstream surface water monitoring

The same water sampling procedure and timing (twice a month) set out for the groundwater monitoring above, was followed for the surface water monitoring. The identified downstream

surface water monitoring point (Beestepan Dam) was chosen as the point where any potential impact of irrigation could be monitored. After deliberation with the research team's reference group, sulphate was chosen as the identifiable "flagging" constituent, and if a 20% increase in original concentration (before irrigation), attributable to irrigation, was observed, irrigation should cease as the impact would be seen as unacceptable. This, however, proved an ambiguous threshold, as the monitoring point is also downstream from one of the mine's discard dumps, and any increase in sulphate (or any other element) cannot easily be related to irrigation alone. It is thus noted that an understanding of the specific site's local hydrogeology and hydraulic flow characteristics will allow for greater insight into setting site-specific thresholds.

Stable isotope

An additional stable isotope study was also conducted to determine if there were any interactions between water sources at different monitoring points. The aim was to assist in identifying the impact the irrigation mine water had on ground and surface water resources. Understanding the connection between the irrigation water and the surrounding environment is crucial when looking at the transport and fate of the constituents from the irrigation water.

Water D/H ($^{2}H/^{1}H$) and $^{18}O/^{16}O$ ratios were analysed at the Environmental Isotope Laboratory of iThemba Labs, in Johannesburg. For the stable isotope analysis, the Los Gatos Research (LGR) liquid water isotope analyser was used. Laboratory standards, which were calibrated against international reference materials, were analysed with each batch of samples.

The analytical precision is estimated at 0.5‰ for O and 1.5‰ for H. Analytical results are presented in the common delta notation:

$$\delta^{18}O(‰) = \left[\frac{(^{18}O/^{16}O)_{sample}}{(^{18}O/^{16}O)_{standard}} - 1 \right] \times 1000$$

which applies to D/H ($^{2}H/^{1}H$), accordingly. Delta values are expressed as per mille deviation relative to a known standard, which was standard mean ocean water (SMOW) for $\delta^{18}O$ and δD. The stable isotope analyses for all the water samples were well reproduced within the expected analytical error limits.

3.2.4 Crop monitoring

Zea mays L., a white maize variety PHB 32B07BR (genetically modified with stacked genes for stalk borer and herbicide resistance), was planted at a population density of 80000 plants per hectare each season (2017/18, 2018/19 and 2019/20). Adjacent to the pivot, dryland maize was planted at a population density of 50000 plants per hectare to another white maize variety, DKC 7883R. In the 2016/17 season, only dryland maize was planted and monitored.

Crop Growth Parameters

The white maize crop was sampled and measured every two weeks, throughout the pivot and dryland areas, for the entire crop growing seasons. The following crop parameters were assessed: Plant height; growth stage; Leaf Area Index (LAI); and Fractional Interception (FI_{PAR}) of Photosynthetically Active Radiation (PAR). Sufficient measurements were taken to statistically analyse the population data, to ensure a representative average.

Plant height was measured every two weeks, with a measuring tape, from ground level to the tip of the maize plant. The crop growth stage, (emergence, flowering and physiological maturity) was noted with each sampling campaign. The phenological growth stages depicted in He et al. (2010) were used to evaluate vegetative and reproductive growth progression.

Crop biomass production is attributed to the efficiency of converting captured radiation into biomass, so called radiation use efficiency (RUE) (Louarn et al., 2008). The amount of photosynthetically active radiation (PAR) intercepted by the crop canopy is dependent on the leaf area. The Leaf Area Index (LAI) and the photosynthetically active radiation (PAR) were measured with each plant measurement point within the irrigated and dryland areas of the trial site.

Leaf Area Index (LAI) is a measure of crop canopy cover and is defined as the adaxial green leaf area per ground surface area, measured in $m^2 \cdot m^{-2}$. The LAI provides an indication of photosynthetically active area of the maize crop. LAI curves indicate the general sigmoidal trend for maize crop growth over the growing season. Random, destructive sampling (±10 plants) were harvested every two weeks from a 2 to 3 m^2 area throughout the trial site and put through the Licor LI-3100C area meter, at the University of Pretoria's Experimental Farm within a few hours of collection.

Using a Decagon AccuPAR LP-80 ceptometer, PAR was measured both above and below the crop canopy in order to quantify the transmission and interception of photosynthetically active radiation. PAR was measured below the canopy (PAR_{bottom}), both within and across the row, covering the total area occupied by plant stand, and in full sun (PAR_{top}) where measurements were made in an open area in the trial site, without any obstructions. At each sampling point, all measurements were taken between 11:00 and 14:00, under clear sky conditions. A

radiation extinction coefficient, Fractional Interception (FI_{PAR}), was calculated, indicating the fraction of the PAR that is intercepted by the crop canopy. This parameter can be used for modelling the partitioning of available evaporative energy into energy for transpiration and energy available for direct evaporation from the soil.

Crop yield determination

Monitoring Total above-ground Dry Matter (TDM) production and grain yield, provides some insight into the effect of mine water irrigation on production and economic feasibility of crop production. The maize crop yield was measured on an individual plant basis by means of hand harvesting, at each monitoring station, at the end of each growing season (reproductive growth stage R6). Sampling of the white maize was at around 150 days after emergence, where the whole plant was harvested from approximately 1 – 2 cm above the soil. Roots were not collected, and the whole plant was divided into its component parts: stem, leaves and cob. The sampling procedure was to use seven sampling points within the irrigated area and three sampling points within the dryland area. Three 10 m row lengths were measured out at each site, with ±10 plants per row length sampled. After sampling, the plants were stripped of their stems, cobs and leaves, and each plant part was weighed separately. The separate plant parts were then oven dried at 70 ºC for ±7 days, or until plant parts displayed a constant mass. The average masses determined were corrected for plant density in order to estimate yield per unit surface area.

Total dry matter (TDM) (in ton/ha) at harvest, includes stalks, leaves, cob, and grain mass. The Harvestable Dry Matter (HDM) was measured by hand harvesting the ears, removing the grain from the cob (main marketable portion) and weighed to determine the Grain Yield (in ton/ha). Dry Matter was increased to 12.5% moisture content to compare to commercially harvested grain yields. Cob size, length and mass, was also measured at each sampling point, as this allowed another comparison of crop development. The Harvest Index (HI) is calculated as the ratio of Grain Yield to Total above-ground Dry Matter (TDM), and can be used as a measure of reproductive efficiency (Unkovich et al. 2010). HI is a key partitioning index; it quantifies the effectiveness of the crop in the grain development and filling reproductive stages. HI can also be used as an indicator for the crop experiencing environmental stress, for example water stress (Hütsch & Schubert, 2017; Beebe et al. 2008).

Economic Analysis

A summary of each season's input costs (fertilizer, pesticide and herbicide applications and irrigation costs), the yields, and market prices were used to determine the economic profitability of irrigation with mine-affected waters at this unmined trial site.

Food and fodder analyses

The food and fodder quality assessments of the maize crop were performed at the end of each growing season. The elemental composition of the three edible portions (grain for human and animal consumption, as well as leaves and stems for livestock consumption) of the plant were determined. The vulnerability and efficiency of each plant part for the partitioning of elements from solution can be identified. Comparisons of analysed maize quality were made to current food and fodder thresholds and guidelines, to determine the suitability for consumption and subsequent profitability of the mine water irrigated maize crop. Although most mine-affected waters contain a range of metals, including iron, aluminium and manganese, local and international guidelines and thresholds focus on arsenic, cadmium, chromium, lead and mercury, as the important food safety elements of potential concern. It is important to identify which elements of potential concern are present in the mine-affected water body which one is proposing to utilise for irrigation. Some unusual elements may be present in the irrigation water, and these may partition into plant parts, thereby having the potential to be of toxicological concern, despite not being explicitly specified in food and fodder guidelines. This is the reason for suggesting elemental analyses on the useable parts of the crop.

The US EPA 3052 analytical method was deemed appropriate as the test method, as the plant tissues would be totally decomposed by reagents, and the production of an amorphic siliceous precipitate is avoided (Raymont & Lyons, 2011). This method would therefore allow the most accurate results for quantifying the total extractable elemental concentrations of each plant part of the maize crop. After weighing each plant part, they were put into an oven and dried until a constant mass was reached. Each labelled plant part was again weighed, and then milled. Each dried plant part was weighed out using a WS-P bench scale (each sample was 0.3 grams) and put into individually marked test tubes. 9 mL of concentrated nitric acid and 3 mL of hydrochloric acid was added to each sample and put into an Anton Paar Ultrawave digestor for 15 minutes. After cooling, the solution was decanted into conical flasks and 35 mL of deionised water added to each. Samples were then analysed by ICP-AES. The ICP-AES was calibrated using standards for each element.

3.2.5 Soil characterisation

Physical and chemical analyses

A soil sampling grid was set up at the start of this trial, in 2016, with 14 sampling locations identified in the irrigated field (Blue) and six sampling locations identified in the adjacent dryland area (Brown) (Figure 3.5). Soil samples were taken at the beginning of the trial (September 2016), and subsequently, at the beginning of each irrigation season to follow. Soil samples were taken in three 30 cm increments, from the surface down to 90 cm. All soil analyses were performed in triplicate. Quantifying the physical characteristics and chemical

constituents, allows for a comparison between irrigation seasons, and any changes (detrimental or not) in soil chemistry can be identified.

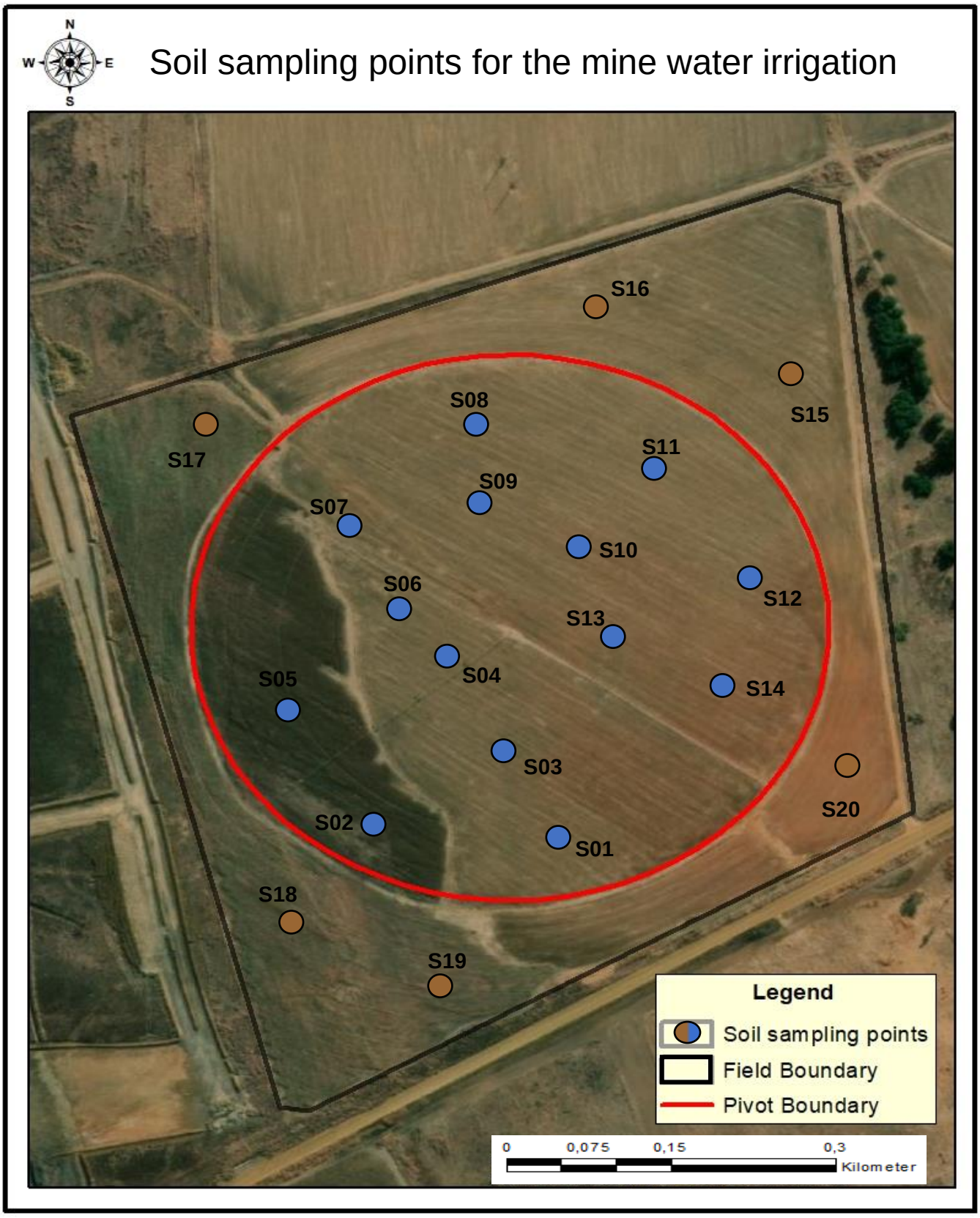


Figure 3.5: Soil sampling locations, dryland (brown) and irrigated (blue), of the unmined trial site.

Soil Physical Analysis

Soil Texture

The soil texture analysis used was adapted from the Bouyoucos (1962) method, the particle size analysis was determined via hydrometer. The results were plotted on a USDA soil textural triangle (SSM, 1993).

The soil preparation and pre-treatment were as follows:

To remove the organic matter, 20 mL hydrogen peroxide was added to each 50 g soil subsample. The samples were placed onto sand baths where they were heated, and excess water could evaporate. De-ionised water was added intermittently to slow the soil and hydrogen peroxide reaction, as this is a very aggressive exothermic reaction.

Soil texture determination was as follows:

Following the removal of the organic matter, pre-treatment, 10 mL of Calgon dispersing agent and 200 mL deionised water was added to each sample. The samples were decanted into separate dispersion cups and mixed for 5 minutes with an electric beater. Samples were then passed through a 0.053 mm wire mesh sieve until the solution appeared clear, to ensure the sand fraction was separated from the clay and silt fractions. Deionised water was added to the silt and clay fractions to make up a 1L container.

Sand fraction determination:

The fraction of the samples that did not pass through the 0.053 mm sieve, were carefully collected, and transferred to containers and dried in an oven. The dry mass sand fraction was weighed, and the sand fraction percentage determined.

Clay fraction determination:

A blank sample of 1L was made up of 10 mL Calgon dispersing agent and deionised water. The 1L samples were thoroughly mixed with a plastic plunger. After 6 hours and 35 minutes of the samples being undisturbed, a standard hydrometer (ASTM no 152 H) was slowly placed into the 1L cylinders and the hydrometer readings were taken. The clay fraction percentage was determined using the appropriate temperature column.

Silt fraction determination:

The silt fraction percentage was calculated from subtracting the clay and sand fractions from 100 percent.

Soil Chemical Analyses

Soil pH

Soil pH was used to determine the relative hydrogen ion activity in the soil. To each 10 g soil subsample, 25 mL of 1M KCl solution was added (pH(KCl)). These were agitated and left undisturbed for 1 hour, after which a calibrated pH meter was used to measure the pH of the supernatant. This process was repeated on another 10 g soil sample with 25 mL of deionised water (pH(H2O)), still having the 1:2.5 soil/water mass basis ratio (AgriLASA 2004).

Percent Carbon (%C)

The standard Walkley-Black method was used to determine percent organic carbon of the soil samples. Each soil sample was ground down to pass through a 0.35mm sieve and air dried. 1g of soil was added to a 500mL Erlenmeyer flask. Then 10mL of $K_2Cr_2O_7$ solution was added by pipette to the sample. The flask was then swirled to disperse solution in the soil. Twenty millilitres of concentrated Sulphuric acid (H_2SO_4) was added to the sample, swirl to allow reagents to mix. Allowed to cool for 30 minutes. One hundred and fifty millilitres of deionised water and 10mL of phosphoric acid was added. One millilitre of indicator was added, and the solution titrated with iron (II) ammonium sulphate solution. The calculation for determining Organic C% can be found in AgriLASA (2004) and Nelson & Sommers (1982).

Electrical Conductivity of a saturated paste extract (ECe)

Saturated paste

A 250 g air-dry soil sample was placed in a suitable container and moistened with de-ionised water while mixing with a spatula. Tested for the properties of a saturated paste and added more de-ionised water if necessary. Allowed to stand for an hour and test whether it still has saturation properties. Ensured that water does not collect and that the paste does not dry out too much. Noted the total volume of water added. Properties of a saturated paste can be found in AgriLASA (2004). Calibrated the conductivity cell with 0.01 mol dm^3 KCl solution. This solution has an electrical conductivity of approximately 141 mS m^{-1} at 25°C. Rinsed the conductivity cell with saturation extract. Determined the conductivity of the saturation extract and calculate the electrical resistance from this value. Conductivity of the saturation extract is expressed in mS/m.

Extractable cations and anions

Ammonium acetate extraction

The ammonium acetate extraction method was used to determine the amount of soluble and exchangeable bases (Ca^{2+}, Mg^{2+}, Na^+ and K^+). Five grams of air-dried soil was placed in a 100 mL extraction bottle. Fifty cm^3 of NH_4OAc was added to the bottle and shaken on a reciprocating shaker at 180 oscillations per minute for 30 minutes. The solution was filtered

through a Buchner funnel and collect the filtrate. Refilter if extract is not clear. The calculation for determining extractable Ca; Mg, Na and K, can be found in AgriLASA (2004).

Mehlich 3 extraction

A Mehlich-3 extraction was used to determine the total extractable portion of S, P, K, Ca, Mg, Na, Cu, Zn, Mn, B, Al, and Fe. Three grams of air-dry soil should be weighed out into a 125 mL Erlenmeyer flask. Thirty millilitres of the Mehlich 3 extracting solution added (soil: solution ratio 1:10). Shaken immediately on reciprocating shaker for 5 min (120 oscillations per minute). Filtered through Mehlich 3-rinsed Whatman No. 42 filter paper into plastic test tubes. Finally, the elements are analysed for in the supernatant, using an ICP-AES machine. Procedures on how to make the M3 extracting solution can be found in Mehlich (1984).

EDTA extraction

Ethylenediaminetetraacetic acid (EDTA) was used to extract heavy metal contaminants, namely Pb, Cd, Zn, and Mn from soils. 2.5 g of air-dried soil was shaken with 10 mL of 0.05 mol/L EDTA solution for 60 minutes on a rotary shaker. More EDTA solution was added to the mixture until it reached 25 mL. The supernatant was filtered through Whatman No. 42 paper.

Soil monitoring stations

Four soil monitoring stations were set up, two within the irrigated land and two in the surrounding dryland field. A CR300 data logger was housed in a waterproof box, with the battery being replaced every two weeks with a fully charged replacement battery. The monitoring stations within the irrigated land had one unit placed in well-drained soil, near the eastern border, and one unit placed within the more waterlogged area, on the western border (Figure 3.2). Two other units were also placed in the dryland area of the trial site. This allowed for a representative monitoring of changes in soil water conditions throughout the pivot.

Each monitoring station consisted of three CS 655 water content, temperature and salinity probes, placed at 30, 60 and 90 cm depths. The soil loggers monitored soil volumetric water content (VWC), bulk Electrical Conductivity (EC), and temperature. The unit was also set up with an automatic TE525 tipping-bucket rain gauge to monitor irrigation and rainfall with a resolution of 0.254 mm per tip.

3.2.6 Nutrient Mass Balance

Understanding the irrigated environment, and quantifying its nutrient cycles, is crucial for sustainably and responsibly producing crops. Nutrient mass balances are used to determine potential drivers and hinderances of nutrient depletion or accumulation in agroecosystems, as well as determining the irrigation practices environmental footprint (Soberon et al. 2015). Sustainable management of nutrient balances ensures profitable crop production, while maintaining soil fertility, and environmental integrity (Parris, 1998).

Fundamentally, what is put into the irrigated system should equal what is going out of the system, and one's monitoring practices should accurately quantify this. The top ninety centimetres of soil was chosen as the primary measurement area. The top thirty centimetres of the soil profile is the active root zone, and the sixty centimetres below would be largely the remaining nutrient exchange zone. It is noted that there are seasonal fluxes in plant available elements throughout the soil profile, as part of the field's natural nutrient and hydrological cycles. Within the realm of realistic sampling and analysis costs, soil samples were therefore only taken before and after each irrigated season. Chemically quantifying the system before and after each irrigating season, provides insight into the systems total additions, losses, and changes. Amalgamating the soil and crop chemical results, a nutrient mass balance can be determined for the unmined trial site. The mass balance diagram (Figure 3.6) aims to integrate the additions and losses of the irrigated soil system, up to the sampled 90 cm soil depth.

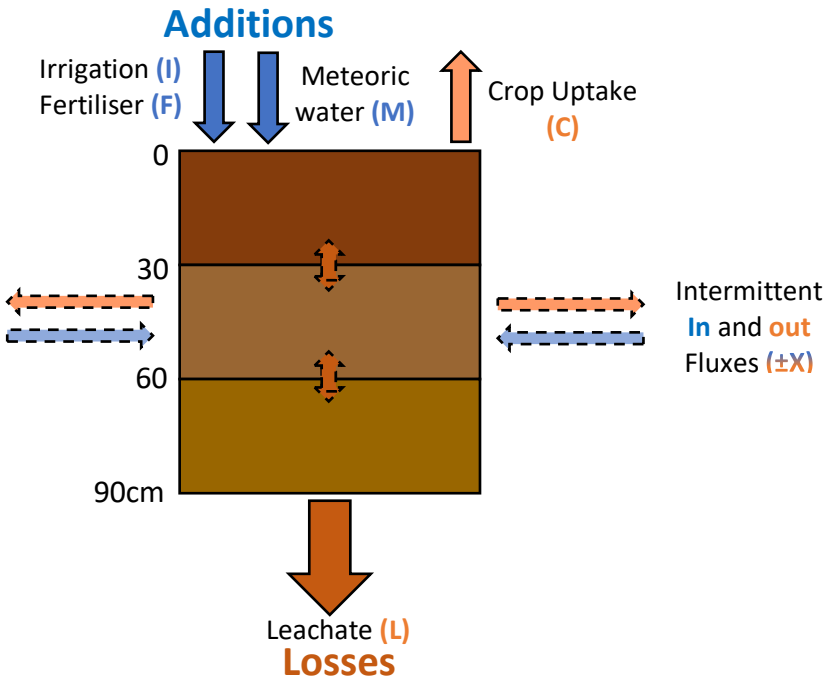


Figure 3.6: A representation of the typical additions and losses a soil unit (0 – 90cm's deep) experiences under irrigation at the unmined trial site.

The deficit between residual concentrations in the soil (S_f - S_i = ΔS), what nutrients are added through irrigation (I), fertilizer (F) and through meteoric (M) processes) and what nutrients are removed (crop uptake (C)) on the trial site, are then attributed to 'leachate loss (L)'. The following simplified equations were used to characterise the leachate losses of the 0 to 90-centimetre soil unit at the unmined trial site:

$$S_f = S_i + \mathrm{I} + \mathrm{F} + \mathrm{M} - \mathrm{L} - \mathrm{C} \pm \mathrm{X}$$

$$S_f - S_i = \Delta\mathrm{S} = \mathrm{I} + \mathrm{F} + \mathrm{M} - \mathrm{L} - \mathrm{C} \pm \mathrm{X}$$

$$\mathrm{L} = \mathrm{I} + \mathrm{F} + \mathrm{M} - \mathrm{C} \pm \mathrm{X} - \Delta\mathrm{S}$$

S_f is the soil final concentration; S_i is the soil initial concentration; ΔS is the change in soil concentration; I is the addition of nutrients through irrigation; F is addition of nutrients through fertiliser; M is addition of nutrients through meteoric water; L is leachate loss of nutrients from the soil unit; C is removal of nutrients through crop uptake and ±X is the flux of nutrients (addition or loss) to the system (site and temporal specific). All values used kg/ha as the unit of measurement.

The addition of nutrients from the fertilisers (F) and Irrigation (I) are quantified in Chapter 3 Section 3.3.2. These additions (I + F) provide insight into nutrient loading rates, and subsequent adjustments that should be made to irrigation and fertiliser programs, for optimal crop nutrient supply, and minimal nutrient losses from the irrigated environment. The salt content of natural precipitation (meteoric water as an input, M) added minor amounts of nutrients, and was therefore deemed insignificant, and taken as zero.

At a large field scale, the system is open to various natural in and out fluxes (±X). It is challenging to ascertain all partial and temporal additions and losses and is subsequently difficult to accurately quantify these fluxes. Quantifying a nutrient mass balance, uses total additions and removals, partial temporal losses and additions are not included, and it is therefore classified as a partial nutrient budget. However, it is noted that they do exist and can influence the nutrient mass balance of the unit measured.

Some fluxes which are difficult to quantify and were therefore removed from the mass balance calculations were: Losses from erosion, runoff and horizontal percolation, some additions are atmospheric and run-on depositions, and horizontal percolation accumulates. These fluxes are generally site-specific and require many different factors to be considered when attempting to quantify their effects. Due to the indefinite nature of 'in and out fluxes' within the soil profile, they will be considered as zero, and outside the scope of study.

The plant uptake (C) amounts are perhaps a slight underestimation of total crop nutrient removal, as the roots of the crop were not sampled, and those assimilates not accounted for. However, the effect can be deemed negligible, due to the primary function of roots facilitating osmosis and translocation and only small amounts of nutrient assimilation present for the root structure. However, the total crop uptake values used represents the majority of the nutrient removal each season from the maize crop, within an acceptable margin of error.

The loamy soils of the unmined trial site had a bulk density of 1400 kg/m^3. The soil chemical characteristics are quantified in Section 3.2.5. Annual measurable changes (ΔS) in the chemical constituents of the soil indicates the capacity of a plant-soil continuum to receive a nutrient load. Temporal changes in soil chemistry indicate how an irrigated environment utilises or discharges nutrients and provides some indication of the fate of the nutrients within an agricultural setting.

The leachate (L) is a nett loss of nutrients from a soil unit, where the nutrient inputs into the system are more than the crop uptake and usage of the nutrients (I +F > C). One of the hypotheses of this study was if the input irrigation water was gypsiferous in nature, there would be gypsum precipitation in the soil, and therefore less salt leaching into the groundwater than that applied to the field.

The simplified mass balance diagram (Figure 3.7) is the schematic used to quantify the partial mass balance at the unmined trial site:

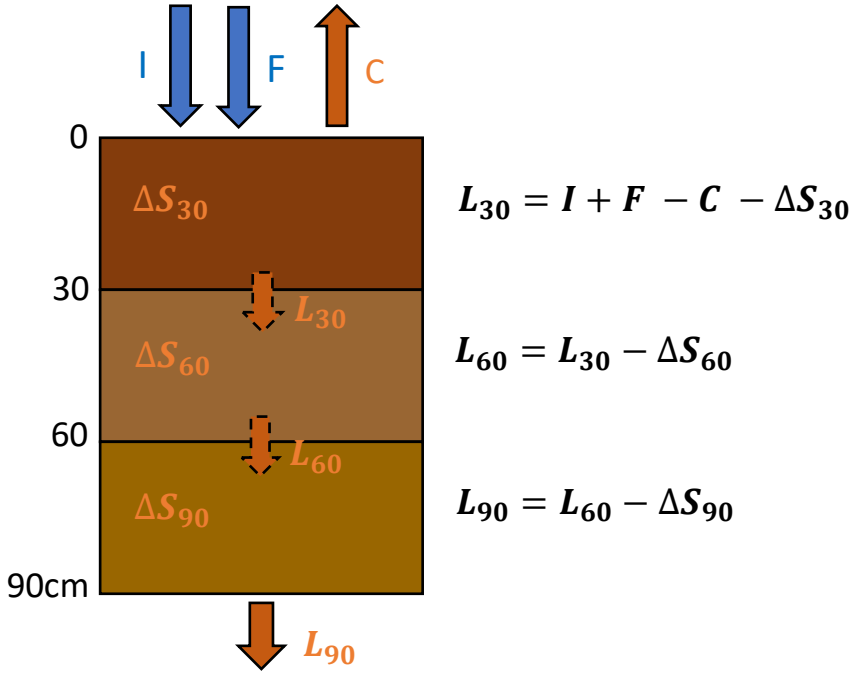


Figure 3.7: A representation of the partial mass balance calculations used for the unmined trial site.

3.3 Results and Discussion

3.3.1 Weather monitoring

The mean daily air temperature throughout the trial's period was 19.2°C, with a lower mean air temperature of 17.1°C in winter and a higher mean air temperature of 21.2°C in summer (Figure 3.8 A). Temperature is not seen as a limiting factor for crop growth and performance.

The subtropical savanna area of the highveld of Mpumalanga has strong seasonal rainfall, with wet summers and dry winters (Nix 1983). A total of 2 367 mm of rain fell throughout the trial period, with an annual mean precipitation amount of 592 mm (Figure 3.8 B). The 2016/2017 season had a positive or right skewed rainfall distribution, meaning most rainfall occurred in the early summer months (October to early January), with little occurring thereafter. The 2017/2018 and the 2019/2020 seasons had a left skewed rainfall distribution, meaning the bulk of the rainfall occurred later in the summer rainfall season. Supplemented irrigation during the germination, emergence, and early crop establishment periods (early summer season) are imperative for good crop performance. Irrigation can ensure that drier periods' water availability is supplemented, especially during crucial crop stress periods, thereby negating the effects of intermittent rainfall. The 2018/2019 season had a more symmetrical or normally distributed rainfall pattern.

The solar radiation patterns at the trial site over the 4-year period (Figure 3.8 C) followed the same pattern as stated in Schulze (1997a) and Rutherford et al. (2006). It was stated that in summer, solar radiation is usually less than 38 MJ/m^{2}day and in winter it is usually less than 13 MJ/m^{2}day. This stated pattern was generally observed at the unmined site, with a few outliers noted. Periods of higher rainfall in the summer periods (September – March), had overall higher solar radiation values, but a greater variation was also observed when compared to the winter periods. As expected for this climatic region, the summer rainfall patterns (Rutherford et al. 2006) are coupled with frequent full cloud cover and overcast conditions, thereby resulting in lower recorded incoming solar radiation during these rainy times. The overall solar radiation (Figure 3.8 C) trend observed over the trial period follows the seasonality of this climatic region. Solar radiation is not seen as a limiting factor for crop growth and would have had no adverse effects on the yearly crop performance.

The air vapour pressure deficit (VPD) is highly variable. Over the trial period a maximum daily value of 3.38 kPa, and an annual mean value of 1.035 kPa was measured (Figure 3.8 D). As expected, the air's VPD was highest in the summer months and reached a high of 1.85 kPa (Summer 2016/2017), 3.38 kPa (Summer 2017/2018), 2.65 kPa (Summer 2018/2019) and 2.95 kPa (Summer of 2019/2020) respectively.

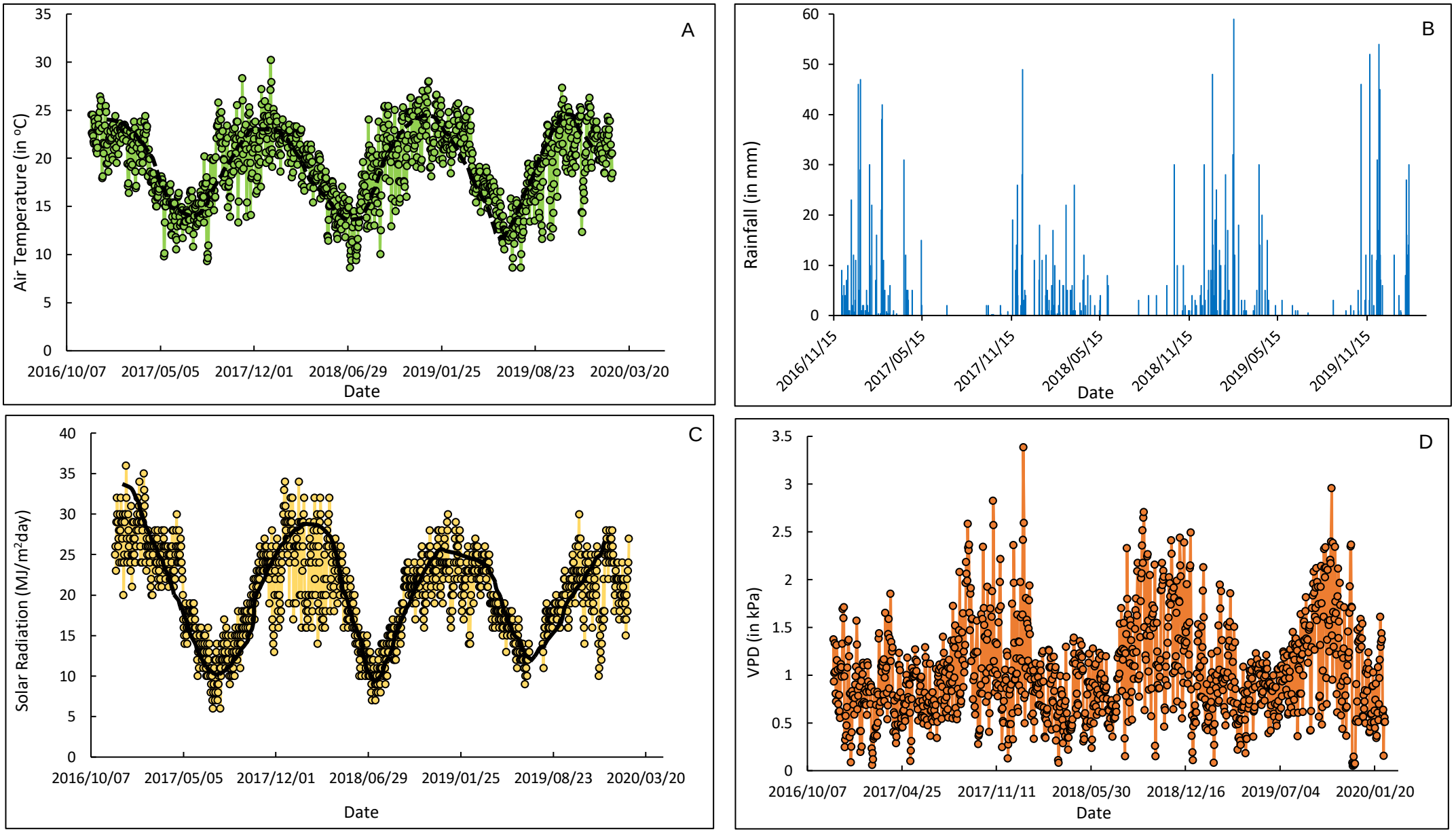


Figure 3.8: Daily weather variables measured at the unmined trial site. (A) Average daily air temperature (in °C). (B) daily rainfall (in mm). (C) Maximum daily Solar Radiation (in MJ/m^{2}day). (D) Average daily Vapour Pressure Deficit (VPD) (in kPa).

3.3.2 Water quality monitoring

Irrigation water

The annual cumulative rainfall and irrigation amounts can be seen in Figure 3.9. This summarises the total irrigation and rainfall the trial site has received over the three irrigation seasons.

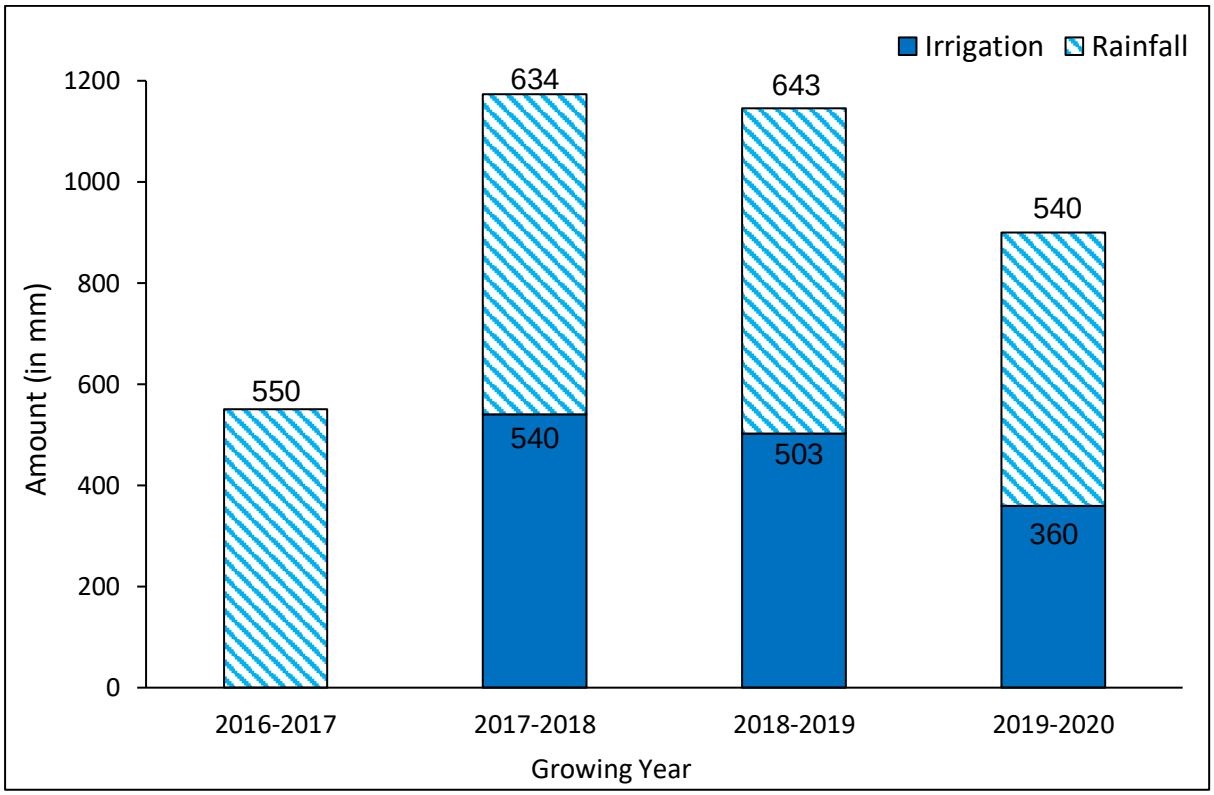


Figure 3.9: Total seasonal rainfall and irrigation over three irrigated maize-growing seasons at the unmined trial site.

Although each season saw over 500 mm of rainfall over the maize growing seasons, a regularly supplemented water supply during dry periods and at critical phenological stages ensured the crop received enough water at crucial times, to enhance production over dryland growth.

It is noted that in the winter of 2018, half a season of stooling rye was planted and monitored by another scientist. This trial terminated halfway through the growing season and was reported as receiving 236 mm of irrigation water, and 0 mm of rainfall. Table 3.1 provides a summary of each growing season, the accompanying crop, and the irrigation and rainfall amounts. The total irrigation amount, including the winter stooling rye, will be considered when the salt loading rates are calculated.

Table 3.1: A summary of seasonal irrigation and rainfall at the unmined trial site.

Year	Growing season	Irrigation amount (mm)	Rainfall amount (mm)
2015/16	Dryland maize	-	480
2016/17	Dryland maize	-	550
2017/18	First irrigated maize	304 (summer)	634
2018	Half-season irrigated stooling rye	236 (winter)	-
2018/19	Second irrigated maize	503	643
2019/20	Third irrigated maize	360	540
Total		**1 403**	**2 847**

The temporal irrigation water chemistry graphs (Figures 3.10, 3.11 & 3.12) show the change in water chemistry over the irrigating period on the trial site. The red dotted line on the irrigation water chemistry graphs, annotated IC, is the irrigation commencement date, September 2017. The blue stars on the x axis of the graphs indicate the date of the grab sampling and data verification spot checks. The summary of the mine supplied irrigation water quality as well as the results from the grab water samples from the irrigation pivot, can be found in Appendix A (Table A.1 & A.2). The spot check samples revealed the mine's water quality results to be accurate and within one standard deviation of the mean. This irrigation water quality data provided, can therefore be seen as reliable.

According to mine personnel, in the period just before the void water was used for irrigation, there was a period of no void water supply. This is reflected in the water chemistry results, where a steep drop in concentration is seen in the year before irrigation commenced (IC). This sampled water can therefore be rainwater diluted void water, which occupied the water holding space of the void water. Once void water is topped up to normal levels, the chemical constituent concentrations increased to somewhat stable levels.

After irrigation commenced in September of 2017, the EC showed a steady increase over the three-year period, peaking at about 320 mS/m in October of 2019 (Figure 3.10). After irrigation commenced, the pH has remained fairly constant, being circum-neutral to slightly alkaline.

After irrigation commenced in September of 2017, the calcium and magnesium also show a steady increase over the three-year period. This may be indicative of water treatment additives being added to the void water. Although the mine correspondents were not able to confirm this, this may be a possible explanation for this observed increase. The sodium, chloride and potassium concentrations remained stable over the three-year period, with no major changes observed.

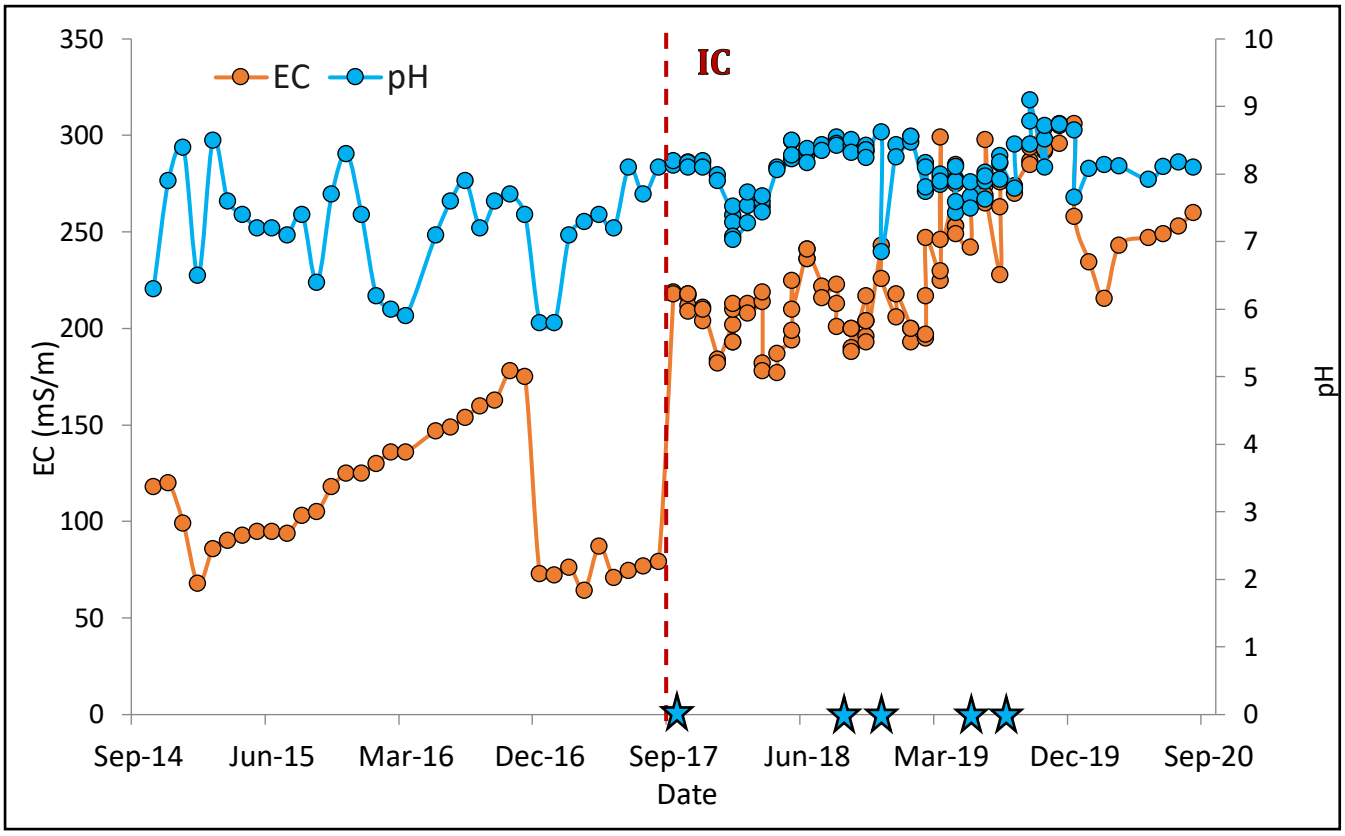


Figure 3.10: Change in pH and electrical conductivity of the irrigation water from October 2014 to August 2020.

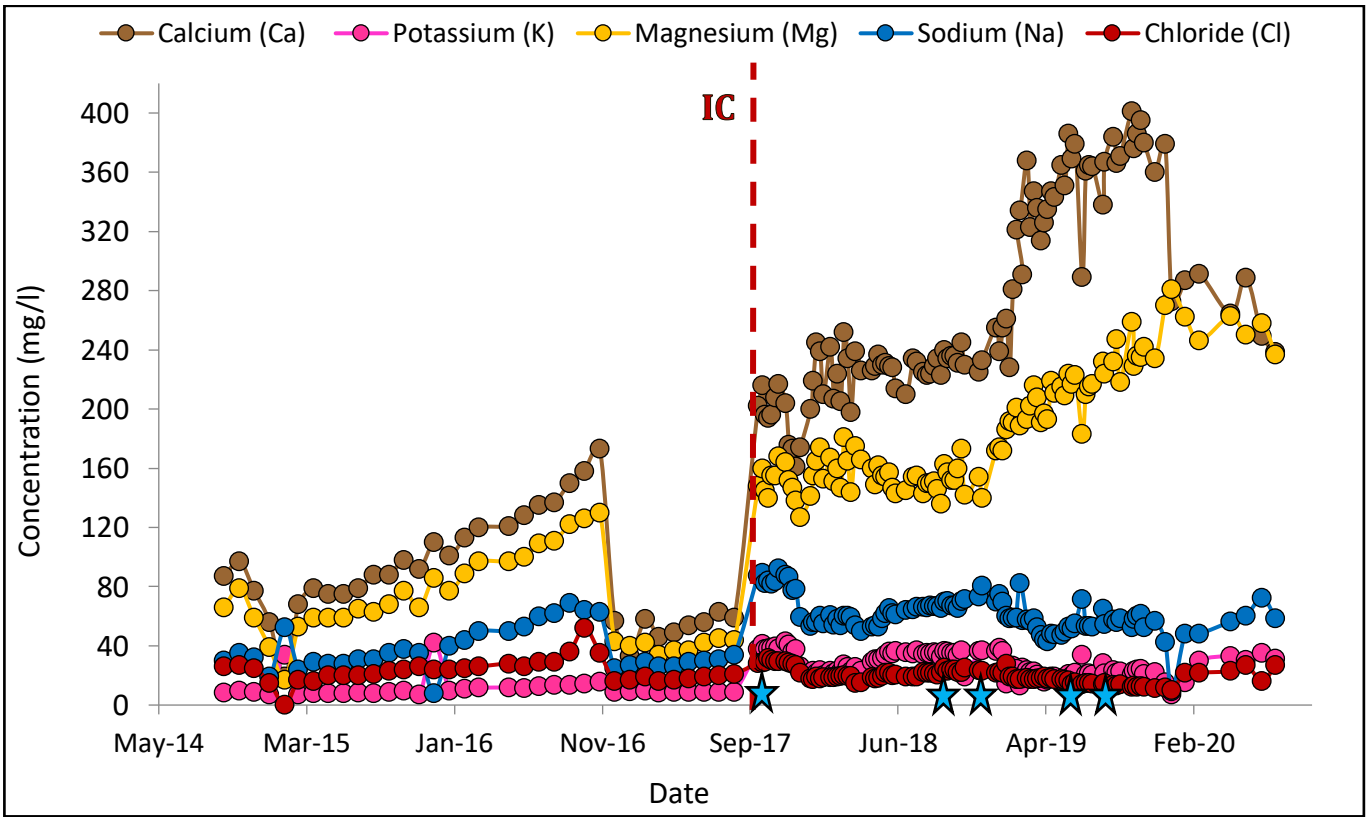


Figure 3.11: Change in major cation concentrations of irrigation water from October 2014 to March 2020.

The sulphate concentration, after irrigation commenced in September 2017, showed a steady increase from 1100 mg/l to 1900 mg/l over the three-year period (Figure 3.12). The irrigation water chemistry is regulated by the co-operating mine, their pump regimes, and natural pit outflow volumes and chemical interactions.

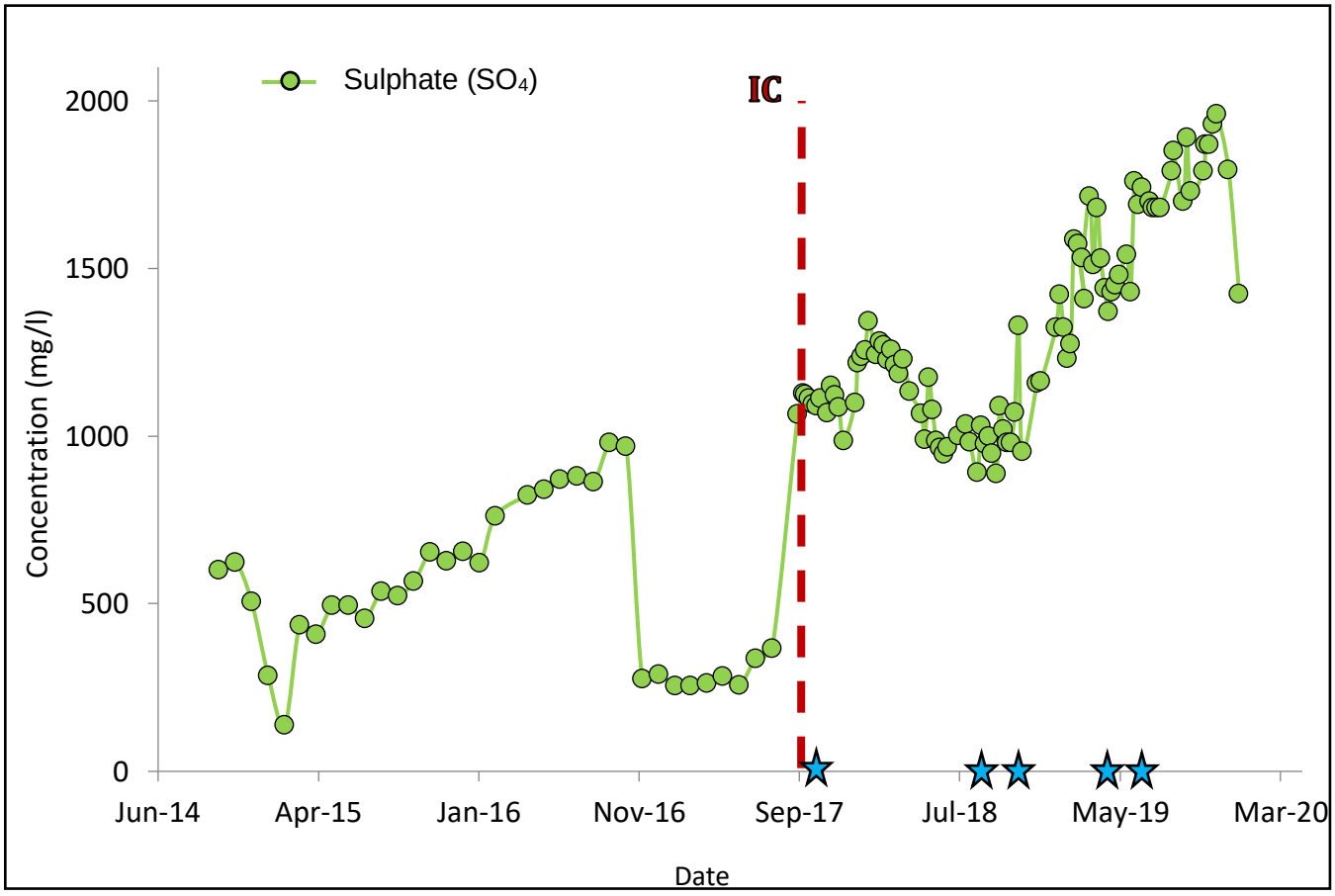


Figure 3.12: Change in sulphate (SO_4) concentrations of irrigation water from October 2014 to March 2020.

No clear distinction can be made in the irrigation water chemistry regarding the effect of rainfall during wetter (summer) and drier (winter) periods on the constituent concentrations. This effect is ruled out as no trend between irrigation water chemistry and rainfall timing and amounts can be identified. Smaller peak and trough changes are therefore attributed to natural variation in the void water chemistry.

The total salts applied to the trial site over all the growing seasons are as follows: 19 034 kg/ha SO_4, 2 709 kg/ha Ca, 1 746 kg/ha Mg, 1 596 kg/ha Na, 431 kg/ha Cl and 450 kg/ha K. A salt mass balance, including the loading rates from the irrigation water as well as the soil's salt contents, will be discussed in Chapter 3.3.5 and 3.3.6.

Groundwater Monitoring
Onsite piezometers

Figure 3.13 shows the changes in the water level of the upstream piezometer (Pz 1) over the trial period. For Pz 1, typical groundwater response curves are seen. The water level increases sharply due to the rainfall experienced in the summer rainy months, after which it drops and remains constant due to low or absent precipitation in the winter months at a shallow groundwater level (±140 to 170 cm below ground level). Due to the piezometers monitoring shallow groundwater, there is very little to no delay or lag in the response time of the water level to precipitation events. Figure 3.14 shows the changes in the water level of the downstream piezometer (Pz 2) over the project period. The groundwater response is similar to that for Pz 1. The perched water table seen in these piezometers is due to their location within waterlogged soils, the groundwater does not freely and easily drain away due to the soil's clay content. This is also the explanation as to why there is a little to no lag time between rainfall and response in shallow groundwater level.

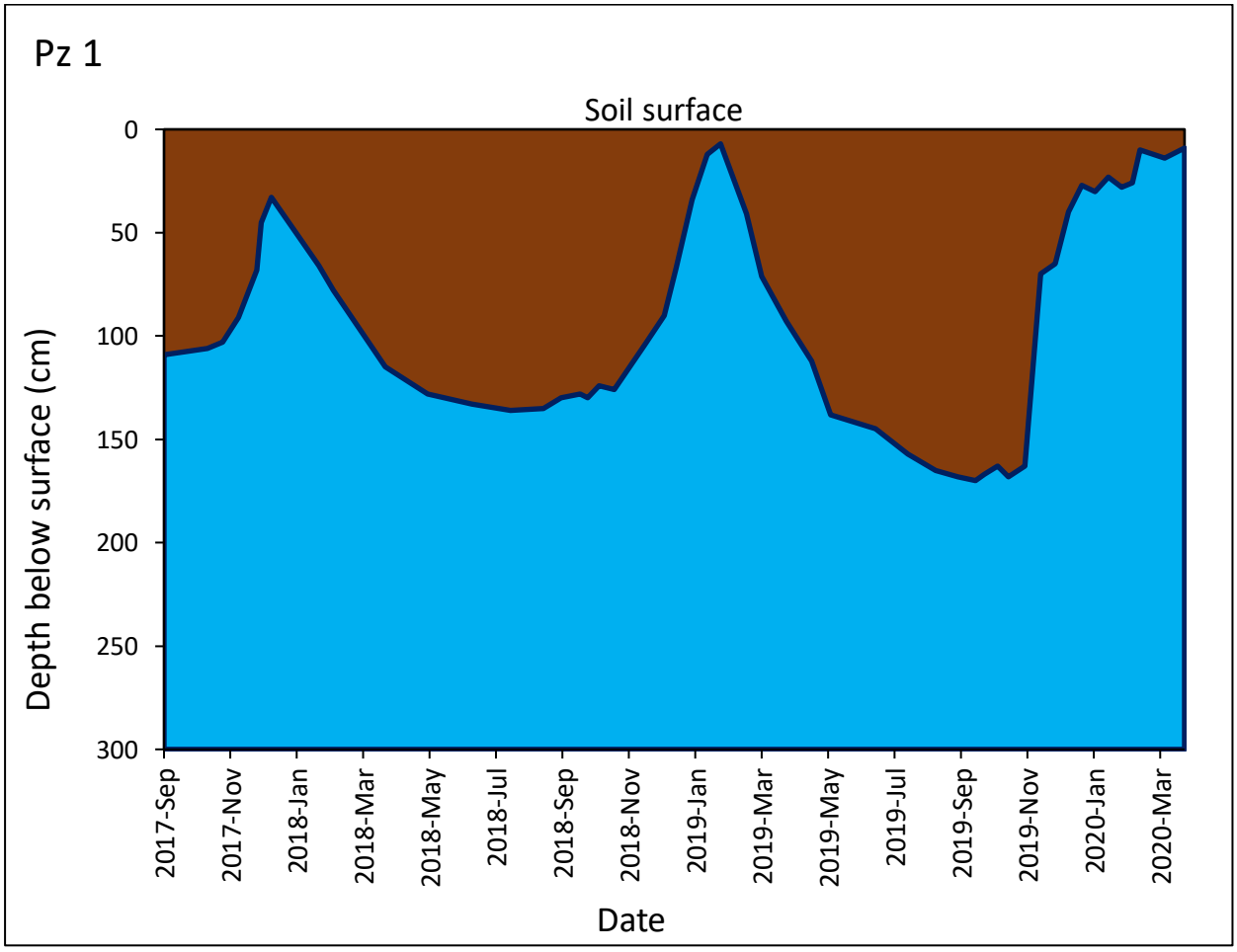


Figure 3.13: Water level (in cm) measured for the upstream shallow piezometer (Pz 1).

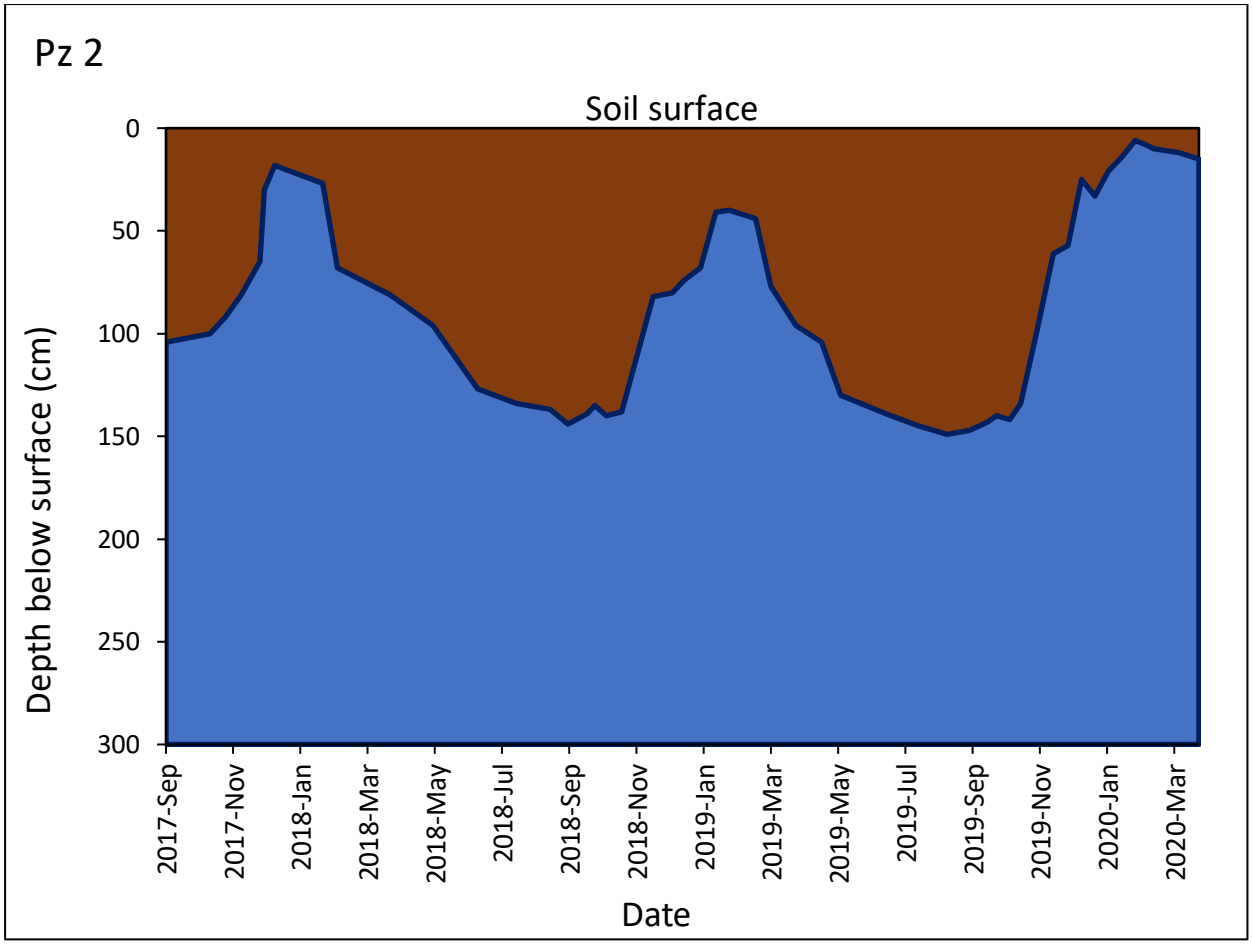


Figure 3.14: Water level (in cm) measured for the upstream shallow piezometer (Pz 2).

A different chemical concentration trend can be seen between the upstream (Pz 1) and downstream (Pz 2) piezometers (Table 3.2). Although these shallow groundwaters are still within normal ranges for the environment in which they are in, the concentrations of the listed constituents were higher at the downstream (Pz 2) piezometer than the upstream (Pz 1) piezometer. This can possibly be attributed to the acid surface runoff and water seepage from the discard dump, situated slightly west of this piezometer.

The eroded slopes of the coal stockpile situated next to the unmined field, provides an indication of the reaction between the discard dump material and rainwater, producing acid mine water runoff. The acid runoff is translocated laterally towards the topographically low point, expressed as a wetland, flowing into and through this, directly towards the western side of the dryland maize. The grab water sample from the seasonal acid water runoff near the downstream (Pz 2) piezometer, has high concentrations of all listed constituents as well as a lower pH (Table 3.2). The ponding acid water runoff, combined with subsurface seepage from the discard dump, is the probable cause in the altered, higher constituent concentrations and poorer water quality expressed in the downstream piezometer (Pz 2).

Table 3.2: Summary of average elemental concentrations observed at the two piezometers over the three irrigation seasons, as well as the discard dump acid water runoff.

Unit	Parameter	Piezometer						Discard dump acid runoff water (Jan 2019)
		Upstream Pz 1			Downstream Pz 2			
		2017/18	2018/19	2019/20	2017/18	2018/19	2019/20	
	pH	6.5	6.9	6.3	5.9	6.1	5.7	4.3
	EC (mS/m)	63	60	78	174	160	293	331
	Suspended solids	20	25	13	45	57	61	87
mg/ℓ	**TDS**	130	112	141	378	446	568	613
	K	8	2.3	1.8	10	5.3	3.1	4.7
	Mg	23	22.5	23	30	25	55	69
	Ca	18	25	34	19	33	87	107
	P	0	0.01	0.4	0	0.08	1.4	1.3
	SO_4	86	52	72	328	202	204	279
	Na	45	19	24	328	285	252	261
	Cl	229	64	45	435	313	289	294
	Fe	0	0.02	0.02	0	0.04	0.7	1.2
	Al	0	0	0	0	0.03	0.1	0.3
	Mn	0	0	0	0	0	0.5	0.8
	Pb	0	0	0	0	0	0.02	0.04
	Zn	0	0.015	0.02	0	0.02	0.05	0.06

Onsite boreholes

The temporal water quality graphs for boreholes 1, 2 and 3 can be found in Appendix A (Figure A1 – A3). The temporal water quality graphs of the shallow downstream borehole BH04 are shown in Figure 3.15. This borehole was chosen as it was representative of the onsite groundwater environment, considering data from all four onsite boreholes.

The water quality trend of the shallow and deep boreholes is similar. The deeper boreholes (BH01 & BH03) have greater concentrations of all elements as they are seated within the fractured metamorphosed shale, thereby receiving mostly uninfluenced groundwater, whereas the shallower boreholes (BH02 & BH04) experience greater surface effects (such as rainfall dilution) as they are seated within the shallower, weathered rock zone, therefore having a lesser concentration of all elements. All boreholes show similar chemical signatures, dominated by sodium chloride, indicative of the effect the *in-situ* geology has on natural groundwater chemistry. The boreholes show a clear seasonality trend in the chemical constituents' concentrations. During drier, winter months, increased electrical conductivity, sodium, chloride, and sulphate concentrations are seen, while during wetter, summer months, decreased values of the stated constituents are observed. The onsite boreholes show no clear influence from the mine-affected irrigation practices.

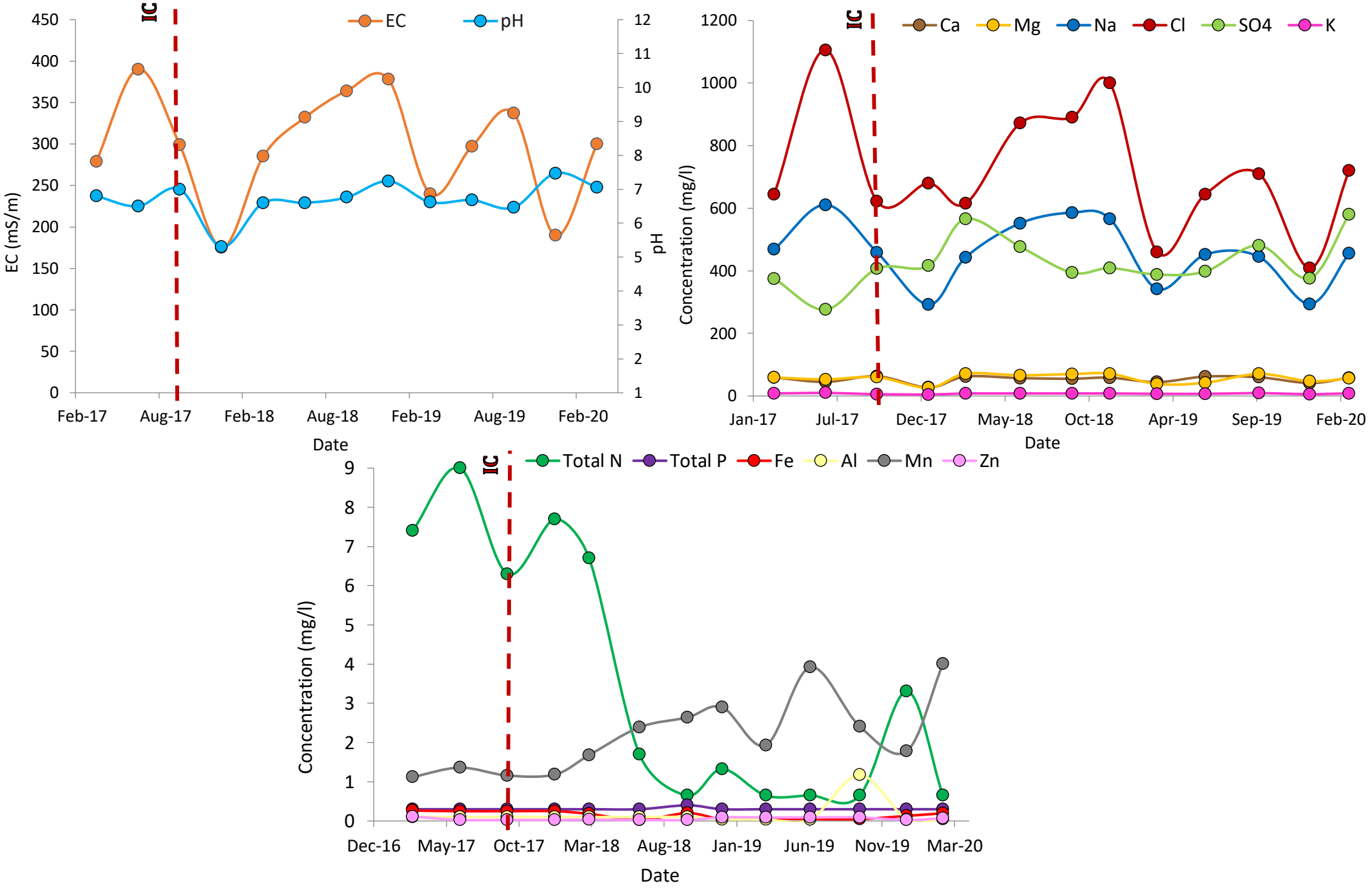


Figure 3.15: Temporal water quality graphs for the onsite, shallow borehole, BH04.

Downstream surface water monitoring

The red dotted line, annotated IC (Figure 3.16 & Figure 3.17), is the irrigation commencement date, September 2017. The blue dotted line is the mine's pre-determined sulphate concentration threshold line, set at 640 mg/l. The results of the temporal water chemistry graphs do not indicate any unexpected trends.

The pH remained circumneutral throughout the period of monitoring, fluctuating from a low of 7.2 to a high of 8.1.

The electrical conductivity (EC) saw a steady increase before irrigation commenced to 100 mS/m, followed by a steep drop directly after irrigation commenced to a low of 35 mS/m. The EC then steadily increased over the next two years, peaking at 145 mS/m. The general trend seen in the EC data is during the rainy season (September to February), where the EC either decreases or plateaus. This is likely due to the surface water being diluted by rainwater in the wet periods. During the dry season (March – August) the EC values increase as there is limited dilution, and therefore represent the natural groundwater chemistry from which the dam is partly filled, and the concentration of constituents within the remaining summer seasons water.

The major cations showed no significant fluctuations in concentration over the 3-year period, remaining at an almost constant concentration throughout.

The sulphate concentration over the 3-year period saw some relative fluctuations. After irrigation commenced, the concentration dropped from 450 mg/L to 70 mg/L, thereafter for the next 1.5 years a steady increase in concentration to 630 mg/L was evident. The continuous water quality monitoring has demonstrated that the sulphate threshold level, of 640 mg/L, although close, was not reached, and no stop-start irrigation action was required. A decrease in concentration in December of 2019, saw a stabilization of the concentration at 380 mg/L.

The results of the water chemistry monitoring do not indicate any definite influence from just the trial site's irrigation. Other potential pollutant factors may be the mines discard dump, coal wash plant, the road and other farmlands are in between the irrigated trial and the surface monitoring point, and these all may influence both the runoff and groundwater water quality intercepted by this dam.

The surface water body is fed by the farmers borehole and rainwater during the rainy season. The observed changes in constituent concentrations can therefore most likely be attributed to natural changes in ground and rainwater water chemistry, and less likely due to irrigation on the trial site. It is also noted that quantification of the extent of the discard dump's pollution plume will provide a better understanding as to its effect on the downstream monitoring point.

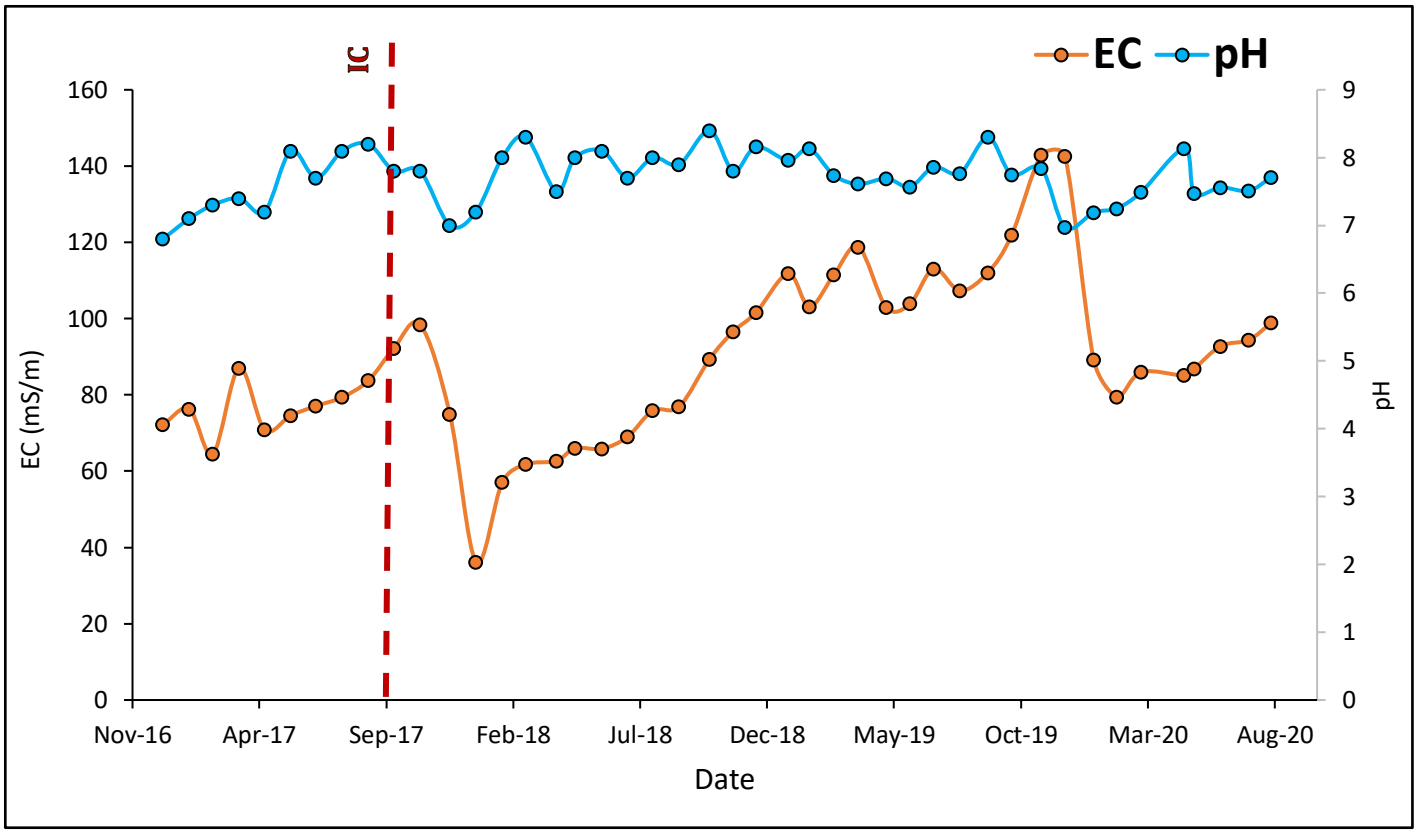


Figure 3.16: Changes in the pH and electrical conductivity (mS/m) in Beestepan Dam from December 2016 to August 2020.

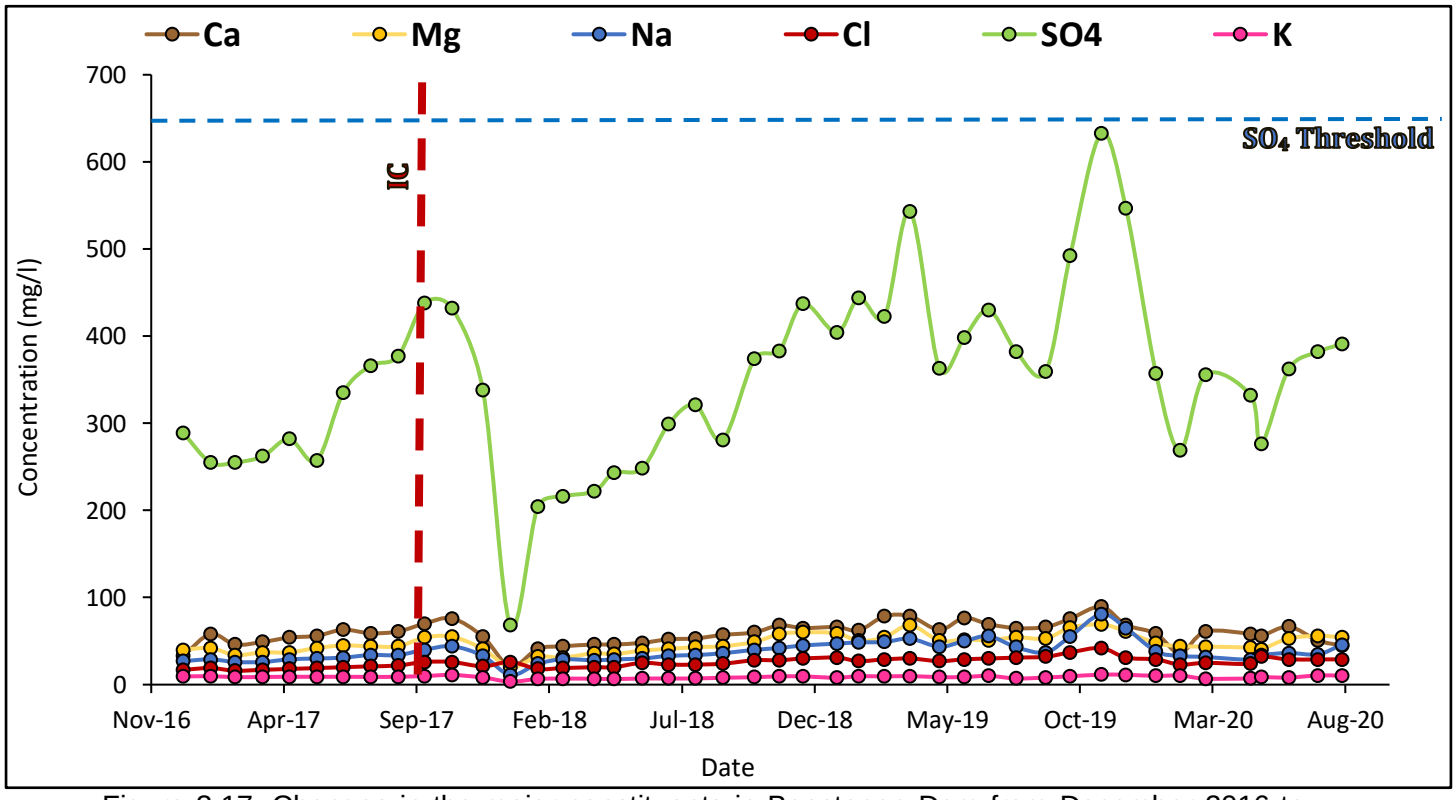


Figure 3.17: Changes in the major constituents in Beestepan Dam from December 2016 to August 2020. The horizontal dashed blue line represents the established threshold value for sulphate.

Stable Isotopes

The results of the stable isotope samples (Figure 3.18) showed two distinct trends, one linear series for groundwater (dotted orange line) and a second cluster series for waters exposed to the atmosphere (dotted blue line).

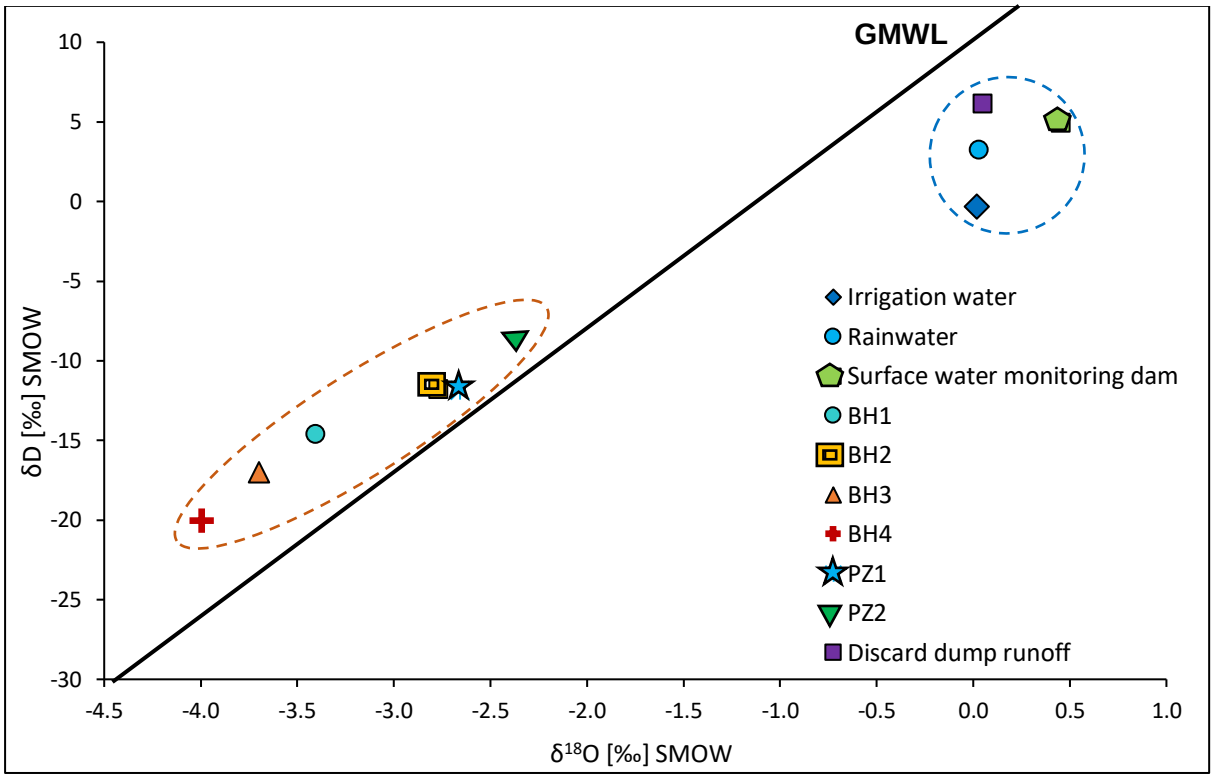


Figure 3.18: Stable isotope data relative to the global meteoric water line (GMWL) (Craig, 1961).

Both the irrigation and surface water monitoring dam are surface waters. These waters have been stored in open dams and are both exposed to large amounts of meteoric water recharge and evaporation. Both these samples plot in the light isotope-depleted region, and plot on the right of the GMWL (Craig, 1961).

Rainfall water is also enriched in light isotopes, providing evidence that both surface water points are rainfed or experience some degree of rainwater recharge. Both surface water samples can also be influenced by runoff recharge (Abiye et al., 2015). The discard dumps' runoff water is rainwater that interacts with the sulphate rich discard material and forms acidic runoff water. This is the reason the discard dump runoff water has a similar isotopic signature to rainwater. No clear distinction can be made between the isotopic signatures of the rainwater, the discard dump water, irrigation water and the downstream surface water monitoring dam.

The groundwater samples show less enrichment in lighter isotopes, indicative that these waters are not exposed to high rates of evaporation (Abiye et al., 2015; Akwensioge et al., 2019; Butler et al., 2018). The groundwater's isotopic signature is due to base flow, or the geological formations signature, and not rainfall recharge. The irrigation water is thus not from the same source water as the groundwater, as their isotopic signatures are very different. With a fair amount of confidence, it can be concluded that the irrigation water is not interacting with the groundwater in the near vicinity.

It is noted that the stable isotope analyses are a conservative approach to contaminant studies. Factors such as dilution, dissolution, mineral deposition, chemical reactions, and cation exchange play a role in the accuracy of isotope results. It is also highlighted that the impact and interaction of the discard dumps' acidic runoff, located directly next to the irrigation trial, are unknown and have not been fully quantified, as this is on the mine's property. Interaction from the direct runoff and groundwater seepage may play a role in the results of these isotope tracer tests.

Further recommendations for isotope tracer tests at the pivot include further seasonal interaction studies to assess and identify if any further interactions occur. Any additional water input into the system should be identified and samples analysed to increase the confidence in the findings of this study.

Water quality monitoring summary

The Piper diagram indicates the hydrofacies in which each water sample falls. This provides an indication as to the chemical signature, and dominant constituents in each water resource (Figure 3.19). A comparison of the hydrofacies shows a clustering of the shallow and deep groundwater points, while the surface waters show no predominant cluster. Below is a further description of the possible hydrological behavior, underlying physical and chemical processes and subsequent facies distribution.

The irrigation water has a calcium sulphate hydrofacies, confirming this to be a gypsiferous mine water quality (Ca + SO_4 dominated water). This is in line with expected mine-affected water qualities for coal mining in this area. The surface monitoring dam also has a calcium sulphate hydrofacies but has greater concentrations of chloride, calcium and magnesium. In combination with the previous sections results, it can with some certainty be said that the downstream surface water monitoring point does not show signs of being influenced by the mine-affected irrigation water.

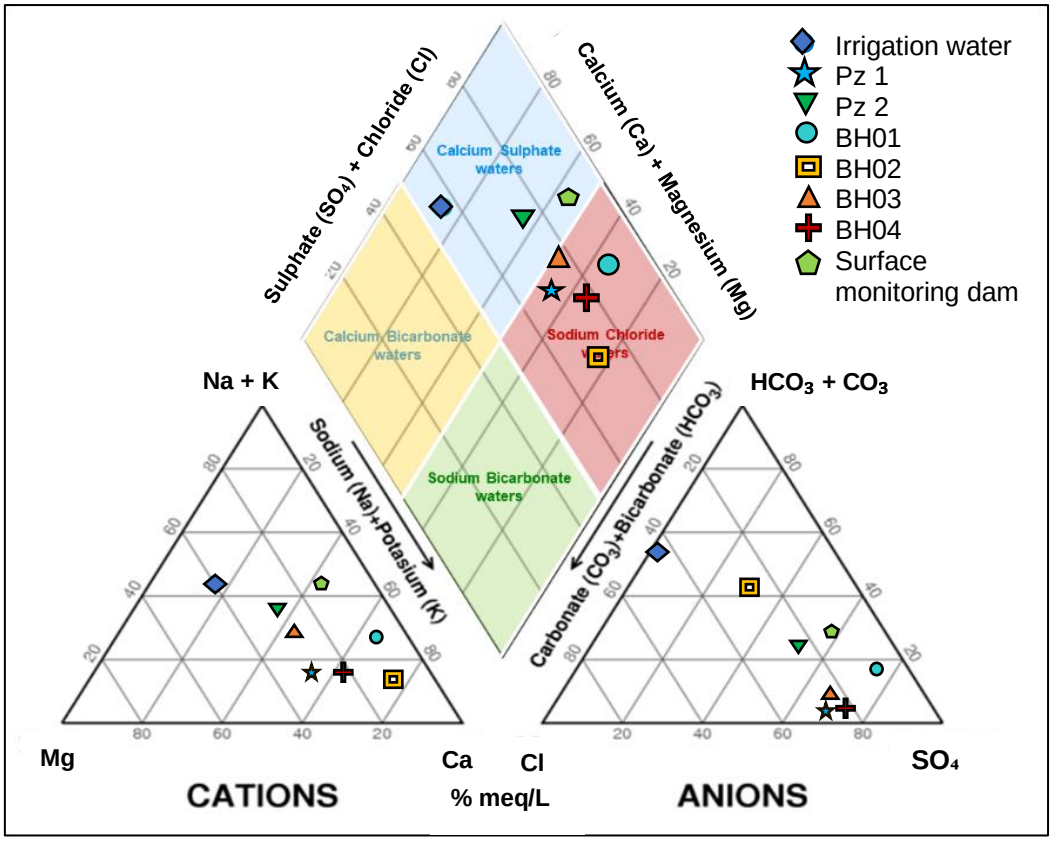


Figure 3.19: Piper diagram of the on-site monitoring piezometers, boreholes, irrigation water and downstream surface water monitoring dam for the unmined trial site.

The onsite boreholes (BH01 – 04) show a similar groundwater chemical signature, mainly sodium chloride-dominated water, indicative of the Ecca Group's metamorphosed shales, mudstones, and sandstones in which these boreholes are drilled. Borehole 03 is 30 metres deep, and has a borderline Calcium Sulphate – Sodium Chloride chemical signature and is not solely dominated by Sodium-Chloride like the three other boreholes. One reason for this, is the vertical and lateral extent the plume the discard dump creates. The wetland and mine dug trenches, which lie between the discard dump and the trial's boreholes, act as boundary conditions, with higher retardation coefficients, limiting the lateral extent of the plume. The deeper borehole (BH3), perhaps intercepts a small part of the vertical plume's extent, influencing the increased calcium-sulphate hydrofacies tendency. The shallower borehole (BH04 – 10 metres deep) perhaps has less of an influence from the discard plume and is thus less influenced by the calcium sulphate influx.

The upstream piezometer (Pz 1), has a sodium chloride hydrofacies, similar to the deeper boreholes, and has a solute signature indicative of the expected underlying geology's influence on the groundwater. The downstream piezometer (Pz 2), has a calcium sulphate hydrofacies, and has higher concentrations of calcium and magnesium than Pz 1. This is

perhaps attributed to the intermittent acid runoff which pools in the near vicinity of Pz 2, thereby also increasing the calcium-sulphate hydrofacies tendency.

Using a Wilcox diagram (Wilcox, 1948), a widely used, rapid and simple irrigation water quality assessment tool, comparisons between water sources can be made. This diagram provides an indication as to the approximate suitability of each water source for use as irrigation water, looking at the electrical conductivity, and sodium absorption ratio (SAR) and its propensity to reduce soil permeability. It is largely used for a determination of a water's potential for salinization, sodification and soil degradation. Figure 3.20 displays the plot of the hazard classes of each sample. Table 3.3 indicates the sodium alkalinity and salinity hazards, and their associated descriptions.

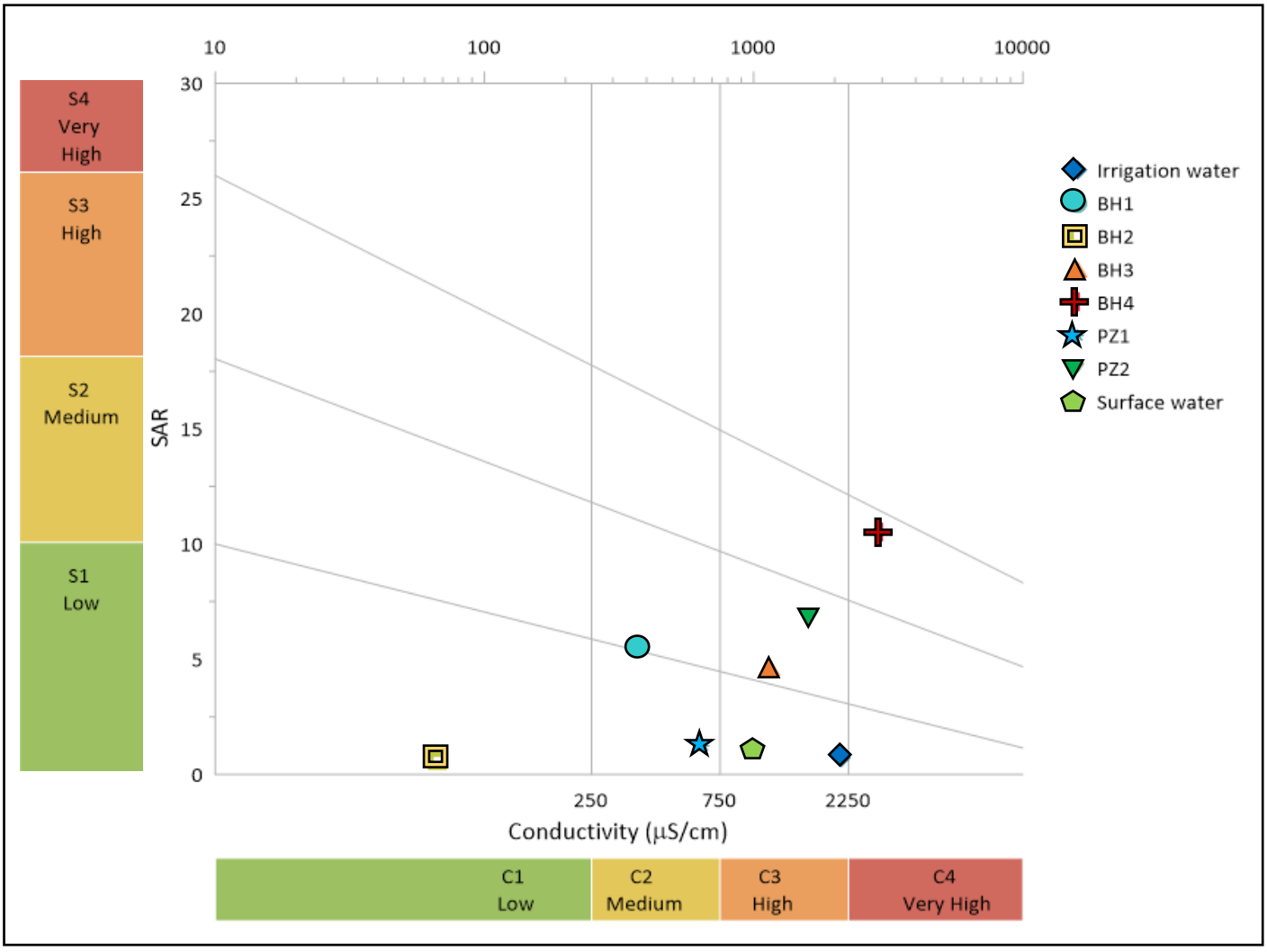


Figure 3.20: Wilcox diagram of the on-site monitoring piezometers, boreholes, irrigation water and downstream surface water monitoring dam used for irrigation water quality assessment.

Table 3.3: Summary of sodium alkalinity and salinity hazards for all water monitoring points for the unmined trial site (Wilcox, 1948; Ahamed et al. 2013).

Monitoring Point	Salinity – Sodium class	Description
Irrigation water	C3 – S1	Could only be used to irrigate certain semi-tolerant crops.
BH01	C2 – S2	Irrigation on most soil types, with little to moderate danger of the development of harmful levels of exchangeable sodium.
BH02	C1 – S1	Irrigation on all types of soil, with little danger of the development of harmful levels of exchangeable sodium.
BH03	C3 – S2	Satisfactory for plants having moderate salt tolerance, on soils of moderate permeability with leaching.
BH04	C4 – S3	Classified as doubtful for irrigation usage. Irrigation on all soil types not recommended, with great danger of the development of harmful levels of exchangeable sodium.
Pz1	C2 – S1	Irrigation on all types of soil, with little danger of the development of harmful levels of exchangeable sodium.
Pz2	C3 – S2	Satisfactory for plants having moderate salt tolerance, on soils of moderate permeability with leaching.
Surface water	C3 – S1	Could only be used to irrigate certain semi-tolerant crops.

Analysis of the different water sources shows the groundwater is of “good” quality for irrigation use, according to the classification. The surface water, borehole 3, piezometer 2 and the gypsiferous mine water can be used to irrigate certain crops, but are classified as having doubtful to permissible water quality due to their higher salinity categories. Although this classification does not provide a comprehensive rule of usability of irrigation water based on its quality, it provides a simple categorisation as to the water types applicability for irrigation use.

3.3.3 Crop Monitoring

Crop Growth Parameters

Knowing the phenological growth stage (Figure 3.21) of the crop helps keep track of overall crop development. This is very important information when modelling crop growth and production. Pictures of the crop have been incorporated into this diagram from various seasons to indicate the visual status of the maize crop.

The average plant height was monitored for the irrigated and dryland maize throughout the three growing seasons. The plant height curves follow the typical maize sigmoidal growth pattern (Figure 3.22). There is an increase in plant height, following an exponential growth curve, between planting date (0) and 90 days into the growing season. This rapid growth period is consistent with the vegetative growth phases of the crop during this time. A plateau in plant height is observed at ± 90 -100 days into the growing season, as this determinate crop reaches the reproductive growth stage and assimilates are directed away from foliage growth and stem elongation and into cob development and grain filling. A slight decrease in plant height was observed over all three growing seasons as physiological maturity was reached and upon commencement of field crop drying.

During the 2018/19 growing season, severe hail damage was experienced about 100 days into the growing season. This is reflected in the sharp decrease in crop stand area, leaf defoliation and plant height.

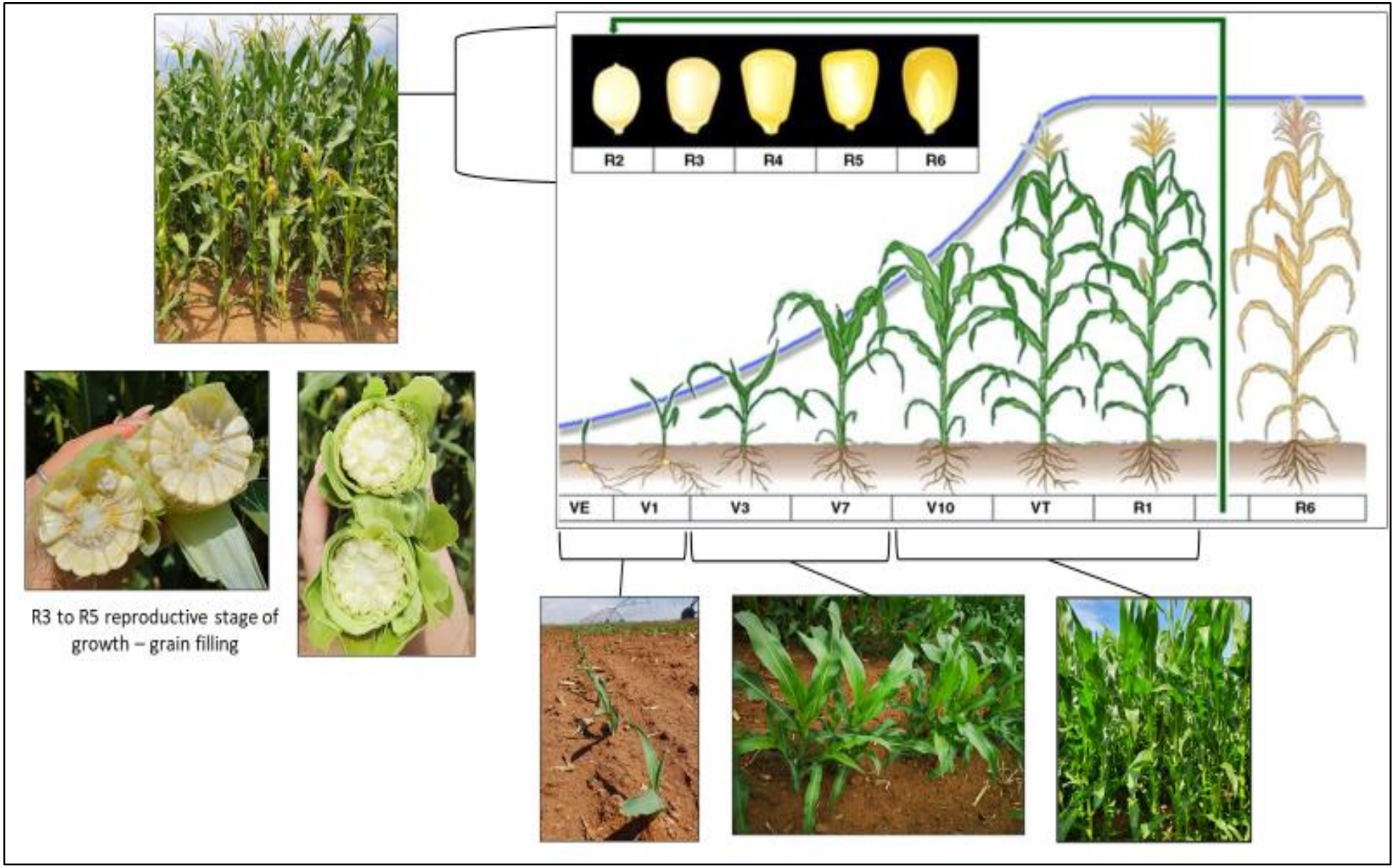


Figure 3.21: Phenological growth stages and photographs of the maize crop grown at the unmined trial site in Arnot (Adapted from He et al. (2010)).
(VE = Emergence; V1-VT = Vegetative Phases; R1-R6 = Reproductive Phases)

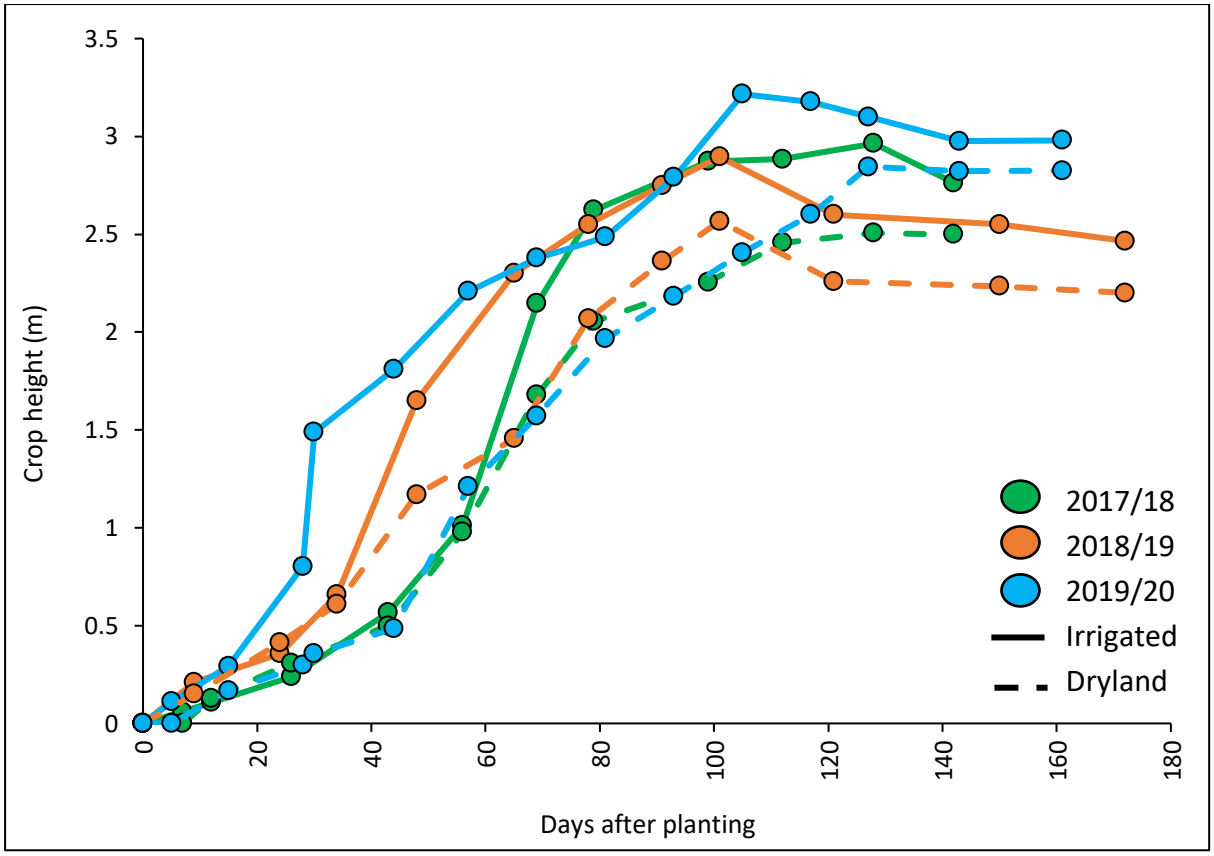


Figure 3.22: White maize crop height measured for the irrigated (solid lines) and dryland (dotted lines) portions of the unmined trial site.

The LAI curves (Figure 3.23) all follow the expected general sigmoidal trend for a maize crop for all three growing seasons. During the 2018/19 growing season, hail damage was experienced about 100 days into the season. This is reflected in the sharp decrease at about 100 days in LAI (orange curves) due to loss in the photosynthetically active area of the crop.

The following general trend was seen for both the dryland and irrigated maize on the trial site: A rapid canopy development within the first 30 to 40 days after emergence, as the maize develops vegetatively and sharply increases its leaf area, leaf number and stem elongation. A peak LAI of 4.5 to 5.5 $m^2 m^{-2}$ at about100 days after emergence is observed, when the maize crop reaches its reproductive growth stages. With maize being a determinate crop, once it has reached the tasselling reproductive stage (VT), no further vegetative growth occurs. As kernel development and filling now begins (R1 – R6), the LAI of the crop plateaus. Hereafter, a decline in LAI is observed, when physiological maturity is reached, due to leaf senesce and the crop drying out in-field before harvest.

The LAI of the mine water irrigated maize, measured over the three-year period, was higher than the dryland LAI. The 2017/18 season exhibited the lowest LAI peak (±4.2 $m^2 m^{-2}$) and the 2019/20 season the highest (±5.4 $m^2 m^{-2}$). If it had not been for the hail damage, the 2018/19

season was on track to have the highest LAI peak, and it was also the season with the highest irrigation application.

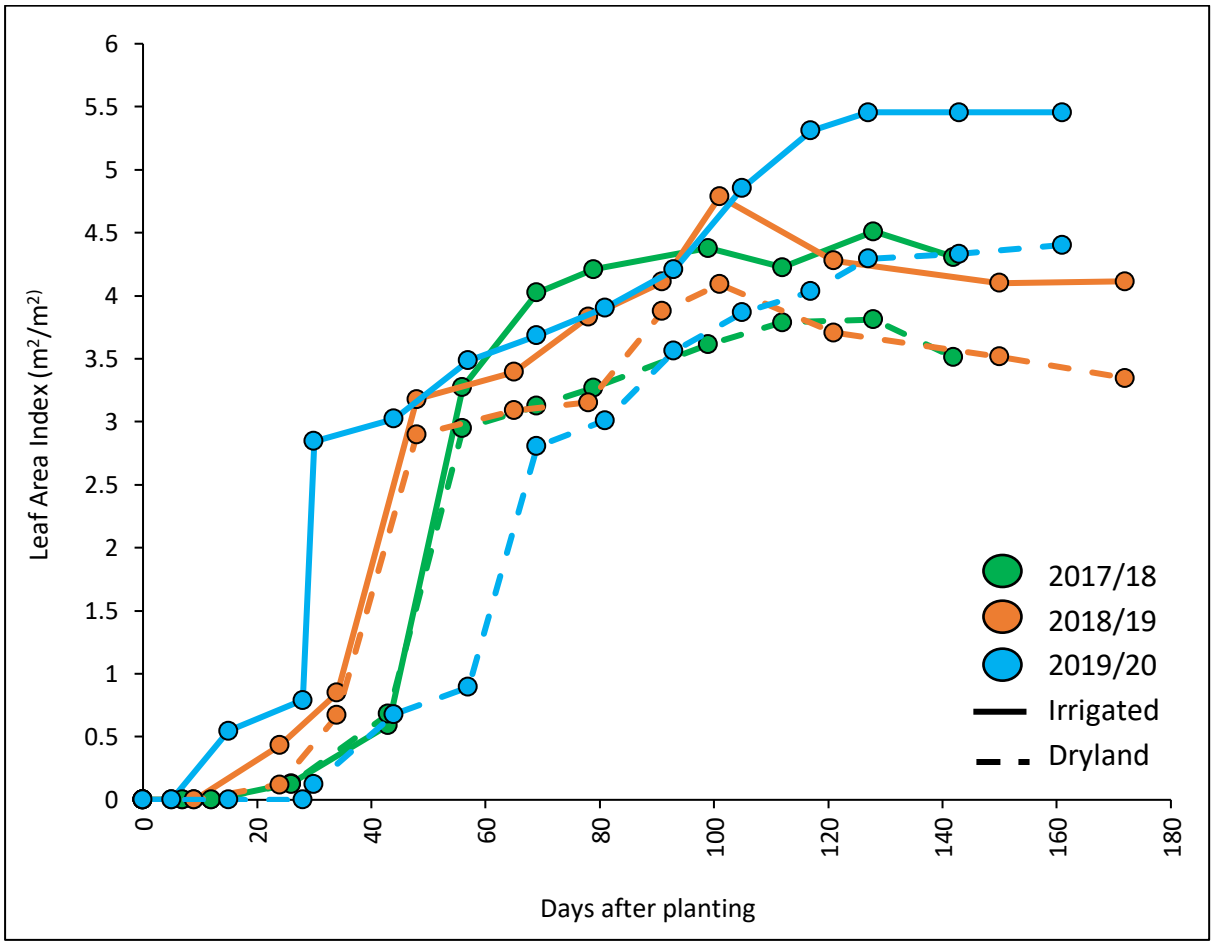


Figure 3.23: Average white maize leaf area index of irrigated (solid lines) and dryland (dotted lines) portions of the unmined trial site over the three growing seasons.

The FI_{PAR} curves (Figure 3.24) also all follow the general sigmoidal trend for a maize crop for all three growing seasons. The FI curves show less of a difference between irrigated and dryland when compared to the greater differences observed in plant height and LAI. The same curve shape, sigmoidal, for both irrigated and dryland is indicative that both have the same growth patterns and go through the same phenological stages. The smaller differences in FI between the two can be attributed to the irrigated maize being planted 15 – 20 days earlier than the dryland. The irrigated maize has a higher LAI which results in greater FI values than that of the dryland maize.

The FI values increase with an increase in plant height and LAI. As the maize plant grows and matures physiologically, so does the plant stand size and plant material denseness increase, until senescence is reached and a decline is seen. There is a direct relationship between incoming solar radiation (calculated as FI_{PAR}) and the plant growth and maize crop canopy density.

At the end of the vegetative stages (V15/16 – VT) and throughout the reproductive stages (R1 – R6) the FI plateaus and remains fairly stable. At this plateau, for the irrigated maize the following average FI_{PAR} were measured: 0.93 for 2019/20; 0.77 for 2018/19 and 0.85 for 2017/18. The maize crop's FI remains constant, in the reproductive growth stages, due to the stagnation of the growth of the total aboveground biomass.

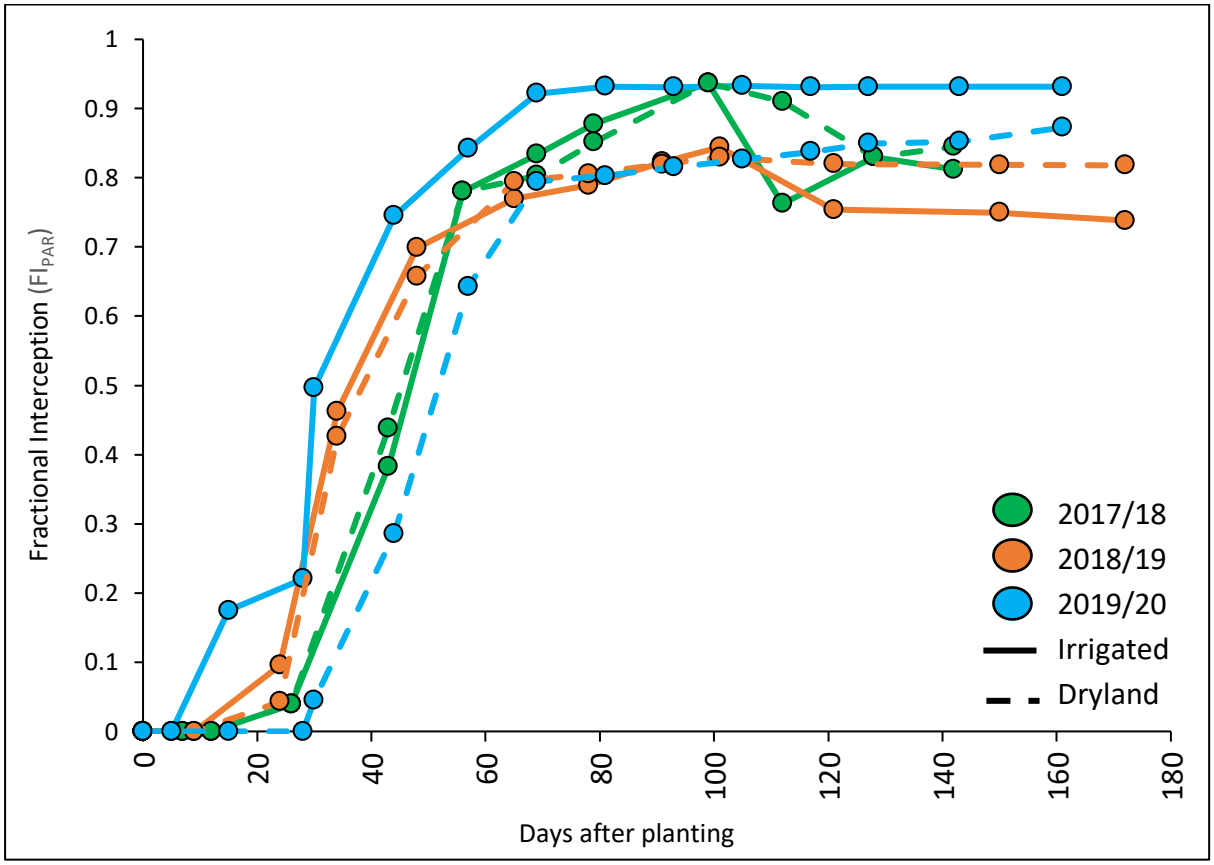


Figure 3.24: Average fractional interception of photosynthetically active radiation of irrigated (solid line) and dryland (dotted line) white maize on the unmined trial site over the three growing seasons.

The irrigated maize had a supplemented water and nutrient supply, both critical to crop growth. The differences in planting date (about 15 – 20 days later for dryland) as well as the additional water supply, between the dryland and irrigated maize had an observable impact on the selected crop growth parameters. It is seen throughout the results of the crop growth parameters, that the irrigated maize had greater values for plant height, LAI and FI than the dryland crop. It can therefore be expected that the yields in the following section will reflect similar trends.

It is also noted that the mine water irrigated maize showed no clear indication of hinderance to the crop growth parameters measured but instead only expedited plant growth when compared to the control (dryland) maize.

Crop yield determination

Table 3.4 gives a full summary of the yields, TDM, HI and average cob length for the three white maize irrigation growing seasons. The Total above-ground biomass or total dry mass (TDM), provides insight into the effect of mine water irrigation on crop production and yield. The TDM includes stalks, leaves, and cob mass, and yield is grain mass alone. These measurements are indicative of the effect of mine water irrigation on white maize production and economic performance.

Table 3.4: Summary of yields, total dry mass, Harvest Index (HI) and average cob length observed at the end of each growing season at the unmined land trial site.

	2016/17	2017/18		2018/19 *Hail damage		2019/20	
	Dryland	Irrigated	Dryland	Irrigated	Dryland	Irrigated	Dryland
Yield (ton/ha)	4,1	13,5	4,5	11,6	5,5	14,3	4,9
TDM (ton/ha)	-	29,6	18,1	25,1	16,6	37,9	27,8
HI (%)	-	55,5	40,2	37,2	27,9	56,1	42,8
Average cob length (cm)	-	19,5	17	19,5	17,2	21	17

The grain yields of the irrigated crop are almost treble those of the dryland crop each growing season. This demonstrates the benefit irrigation can have on crop production.

Due to the field conditions, surface flooding and waterlogging on the western border of the trial, a decrease in the dryland maize yield occurred, as the yield potential of that soil was reduced. For each year's dryland maize yield, the samples on the western border were 1 - 1.5 ton/ha less than the yield of the dryland maize on the eastern border. An average between the two growing areas were calculated, with a low of 4.5 ton/ha achieved in the 2017/18 season, and a high of 5.5 ton/ha achieved in the 2018/19 season. Even though hail damage was experienced at the trial during the 2018/2019 season, the dryland maize still had a higher yield. Due to the about 20-day delay in planting, the dryland maize's yield was not as affected by the hail, as it still had a period of vegetative growth before the critical reproductive growth period was reached, unlike the irrigated maize. The irrigated maize in the 2018/2019 season saw an average loss of around 2 ton/ha, the hail damage was experienced at the silking and blistering stages (R1 & R2), and therefore would have slowed the kernel development, resulting the lower yield obtained.

Approximately 45% of the above-ground dry biomass at harvest is partitioned into the maize grain under non-stress conditions (the so-called Harvest Index - HI). If the HI is much lower than 45%, it is indicative of stress (Unkovich et al., 2010). Under ideal growing conditions,

without water stress, the rate of dry matter accumulation from V7 to V16 should increase exponentially until physiological maturity when there will be a sharp decline in the rate of dry matter accumulation as the crop matures. This is associated with functional and visual leaf senescence. This time period is critical to maintaining good yields, as all assimilates are partitioned to grain filling from silking to maturity. The HI for the all three growing seasons for the dryland maize, were all below 45%. This is indicative that water stress conditions were experienced each year by the dryland crop. This is a notable difference to the irrigated maize yield results, and the production advantage of irrigating with gypsiferous mine-affected waters. Considering the average length of the cobs, a 2 to 4 cm difference was measured between the irrigated and dryland maize.

Economic Analysis

The values reported in Table 3.5 are yield and profit/loss estimates of the white maize crop for the three growing seasons. A full summary of the fertilizer regime and costings, annual costs of cultivation, harvest, transport, storage, and labour can be seen in Appendix A, Table A.3 – A.7. These tables show the breakdown of the agronomic inputs and some of the budgeted costs to produce white maize during the three growing seasons at the unmined trial site. It is also noted that the irrigation cost would usually include another R5000 for pumping costs, the neighbouring Colliery covered this expense. It is noted that the price of electricity will influence all input costs.

The total fertilizers added before, during and after planting per hectare each season amounted to 290 kg nitrogen, 40 kg phosphorus, 64 kg potassium, and 10 kg sulphur. The farmer chose to add a nitrogen (urea) top dressing after crop emergence. Herbicides and pesticides were applied via full coverage tractor drawn sprayers prior to planting. The reasons for use of the crop protection chemicals were for the control of annual broadleaf weeds, grasses, yellow nutsedge, cutworm, stem and stalk borers, and their larvae.

Table 3.5: Average tonnage, cost per hectare, maize price, profit or loss per hectare with and without pumping costs for each white maize cropping season.

	2016/17	2017/18		2018/19		2019/20	
	Dryland	Irrigated	Dryland	Irrigated	Dryland	Irrigated	Dryland
Yield (ton/ha)	4.1	13.5	4.5	11.6	5.5	14.3	4.9
Cost per ha	R9 100	R18 000	R16 000	R18 770	R16 800	R19 980	R17 900
SAFEX maize price/ton	R1 966	R2 103		R2 910		R2 450	
Profit/loss per ha (no pumping costs)	R1 039	R10 390	R6 540	R12 000	R4 600	R15 055	R5 900
Profit/loss per ha (with pumping costs)	R1 039	R5 390	R6 540	R7 000	R4 600	R10 300	R5 900

This demonstrates that dry land agronomic crop production can be extremely risky, and irrigation can usually be expected to stabilise yields, but cannot mitigate against low commodity prices and high input costs. Irrigation can certainly be used to cost-effectively manage large volumes of surplus mine water, but this will definitely be a more resilient option if mines are able to assist growers by, for example, agreeing to cover pumping costs. This is a reasonable request, considering that the liability of managing the water rests with the mine, and alternative treatment options can be very expensive.

The yield and profit results over these three seasons clearly demonstrates the great value irrigation with mine-affected water can present to the agricultural industry, as well as the water management of mines in South Africa.

3.3.4 Food and fodder analyses

The full chemical analyses of all plant parts, over the three growing seasons, are presented in Appendix A, Table A.8. The values reported in Table 3.6 are the average concentrations of constituents analysed for in the irrigated and dryland maize grain, in comparison to selected national and international food safety thresholds. The five elements listed are the stated elements of concern when looking at food safety in southern Africa. A few other country's thresholds have been included for international references. Most elements are partitioned into the leaves and stems of the plant, with very little partitioned into the grain (Table A.8).

Table 3.6: National and international thresholds for grain food safety.

Element	Yearly white maize grain concentration						South African	China	European Union	Ireland
	Irrigated			Dryland						
	2017/2018	2018/2019	2019/2020	2017/2018	2018/2019	2019/2020		CEPA (2018)		
	ppm or mg/kg									
As	0.09	0.1	0.08	0.09	0.09	0.09	-	0.5	-	-
Cd	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.1	0.1	0.1	0.1
Zn	0.157	0.17	0.26	0.143	0.125	0.2	-	50	-	-
Pb	0.005	0.006	0.006	0.006	0.006	0.006	0.2	0.2	0.2	0.1
Hg	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	-	0.02	-	-

According to these selected food safety guidelines, the irrigated and dryland grain concentrations fall well below the stated national and international thresholds. There are no notable differences between the irrigated and dryland concentrations in grain quality over the three seasons, which therefore indicates the safety of irrigating with this circum-neutral mine-affected water.

Not only can the grain be used for food, but grain and other plant parts may also be used for feed for livestock. Identifying the national chemical threshold limits set out for feed is thus just as important, as the producer will want to know whether or not the crop is safe for animal consumption. From safe feed production to production hygiene, if producers know the national limits for feed safety, monitoring a grain's constituent concentrations can form a crucial part of their quality control plan for the use, selling and manufacturing of this raw material.

If a producer wants to have a feed registered or to supply raw materials to a feed company, according to Reg. 11.3, in the Fertilisers, Farm Feeds, Agricultural Remedies and Stock Remedies Act 1947 (ACT NO. 36 OF 1947), published by the Department of Agriculture, the produce will be deemed unfit for use if the listed elements and concentrations are exceeded (Table 3.7). Table 3.7 reports the concentrations for specific elements of concern for animal feed, for specific animal species and some specification with regard to developmental stage of certain animals. All blocks highlighted in green in the table, indicate the grain elemental analysis from the trial was below the stated threshold level, and thus deemed not a problem for feed usage.

Nowhere in the regulations is maize singled out and addressed as an individual feed ingredient, and what is therefore reported here, is thus the general maximum allowable element concentrations in feed. Note that the reasoning for the stated concentrations for the different elements in feeds, and growth stages of the animals, is not discussed and is out of the scope of this dissertation. As maize is a grain widely used as a feed ingredient in a variety of different feeds for different animals, all the feed concentration specifications of the Act were included. For the six identified elements, no limits were exceeded, and the analysed maize parts are deemed safe for use as feed.

Table 3.7: National South African guidelines and thresholds of selected elements for feed safety for various animals and their feed consumption.

Element	Feeds type/ specifications	Maximum Content in mg/kg (ppm)*	Yearly white maize grain: concentration of elements (mg/kg)					
			Irrigated			Dryland		
			2017/2018	2018/2019	2019/2020	2017/2018	2018/2019	2019/2020
As	Feed ingredients	2	0.09	0.1	0.08	0.09	0.09	0.09
	Exception of: Hays, straws, Lucerne, roughages and bagasse	4						
	complete farm feeds for fish and complete feeds for animals	6						
Pb	Feed ingredients	10	0.005	0.006	0.006	0.006	0.006	0.006
	Exception of: Green roughages	40						
	Phosphates and calcareous marine algae	15						
	Calcium carbonate	20						
	Yeast	5						
Cu	Feed for free-range meat pigs	25	0.008	0.004	0.004	0.008	0.005	0.003
	Piglets up to 12 weeks	170						
	Other pigs	25						
	Bovine (before start of rumination):							
	-Milk replacers	15						
	-Other complete feeding stuffs	15						
	Other Bovine	35						
	Ovine	15						
	Fish	25						
	Other species	25						
Zn	Feed for free-range meat pigs	90	0.157	0.17	0.26	0.143	0.125	0.2
	Pet animals	250						
	Fish	200						
	Other species	150						

Element	Feeds type/ specifications	Maximum Content in mg/kg (ppm)*	Yearly white maize grain concentration					
			Irrigated			Dryland		
			2017/2018	2018/2019	2019/2020	2017/2018	2018/2019	2019/2020
Hg	Feed ingredients	0.1	0.001	0.001	0.001	0.001	0.001	0.001
	Exception of: ingredients produced by the processing of fish or other marine animals	0.5						
	Complete feeds for dogs and cats	0.4						
	Concentrates/supplements except complementary food for dogs and cats	0.2						
Cd	Ingredients of vegetable origin	1	0.001	0.001	0.001	0.001	0.001	0.001
	Ingredients of animals origin	2						
	Complete farm feeds for cattle, sheep and goats	1						
	Other complete feeds	0.5						
	Other concentrates/ supplements for cattle, sheep and goats	0.5						

*Maximum content (in ppm) is relative to a farm feed with a moisture content of 120 g/kg.

The elemental partitioning within the maize plant over the three growing periods, showed no significant differences between plant parts (grain, stem and leaves) (Figures 3.25 & 3.26). There was little variation and change in chemical constituent concentrations over the three irrigated seasons. The irrigated maize also produced grain, leaf, and stem material of a similar quality, in terms of elemental concentrations, as the dryland (control) maize. From the elemental distribution within the three plant parts, the leaves exhibit far higher concentrations of most elements when compared to the grain and stems. This concurs with normal published partitioning of assimilates in a crop, as the leaves are responsible for the largest amounts of photosynthetic activity, which requires the greatest need for macro and micronutrients.

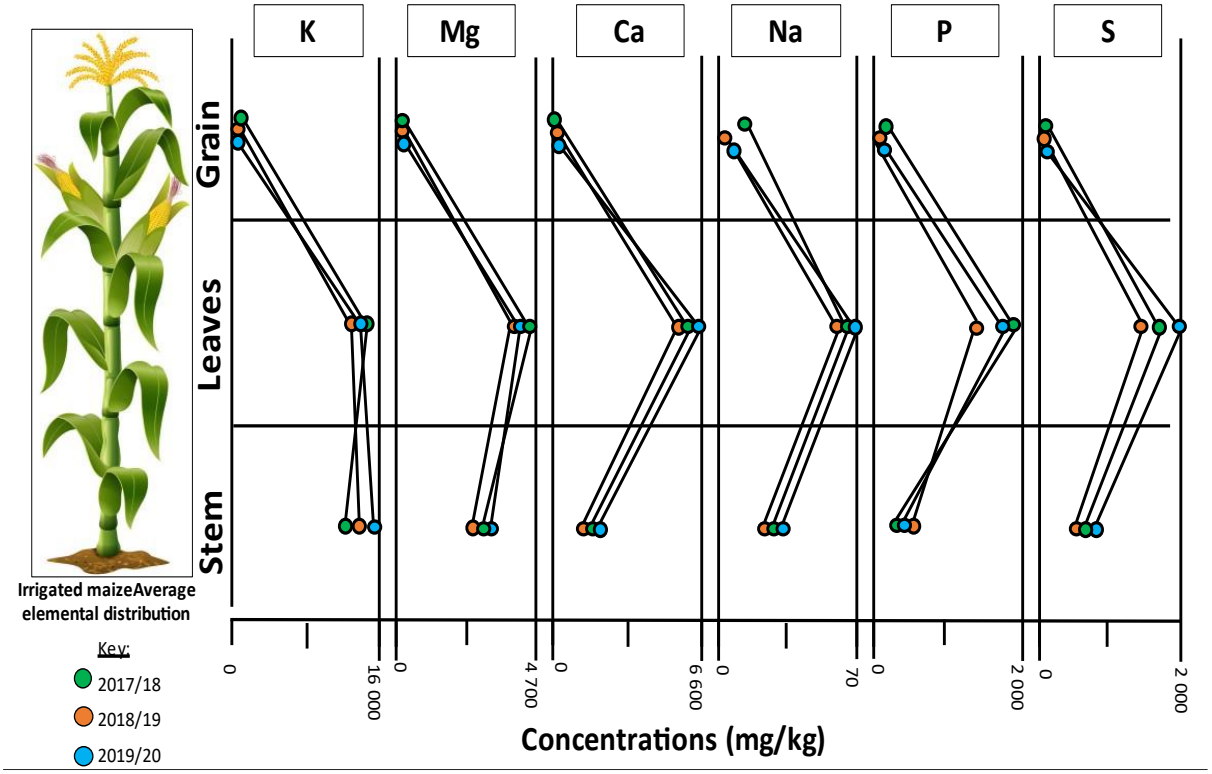


Figure 3.25: Average macro elemental distribution of irrigated white maize plant parts from the unmined trial site.

It is well known that maize is a carbohydrate rich product, that is energy dense (Waters & Sankaran, 2011), but may be classified as a nutrient poor food, as it has very low concentrations of elements present in the edible grain. The results at the unmined trial site confirm that maize has low nutrient concentrations in the grain, but not beyond the normal ranges, and throughout the three growing seasons, neither deficiency nor toxicity symptoms in the maize plants were noted. No relationship could be determined between fertilizer and irrigation amounts and the plant elemental concentrations. This indicates that element bioavailability was therefore not a limiting factor during the uptake and accumulation phases

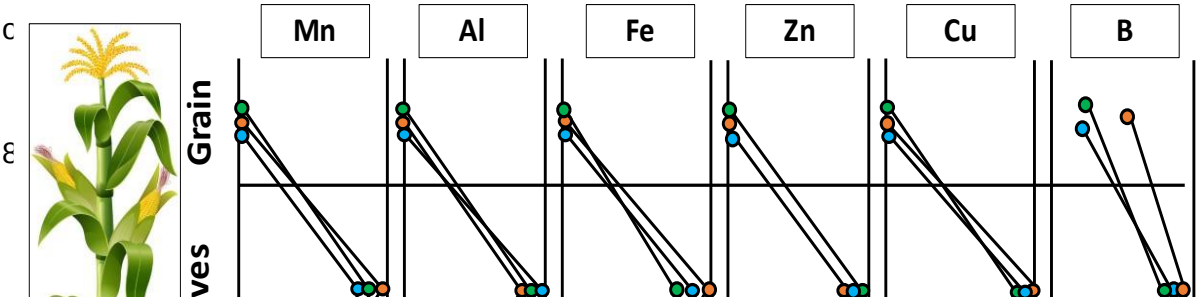


Figure 3.26: Average elemental distribution of irrigated white maize plant parts from the unmined trial site.

There is no one identifiable factor affecting the elemental partitioning within the maize plants, or any signs of toxic bioaccumulation of elements. The elemental distributions show a clear pattern of assimilation: low partitioning amounts into the grain, highest partitioning levels into the leaves and the stem was found to fall in the range between these two. Under these agricultural management conditions, with this specific seed type, the results have shown repeatability in the maize plants uptake and elemental partitioning.

The trial's harvested grain falls well below all the identified constituents of concern in the food safety guidelines. The food and feed safety data clearly illustrate the opportunity created by the availability of mine-affected water for irrigation. Under the current irrigation conditions at the unmined trial site, the irrigated white maize is producing a good-quality grain and feed material, well within the set threshold limits.

Although most mine waters contain a range of metals, including iron, aluminium and manganese, the important potential elements of concern from a human safety perspective were documented as arsenic, cadmium, chromium, lead, and mercury. It is therefore important to identify specific elements of potential concern in each body of mine water with which one is proposing to irrigate. This will ensure a pre-emptive evaluation of the elemental uptake and subsequent grain quality can be made, and if any, appropriate treatment measures brought into place or a prevention plan implemented.

3.3.5 Soil characterisation

Soil Physical Analyses

The full textural analyses of all soil samples can be found in Appendix A, Table A.9. The results are plotted on the USDA soil textural triangle (Appendix A, Figure A.4). Most irrigated and dryland soil samples were clustered and characterised as a loam, with slight variation in sand content. Dryland and irrigated samples nearer to the western border, in the more waterlogged area of the trial, were more enriched in clay, while irrigated samples on the well-drained and more eastern side of the trial site were less enriched in clay and had greater sand contents.

From visual cluster analysis of the USDA textural triangle and site characterisation, there is influence of hydrological processes and landform on the soil textural classifications of the unmined trial site. Due to the slight west sloping nature of the trial site, the depression and subsequent waterlogged conditions at the western border, increased clay leaching, and translocation occurred, with an observed increased clay percentage on the western side. Over time the irrigation pivot will have to be moved eastward, as waterlogging will otherwise continue and anoxic conditions will increase, rendering the western area of the trial unproductive and economically unviable.

Soil Chemical Analyses

The full chemical analyses of all soil samples irrigated and dryland, at the three depths, can be found in Appendix A, Table A.10 – A.12. Figure 3.27 and 3.28 indicate the change in concentration of constituents over the three monitoring depths as well as over the three irrigation periods, for both the irrigated and dryland soils. The pH, EC and sulphate values are plotted in Figure 3.27 and the Calcium, Magnesium, Sodium and Potassium values are plotted in Figure 3.28.

The irrigated soil had little change in soil pH with depth or time over the three years, with the pH range being from 6.1 to 6.3. The dryland soil samples had no change in pH over time but showed an increase in pH with depth. With each 30 cm increase in depth, there is an increase of 0.1 in pH. Due to the dryland samples located in the partly waterlogged side of the field, the maize crop may have experienced waterlogging stress and changes in soil redox potential (Kögel-Knabber et al. 2010). Waterlogged conditions cause an increase in the proton loading of the soil, which decreases the soil pH, and this is the reason for the difference in pH between the irrigated and dryland soils. For the dryland soil, the pH increases to between 5.8 and 6 at the deeper depths (30 – 90cm), indicating less waterlogged conditions, and an increase in internal drainage capacity, allowing the redox potential to stabilise, and the pH to become more neutral.

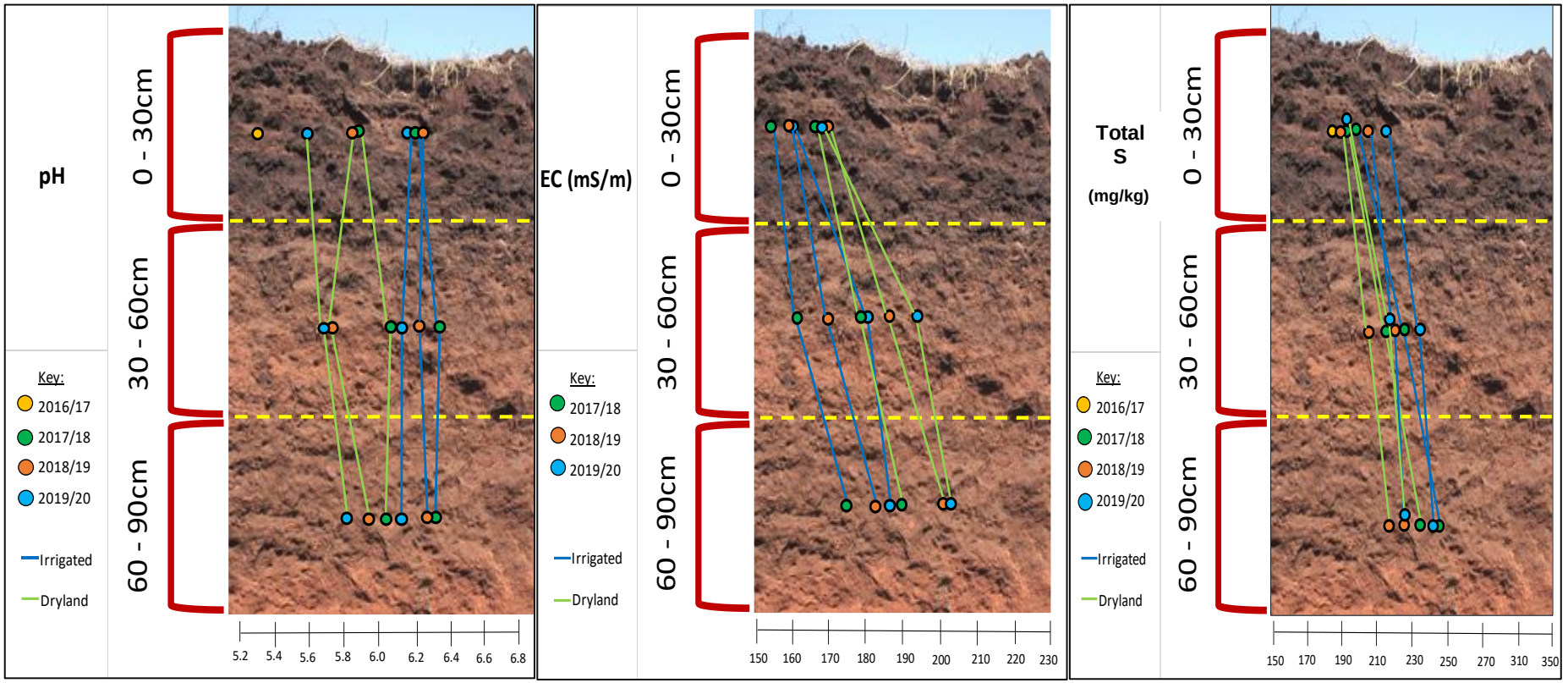


Figure 3.27: Changes in pH, electrical conductivity (mS/m) and total Sulphur (mg/kg), over a three-year irrigation period, at three depths (30, 60 and 90 cm).

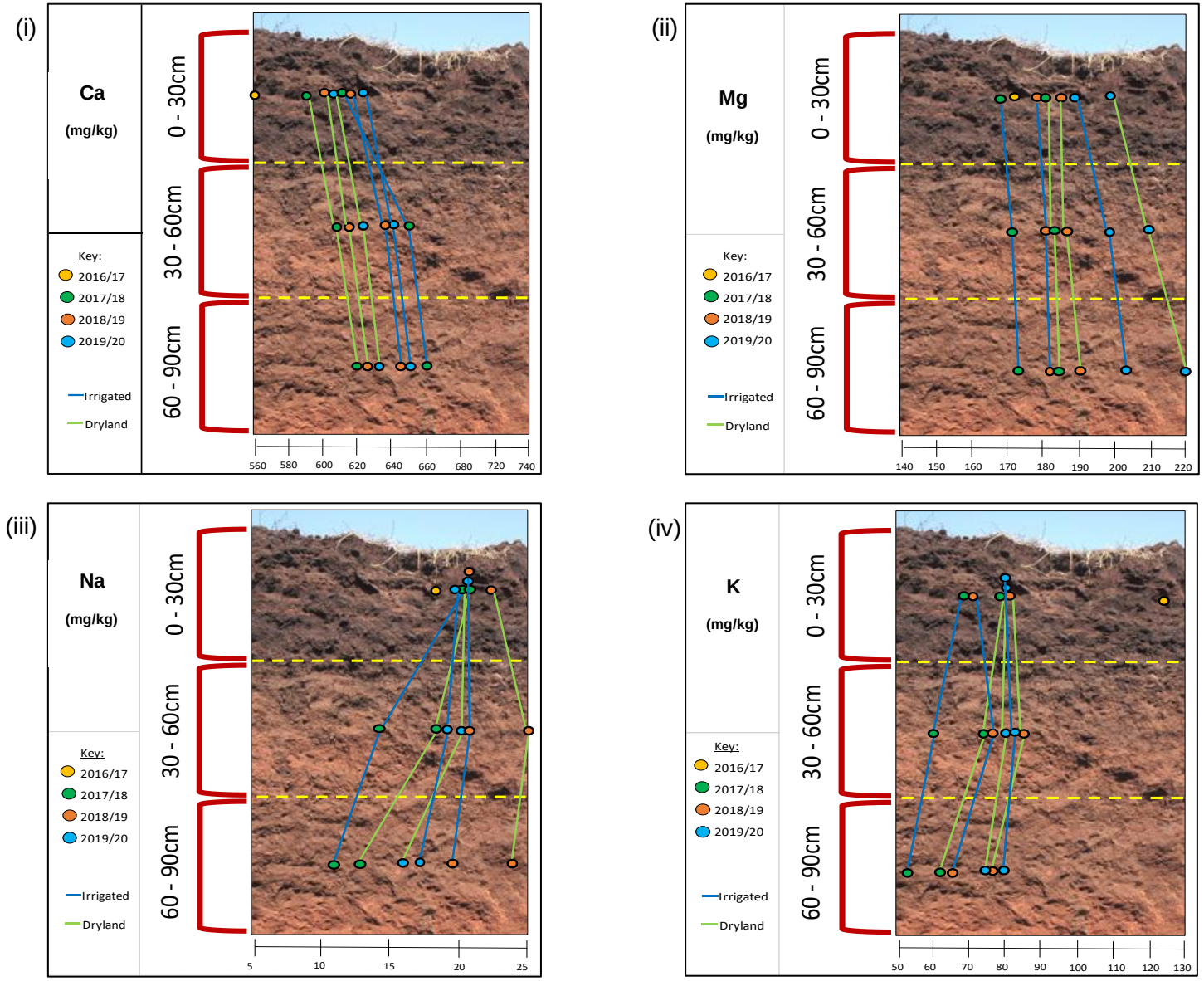


Figure 3.28: Changes in Calcium, Magnesium, Sodium and Potassium (in mg/kg), over a three-year irrigation period, at three depths (30, 60 and 90 cm).

The electrical conductivity (EC) of both the irrigated and dryland soils increases with increasing depth and time. It was expected that the EC of the irrigated soil would be higher than that of the dryland soil, as the supplemented water supply has higher levels of salt than precipitation does. This, however, was not the case at the unmined site, and the dryland soils had slightly higher EC levels than the irrigated soils. It appears that onsite topography and western boundary waterlogged conditions skewed the dryland soil EC results. Due to the lower topographic point, the high clay content, and subsequent increase in redox potential of the western area of the trial site, there is an observed increase in salt content and EC of the monitored soil unit. For the irrigated soils. the EC in the root zone is mostly below the 170 mS/m threshold for maize (Maas and Hoffman, 1977), and therefore no significant yield reduction due to salinity is expected. The dryland maize, however, had soils within an EC range of 170 – 205 mS/m and may experience some yield reduction due to these conditions. In general, for both soils, slight increases in EC are observed (increase of about 10 -15 mS/m) with depth, but according to Ballantyne (1978), are within normal net salt movement changes usually observed in agricultural soils. This increasing trend in salinisation, specifically in the dryland soil, can be better controlled with an improvement in drainage conditions. Although not seen as a problem at the unmined trial site, soil salinity should be continuously monitored, and managed in conjunction with the irrigation and precipitation cycles of the field.

Due to the highly variable rate of sulphur transformations and sulphur species variation typically found in soils, total extractable sulphur was determined for the soil environment. The sulphur supply to the maize crop is not seen as a limiting factor, as the crop showed no sulphur deficiencies over the period of the trial, and plant material analysis showed no S deficiencies. Sulphur in the anionic sulphate, SO_4^{2-} form, is the state in which it is readily available in soil to crops (Prashad & Shivay, 2016). The change in the soil's total sulphur content is thus attributed to the applied sulphate ions in the irrigation water, which can precipitate out in the soil as gypsum, $CaSO_4$. This irrigated site is a high-leaching environment and may require greater volumes of gypsiferous water to be applied for gypsum to aggregate in large amounts in the soil. As stated by Annandale et al. (2002), gypsum, as a partially soluble salt, and its precipitation in the soil, reduces the sulphate load from the soil water system, and potentially reduces the sulphate load leaching through to the ground and surface waters. The total extractable portion (TEP) soil sulphur analysis is therefore seen as representative of the sulphur soil dynamics on site at the trial. The TEP of sulphur of both the irrigated and dryland soils increase with increasing depth and time. The increasing clay content with depth can indicate the greater capacity for sulphate retention and explain the vertical difference in sulphur concentration. It can also be suggested the sulphate concentration difference with depth is part of the salt profile of this particular soil, with higher concentrations with depth. The

TEP sulphur concentration of the irrigated soil is higher than that of the dryland soil, as the supplemented water supply has higher levels of sulphate than meteoric water.

Both the irrigated and dryland soils exhibited an increase in the calcium and magnesium content with depth, with no observable change for time (Figure 3.29 i). For calcium, the irrigated soil had a higher content than dryland soil, in accordance with the calcium load applied through the irrigation water. The fertiliser application program was the same for both dryland and irrigated portions of the field so can be excluded as a source of the increased calcium content on irrigated soils. This shows the irrigation water is likely the source of the higher calcium levels in these soils. With calcium being oversaturated (three times that of sulphate – in both the irrigation water and liming regime), it will not be the limiting factor for gypsum precipitation to occur in the soil, yet with limited sulphate amounts present, the gypsum precipitation progress may be slowed. Magnesium had a gentler gradient for change in concentration with depth, when compared to calcium, yet, magnesium had greater increases in concentration with time (10–20mg/kg) (Figure 3.29 ii). For magnesium, the dryland soil has a greater content than the irrigated soil, at all times and depths. This may be the beginning of magnesium build up in the soil. An increase in soil calcium and magnesium can help increase crop tolerance to various stresses under adverse growth conditions (Gransee & Führs, 2013), and if the levels are within normal limits and remain in balance for an optimised nutrient balance, the extra concentrations of these two constituents is not seen as detrimental.

Both the irrigated and dryland soils showed a decrease in constituent concentration for potassium and sodium with depth, but not over time (Figure 3.29 iii + iv). Marginal differences exist between the dryland and irrigated soils for both constituents. For potassium, at each respective depth, a slight increase in concentration with each irrigation season was observed (+10 mg/kg per season). This perhaps demonstrates the beginning of potassium build up in the soil As the crop uptake amounts (Section 3.3.4) remained similar each season, the increase year-on-year should be monitored going forward to confirm this. Sodium showed no such trend at each respective depth.

For both irrigated and dryland soils, plant available iron, manganese, aluminium, copper, and zinc exhibited very little change in constituent concentration with depth and over the three-year period. Most of these micronutrients are needed by the maize crop in very small amounts and explain why over the three-year period very little change in concentrations was observed in the root zone (0-30cm). These metals are all inherently inert in soil, and the results followed this similar concentration availability trend. These stated metals are poorly bio-accessible at

near neutral pH levels, and correlate well with the minor metal uptake observed by the maize crop.

Further research can be done into the soil's plant available nutrients vs. the soil's bulk nutrient content, and how mine water irrigation affects this relationship, if any. Another field of study could be to monitor the change in constituent concentration over a deeper soil unit (>90 cm), in order to observe the nett salt balance over the complete saprolitic depth within the trial site. This will assist in a greater accuracy of quantifying the irrigated environment's salt balance.

Soil monitoring stations

Figure 3.29 (i – iv) shows the change in soil volumetric water content in m^3/m^3, over each irrigation season. The monitoring of the soil's VWC provides insight into the shallow subsurface water movement, solute residency times, drainage, and leaching rates of the soil profile. Understanding the soil water balance provides an indication of possible gypsum precipitation and dilution patterns, and the effect of gypsiferous mine water irrigation on an irrigated soil system.

It is noted the VWC graph (i) for 2016/2017 had very low and inconsistent recorded water contents. It was discovered the probes were installed horizontally in the soil and not vertically, and the readings were therefore not consistent with on-site field conditions.

The deeper soil layers (60 – 90 cm deep) are expected to have higher soil VWC due to the increased clay content and greater water holding capacity. This pattern was observed some of the time, especially in periods of lower precipitation, but during periods of increased precipitation, the shallower probe (30 cm deep) had a soil VWC which exceeded the deeper soil layers VWC. The deeper soil levels also had greater VWCs at the beginning of each planting season, compared to the 30cm probe, as some residual water from the previous rainy season would have been likely stored and not evaporated as much as from surface layers during the winter period.

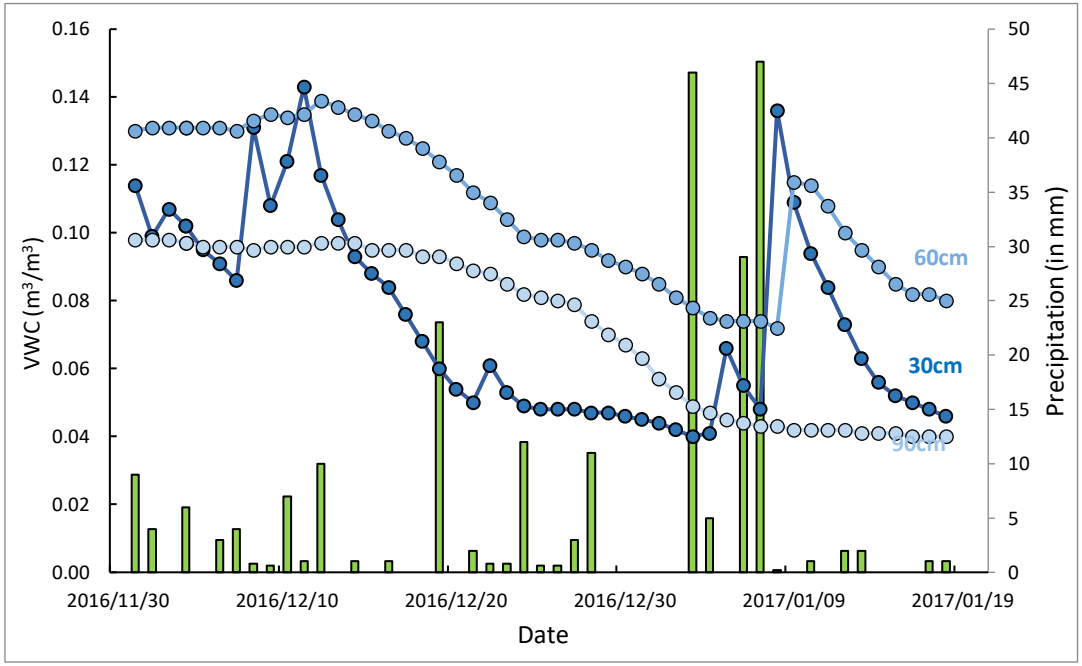
The deeper soil layers (60 – 90 cm deep) are also expected to show less drastic changes in VWC when compared to the 30 cm deep probe. This was observed during the study period, where gradual increases and decreases were observed at both 60 and 90 cm deep. The deeper layers were not highly influenced by evaporation, crop water uptake and surface hydrological movements. The 30 cm deep probe showed these effects clearly by the great variation in rate of loss of the VWC.

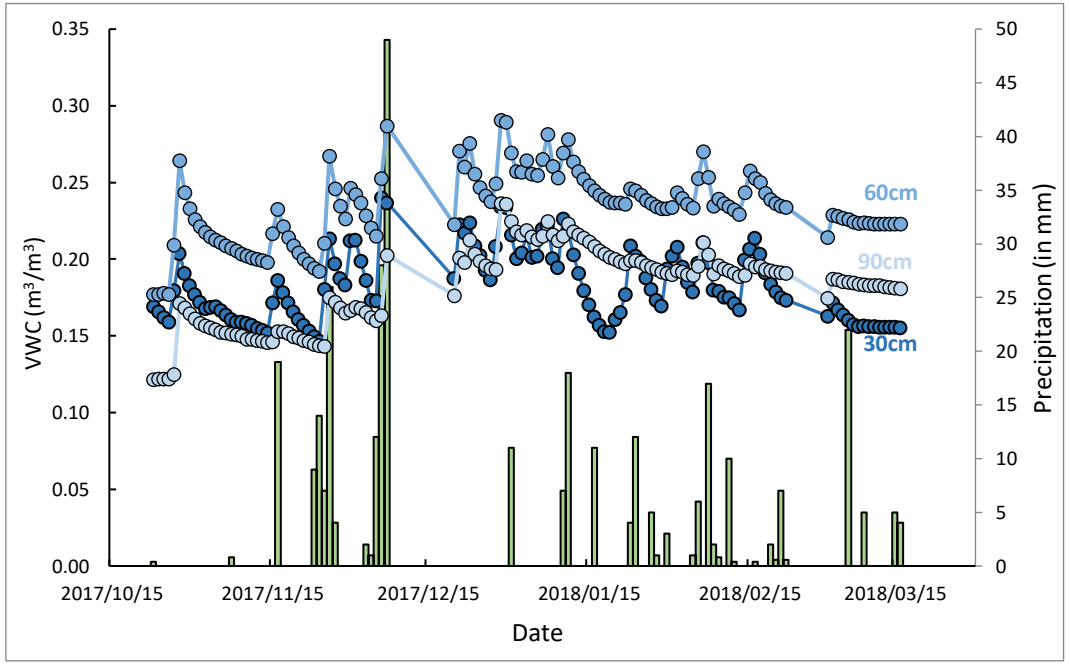
Periods of sustained precipitation throughout the summer rainy seasons (about 7 continuous days), had a visible effect on the soil's VWC. The 30 cm deep probes had the greatest fluctuation in VWC, increasing sharply within 1 day of the first rainfall event, only showing a

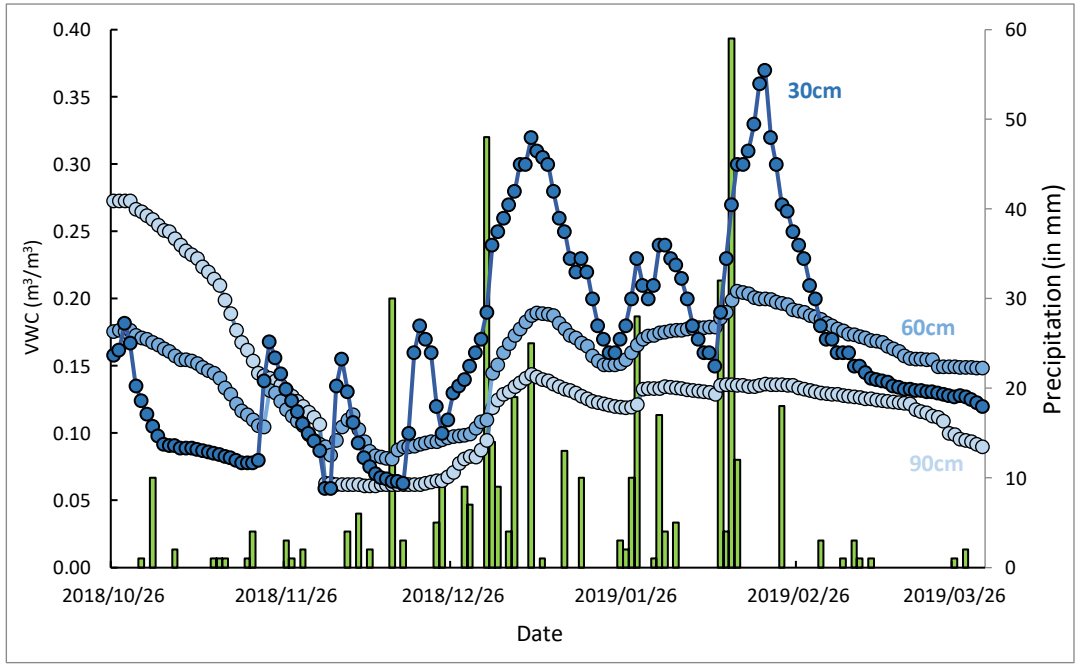
small delay period (a few hours) due to infiltration, followed by a steady increase in VWC with an increase in rainfall. Crop water uptake during these periods was negligibly small and made no impact on the root zone VWC in comparison to the large water influx into the system, as water supply exceeded demand. VWC at 30cm sharply decreases within 1-3 days after the extended rainfall events, due to the relatively quick percolation rate of water to deeper soil layers.

The soil from 60 to 90 cm was less prone to major fluctuations in soil VWC from precipitation and irrigation events. The 60 and 90 cm deep probes had slower response times, and more gradual increases and decreases in VWC with the respective increases and decreases in precipitation. This can be due to the increasing clay content and subsequent slower transmissivity rates of the deeper soil layers. Although not explicitly seen in the results over the three irrigation seasons, localised perched water tables due to clay lenses, or lateral flow may also influence the water content and salt dynamics in the deeper soil layers.

For gypsum precipitation to occur, the soil solution should be saturated with calcium sulphate ions, the residency time in contact with the soil particles should be long, evaporation rates high, and dilution low (Van Driessche et al. 2019). These conditions would ensure an optimal environment for gypsum precipitation to occur. These conditions are expected to have been at least in some part achieved during the early to middle summer season (October to December), when evaporation levels were relatively high, supplemented irrigation was available, and residency times were sufficient for salts to be sequestered. Dilution of salts in the soil would have occurred during periods of high rainfall.







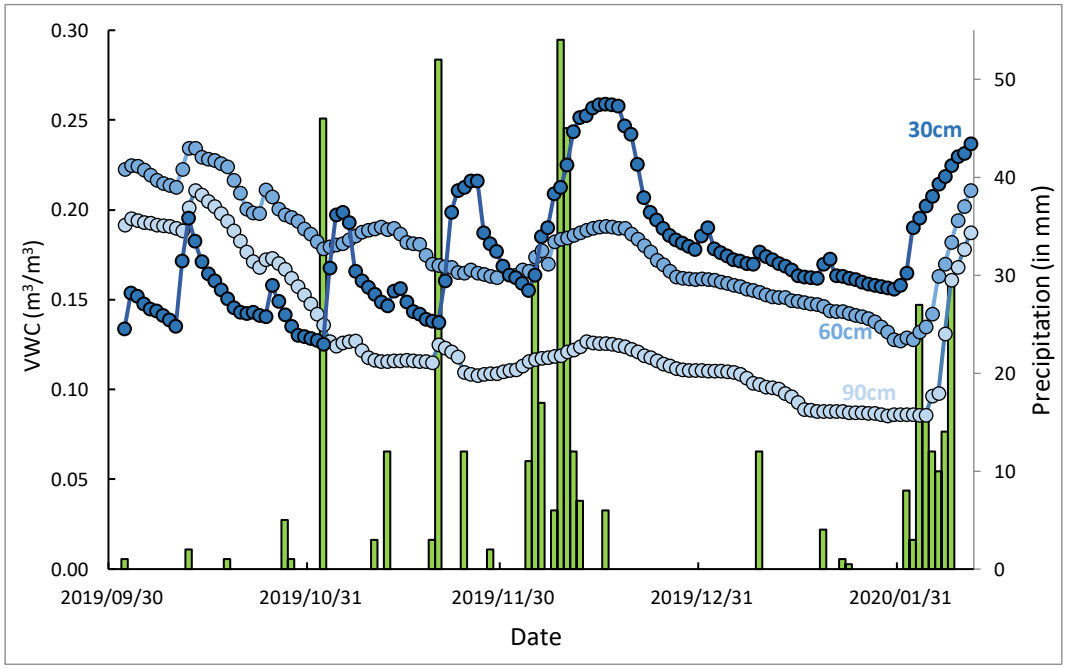


Figure 3.29: Volumetric water content (VWC, in m^3/m^3) for the irrigated pivot (green bar graph), over a four year period, at 3 incremental depths.

3.3.6 Salt Mass Balance

The leachate concentrations (L_{30}; L_{60}; L_{90}) were calculated from the equations in Section 3.2.6. Table 3.8 displays the percentage of the constituent inputs into the soil unit (I + F) that have not been used by the crop or retained in the soil (C + ΔS) at 30, 60 and 90 cm (L_{30}; L_{60}; L_{90}). These percentages represent the total loss of each constituent at each monitored soil depth.

Table 3.8: The total loss (%), in the leachate, of each constituent at each monitored soil depth (L_{30}; L_{60}; L_{90}).

%	L_{30}	L_{60}	L_{90}
Ca	57,5	74,3	99,5
Mg	43,5	97,2	83,5
Na	99,1	94,7	98,5
Cl	98,4	99,5	97,6
K	0	0	0
Total P	0	0	0
Total S	96,8	99,5	99,8

Figure 3.30 shows the breakdown in concentrations of the inputs [Irrigation (I) and Fertiliser (F)] and the outputs [change in soil concentration (ΔS), crop uptake (C) and leachate losses (L_{30})] for the 0 – 30 cm deep soil unit. The breakdown for the inputs and outputs for L_{60} and L_{90} can be found in Appendix A, Figure A5 and A6.

A negative output value on the graph (Figure 3.30) (negative leachate value) indicates this amount was obtained from other means besides the input from irrigation and fertiliser. A negative output value means the constituent would not be observed in the leachate. When the inputs and outputs of the mass balance do not equate, there are additional factors (±X), not included in the original mass balance equation, which play a primary role in the computation. Another possible reason for these mass balance discrepancies could be error in sampling and laboratory analyses. However, this is deemed unlikely due to there being several sampling periods, with duplicate samples taken, all with similar resultant concentrations. The effect of spatial variability is noted to also play a role.

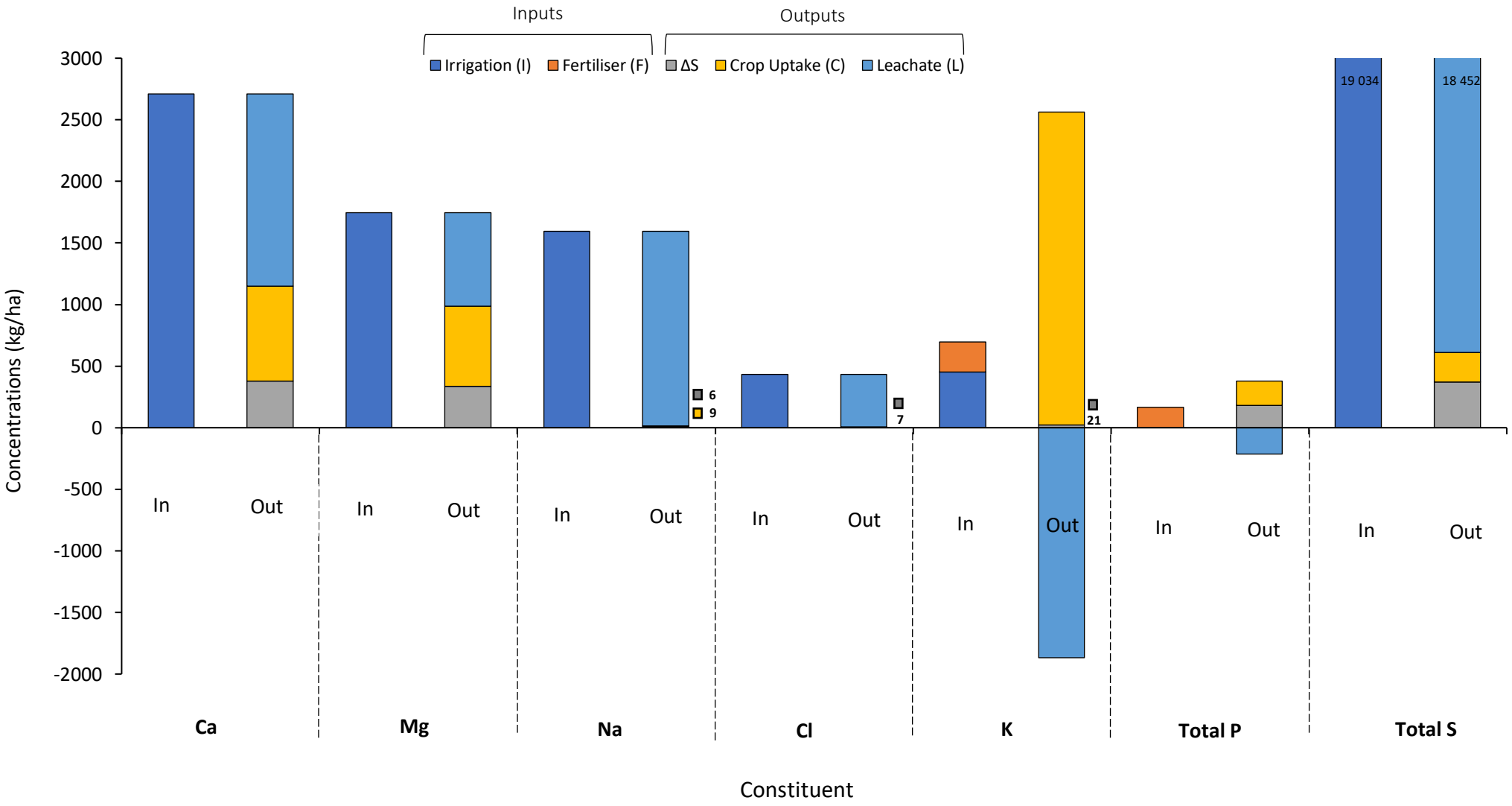


Figure 3.30: Partial constituent mass balance: Each element broken down into Input (I + F) and Output (ΔS + C + L_{30}) in kg/ha for the 0 – 30cm depth.

Potassium and phosphate were the two elements exhibiting this unbalanced mass balance trend. There were more outputs (C + ΔS + L) than there were inputs (I + F). There was no potassium identified in the leachates, the crop had a high potassium uptake (C > I + F) and the soil retained very little potassium. It can be concluded that there was an additional potassium supply entering the soil system via unaccounted for, alternative pathways (±X). Some explanations for the supplemented potassium could be: Additional fertiliser application throughout the seasons (farmer could not corroborate this), or a percolate influx of potassium (±X) into the soil unit (not monitored for). Phosphate exhibited this same trend, albeit on one order of magnitude lower than the potassium. The phosphate crop uptake and change in soil concentration were of similar proportions. This is in accordance with literature, that in highly weathered soils, such as the unmined trial site's kaolinitic soils, with the presence of sesquioxide minerals, P fixation does occur. This is corroborated with the measured increase in soil P concentration (Penn & Camberato 2019). As with potassium, an influx of phosphate would have occurred in order for the negative leachate value to have been observed. Both potassium and phosphate therefore had recorded leachate losses that were zero at all three depths (Table 3.8), as all the constituent inputs would have either been used by the crop or converted in the soil. A supplemented K and P supply would have been necessary to sustain the total crop uptake (C) value measured. Releases from organic matter can also be an explanation for an unaccounted pool of nutrients.

Calcium shows decreasing concentrations with increasing depth. In the active root zone, the 0 – 30 cm soil layer, the least calcium loss occurred, with 43.5% of the input calcium either taken up by the maize crop or an increase in the soil concentration was observed (Table 3.8). Largely, the plant available calcium would have been supplied in the right quantities and timing for these smaller quantities to be lost via the leachate. Magnesium had a similar loss trend, with greater amounts lost in the 30-60 cm interval than in the 60-90 cm layer. Calcium and magnesium have similar chemical behaviours in the soil and crop uptake amounts, both constituents' subsequent leachate losses therefore exhibit a similar trend. Past the upper root zone (> 30 cm), there is less crop uptake of constituents, which possibly results in an increase in the leachate %.

Very little sodium and chloride are needed by a maize crop, and this was reflected in the results as an average of 0.5 and 1,6% of the total inputs for each respective constituent were taken up by the maize crop. An average of 97.4 and 98.5% of each respective constituent leached through the 90 cm deep sampled soil profile. Irrigation waters with high sodium and chloride concentrations are not beneficial to most crops, these stated ions are weakly bound to soil surfaces, and therefore are readily leached from the soil profile. From these

observations and effects on soil physical properties, waters with a Sodium - Chloride hydrofacies should be carefully reviewed when used for irrigation.

It was hypothesised that gypsiferous mine water irrigation would result in gypsum precipitation in the soil. An average of 98.7% of the total sulphur applied, leached through the 90 cm thick soil unit. However, this leached sulphur did not reflect as an increase in the shallow or deep groundwater quality monitored over the three-years. On the basis of the shallow soil and groundwater chemistry results, the bulk of the sulphur leachate is surmised to therefore be present within the deeper soil (>1m deep to above the groundwater table at ±15 - 20m deep) (In accordance with the modelled results of Annandale et al. 1999).

The recommendation on the monitoring of this trial would therefore be to sample deeper into the saprolite to observe if there are any changes in the soluble sulphate and total sulphur concentration of the leachate and soil. According to Reiss et al. (2021), the understanding of the rate of gypsum precipitation in natural environments is not well researched and known, but gypsum precipitation is achieved when the precipitation setting is fully to oversaturated in calcium and sulphate. This means mineral gypsum precipitation within the irrigated environment should occur very slowly and only once greater saturation conditions are reached. In an open environmental system, such as the trial site, there are continuous in and out fluxes (±X) which can also influence the factors required for gypsum precipitation (Reiss et al. 2021). There was an increase in the soil's sulphate content in the 0-30 cm depths and saw a total of 3.2% of the sulphate input (I + F) either taken up by the crop (1.3%) and precipitated out in the soil (1.9%). An increase in soil depth showed an increase in sulphate loss via the leachate. An assessment of sulphate residency time at the unmined site, suggests the Glencoe and Hutton soils on the trial site have exhibited a long residency time of sulphate throughout the profile. The applied sulphate has, after three years of irrigation, not reflected any change in the groundwater sulphate concentration, and is likely present within the deeper saprolite due to expected large groundwater fluxes.

The results of this study are relatively similar to those Vermeulen et al. (2009) found in their study of irrigation at New Vaal and Kleinkopje, for the amount of salts attenuating in the soil and gypsum precipitation amounts. The results stated that the New Vaal and Kleinkopje irrigation sites had a large amount of salts retained in the deeper soil layers, > 1 metre deep, similar to what has been suggested by this study. The other sites of the Vermeulen et al. (2009) study, had the applied salts attenuate and precipitate at shallower soil levels, < 1 metre deep. Vermeulen et al. (2009) stated that the mine water irrigation used did not influence the underlying aquifers to any measurable degree, and that the rate of dilution and leaching is very low. The Vermeulen et al. (2009) study has also concluded that limited salt leaching to

groundwaters has occurred over the period of the trial, with results of the groundwater monitoring to be found in Section 3.3.2. This study has also noted the significance of possible dilution and soil salt migration due to lateral groundwater flow.

It is noted that soil samples were only taken to 90 cm, and that the actual saprolite depth on the unmined trial site is unknown. Having access to borehole logs of previously drilled holes, as well as employing geophysical methods, total saprolite depth, depth to the rock interface and water table, can accurately be determined. Some examples of geophysical methods which can be used to determine the saprolite depth are: Electrical Resistivity Imaging (ERI), Seismic Refraction (SR), and Multiple-Channel Analysis of Surface Waves (MASW) (Groves et al. 2011). With greater knowledge of the saprolite thickness and chemistry, an improved estimation and extrapolation of retained constituents can be ascertained. This is important in calculating the leachate losses from the irrigated soil into the groundwater, and more accurately quantifying the mass balance of the irrigated environment.

From the available monitoring data and the partial nutrient balance results, the following conclusions can be made:

- An average of 58% of all input salts leached through the 90cm deep soil unit;
- A measurable increase in soil salinity was not observed. The partial nutrient balance indicated which constituents were largely leached through the soil unit (K, Na, Cl, & total S) and therefore would not contribute to soil salinity;
- The expectation is the leached constituents from the soil unit would end up in the groundwater. That was proven not to be the case (Section 3.3.2), and from these results, the conclusion drawn is the salts are mainly located within the deeper saprolite;
- Further monitoring is needed of the deeper saprolite (>1 metre thick; Shangguan et al. 2016), the retention pathways and transformation of constituents, and the leachate (L_{90}) discharged at the 90 cm depth, and should therefore be further researched;
- Infield or laboratory lysimeter studies can provide greater insight into quantifying the sites specific residency times of the irrigation salt;
- Greater characterisation of the site-specific surface hydraulic properties is required, for example: runoff volumes and qualities, interflow (if any) (As quantified by Idowu et al. 2008 in a prior mine water irrigation trial)

3.4 Conclusion

An important part of determining a field's salt and water balances is ensuring the relevant and specific environmental data are collected, timeously. Quantifying changes to the soil, crop and water environments are crucial when trying to understand nutrient dynamics.

Monitoring the weather conditions provides insights into the growing conditions of the crop and identifying if there were any limiting climatic factors (Section 3.3.1). Mid-way through the 2018/2019 growing season, there was heavy precipitation (hail). These unfavourable weather conditions caused a heavy loss of leaf area of the maize crop, at a critical growth stage, and this season had significant yield loss (±2 tons/ha loss) (Section 3.3.3). Both the 2017/2018 season and the 2019/ 020 season had no major limitations of climatic conditions for crop growth and were considered 'good' maize growing seasons (sufficient rainfall, solar irradiance, and temperatures).

The downstream groundwater monitoring points were ideally placed for intercepting the leachate from the unmined trial site (Section 3.3.2). Monitoring the groundwater quality over the three-year period saw no significant increase in constituent concentrations, and no relationship could be verified that the irrigation water degraded or influenced the quality of the groundwater. Isotope analyses confirmed that there is no linkage between the different water sources, and therefore no interaction or mixing of the irrigation water with the ground and surface waters. As part of the results to prove Hypothesis 1 correct, no indication was found that large amounts of salts from irrigation entered ground and surface waters.

The added nutrients at the unmined trial, from the irrigation water and fertilisers, were sufficient for sustaining profitable and safe crop production (As part of Hypothesis 1, confirmed and proven) (Section 3.3.3 & 3.3.4). The irrigated maize produced greater yields, two to threefold more than the dryland maize. The gypsiferous irrigation water proved to not hinder crop yield and quality, when evaluated against the control, dryland maize (Hypothesis 2 confirmed and proven).

No significant increase in soil salinization was observed over the three-year irrigation period. The top 90 cm of soil had an average of 58% of all salts leached through the profile, however, the onsite groundwater chemistry did not reflect this salt load increase to the aquifer (Section 3.3.2). At this trial site, in accordance with what Vermeulen et al. stated in 2008, salts leaching from the irrigation trial are attenuated in clay layers between the soil surface and shallow aquifers, while in the short term, gypsum precipitation rates within the soil seem to be following many of the simulated trends determined by Annandale et al. (2006; 2014). There is also a stark difference in the sulphate concentrations between the irrigated and dryland soils; proving

that in part, some of the added salt through irrigation precipitates out in the soil and the salt load is reduced to catchment (As part of Hypothesis 1).

Future research can be conducted on gypsiferous irrigation salt loading rates, residency times and the precipitation dynamics of gypsum in different agricultural soils in South Africa. This will provide site- and region- specific results as to the effects gypsiferous mine waters could have on the various environmental receptors (soil, water, and crop). The gypsum mineral constituents within the irrigated soil can be further investigated, with XRF and XRD methods employed to identify, clarify, and further validate the species of sulphur present in the irrigated soils. It is noted the salt mass balance has many presumptions, and shortcomings, and future research can include refinements, additions, and changes in order to increase the accuracy of the representation of the profiles salt balance.

The unmined trial site has demonstrated a cost-effective, sustainable, and productive utilisation of untreated, circum-neutral mine water. This site is a valuable demonstration for prospective mine water irrigators and the regulators who will be approached to approve such water uses and projects in the near future. The success of this project has clearly shown that productive mine water irrigation is possible, and with further long-term studies, stakeholders such as the Department of Water and Sanitation, the Department of Agriculture, Land Reform and Rural Development, mines and farmers can more confidently enter into the utilisation of mine-affected waters for irrigation.

CHAPTER 4: CROP, SALT AND WATER BALANCE MODELLING OF MAIZE IRRIGATED WITH CIRCUM-NEUTRAL MINE WATER

Chapter 3 presented the monitored commercial scale, field data from 2016 to 2020, for the white maize mono-cropping system at the unmined pivot, near Arnot in Mpumalanga. Data from this regular sampling and monitoring was used to parameterise the computer program-based Decision Support System (DSS) developed by Du Plessis et al. (2017). DSS assessments are used to determine the fitness-for-use of this mine water for irrigation, under the specific unmined trial site conditions (climate, soil, crop, water management options), focusing on associated risks for irrigation equipment and soil and crop resources.

4.1 Introduction

Dynamic agro-hydrological modelling is globally a widely used water management tool, and the validity of such models have been tested under varying climatic conditions. Understanding water management on farm level contributes to sustainable irrigation practices being adopted, and optimising water usage, specifically crucial in water scarce areas (Jovanovic et al. 2020; Pereira et al. 2012).

Li & Ren (2021) summarised the foremost aspects to consider when running simulations for saline irrigation management. Although not just applicable to saline waters, the flow chart presented by Li & Ren (2021) and stages of analysis highlighted, are appropriate for approaching any irrigation scenario simulations. Irrigation modelling can be used to quantitatively assess the sustainability and practicality of using certain irrigation waters in specific areas. This modelling can assist decision making when there is uncertainty around the suitability of alternative water sources, and how these will impact the environmental and food production. Better salt, water and crop management is possible (at farm, local and catchment level) with a better understanding of the local environments and their water flow characteristics (Annandale et al. 2002).

4.2 Decision Support System (DSS)

The Irrigation Water Quality Decision Support System (DSS) developed by du Plessis et al. (2017), uses the South African Water Quality Guidelines for Irrigation (SAWQI, 1996) and a simplified and revised version of the Soil Water Balance (SWB) model to make its predictions, and has incorporated the most appropriate and latest research and practices in this field. This DSS provides site-specific, risk-based guidance on the fitness-for-use for irrigation of water sources, as well as determining water quality requirements for a specific cropping system and water management approach (du Plessis et al. 2017).

The DSS provides colour coded indicators to evaluate effects of the defined water quality on soil quality, irrigation equipment, crop yield and quality. The soil quality indicators are root zone salinity, soil permeability as affected by Na and salinity (infiltrability and hydraulic conductivity), oxidizable carbon loading, and trace element accumulation. The crop yield and quality suitability indicators are leaf scorching when wetted; contribution to N, P and K removal by the crop; microbial contamination, and qualitative crop damage by atrazine. The final category of irrigation equipment suitability indicators considers water quality effects on scaling/corrosion and clogging of drippers.

4.2.1 Tier 1

The DSS is structured into three tiers. Tier 1 encompasses the generic and conservative DWAF (1996) thresholds. The fitness-for-use (FFU) assessment categorises water constituents into different levels of acceptability and implied risk, and a broader overview of potential problems are highlighted. These stated Tier 1 assessments are likely to be of limited use for poorer quality mine-affected waters, and further site-specific analysis (Tier 2) may render them more usable.

4.2.2 Tier 2

Tier 2 allows site-specificity to be considered, with user defined climatic conditions, irrigation management, and selectable soil and crop variables. This is a useful approach to take for the majority of mine-affected waters, as it can assist the user in determining if there are conditions under which a particular mine water is usable for irrigation. Tier 2 permits a more in-depth water suitability assessment than that outlined in Tier 1 DSS simulations, which are similar to the conservative DWAF (1996) irrigation water quality guidelines. Within a given irrigation scenario, specific risks are thus quantified according to the description, consequences, and likelihood that the specific risk would occur.

Where required, in exceptional and ad-hoc circumstances where Tier 2 assessments are inadequate, Tier 3 assessments are indicated. This requires specialised resources and expertise that may not explicitly form part of the DSS.

All further information regarding the DSS description and setup (Volume 1) (du Plessis et al. 2017a), as well as the technical support document (Volume 2) (du Plessis et al. 2017b), can be found on the WRC's website. The DSS is known as SAWQI (South African Water Quality for Irrigation), and can be downloaded from the NB Systems' website, www.nbsystems.co.za.

Using the long-term simulations of SAWQI (16 March 2022 version), the following is a list of inputs used for modelling at this study's trial site: Irrigation water quality (Section 3.3.2); an overhead irrigation system, refilling the sandy loam soil profile to field capacity, the chosen Gemsbokfontein weather station; with several cropping systems considered, namely, double

cropping systems of maize-wheat and soybean-wheat, and single cropping systems of monocrop maize, soybean and wheat, all simulated for 45 years of irrigation.

4.3 Results and Discussion

Tier 1

Tier 1 fitness-for-use (FFU) assessments indicate issues of potential concern at tolerable to unacceptable fitness-for-use levels. These are mainly: soil profile salinity, trace element accumulation, crop yield reduction due to salinity, and slight scaling and dripper clogging. Tier 2, 45-year, site-specific simulations can potentially identify conditions under which these risks can be lowered to acceptable or ideal levels (Table 4.1).

The irrigation water source is mostly near neutral to slightly alkaline, with an EC of around 300 mS/m, but primarily gypsiferous in nature. This EC range under the specified conditions is seen as tolerable at Tier 1 level, and a predicted soil profile salinity of 535 mS/m is expected to result from irrigating with this water. Tier 1 indicates that a 30% reduction in potential yield may be expected due to increased root zone salinity from this irrigation water.

No surface infiltrability and hydraulic conductivity problems were predicted, with problems of slight scaling and clogging of drippers due to pH and Mn possible. However, this would not present a problem under centre pivot irrigation.

The Tier 1 fitness-for-use assessment highlighted some potential problems with regards to manganese (Mn), cobalt (Co), nickel (Ni) and cadmium (Cd) accumulation in the soil. The DSS simulation shows that Mn has the potential to accumulate to its threshold value in the topsoil within 10 years, Cd within 167 years, Ni within 68 years, and Co within 125 years if 1000 mm irrigation is applied per year. It is, however, noted that the irrigation guidelines do not consider the bioavailable amount of these elements in soil, but rather the total amount accumulated over time.

Tier 2

When comparing the site-specific Tier 2 simulations, the five chosen cropping systems indicate how managing on-site variation can influence the suitability parameters and outcomes of potential suitability indicators. Results are given in years, for reaching the accumulation threshold in the soil, or in percent (%), for the percentage of time an element may fall within a suitability class over the 45-years simulated. It is noted double cropping systems add more water to fields than single cropping systems do. Which is important to note as irrigated double cropping systems will have lower leaching fractions due to irrigation during dry winter months, and soil salinity increases to levels that may possibly reduce crop yields.

The mono-cropped maize and mono-cropped soybean gave the best FFU class range compared to the other 3 cropping systems, having an average of 90% (ideal) and 19%

(acceptable) for the % of time the predicted soil profile salinity would be in each respective FFU class. The soil salinity would thus be the least affected if mono-cropped maize and mono-cropped soybean are planted. This results due to the fact that limited irrigation would be applied in the summer rainy months, and leaching fraction would be higher than with double cropping. Although the other 3 cropping systems still fall within an acceptable and tolerable range for soil profile salinity, they would increase soil salinity to levels above those of the maize and soybeans for the reason given.

The predicted affected relative crop yield (%) went from unacceptable (with predicted 0% crop yield) in Tier 1 to ideal (Tier 2) for all cropping systems except the maize-wheat rotation. The maize-wheat rotation had a greater yield depression, and this may be as a result of the reduced salt tolerance of maize and the higher rate at which maize yield declines with increasing salinity (Maas & Hoffmann, 1977). An alternate and appropriate choice of summer crops such as soybean or sorghum will likely reduce yield depressions due to salinity.

All five cropping systems had a similar outcome for soil infiltration and hydraulic conductivity and had little to no influence on the soils permeability status. The scaling and corrosion status of the irrigation equipment remains unchanged. The potential for sodium leaf scorching went from slight to none for all five cropping systems.

The site-specific Tier 2 simulation has shown the accumulation of Mn within a short period of time in the soil to unacceptable levels for all five cropping systems. The natural concentrations of Mn in a large number of soils in South Africa are generally high. Mn oxide has the potential to oxidise and attenuate Mn^{2+} ions in solution, thereby reducing the Mn availability for uptake. The validity of the Mn soil threshold levels used in the DSS are, therefore, debatable. With normal rates of agricultural liming and suitable soil redox conditions, Mn is not deemed to be an element, which once highlighted by the DSS as potentially problematic, should cause a complete cessation of irrigation, but rather available levels in soil solution should be closely assessed as irrigation continues.

Cd remained the same or increased to acceptable or ideal suitability classes for all five cropping systems and is not expected to cause any problems. Co is estimated to take about 150 years longer to reach the soil accumulation threshold for mono-cropped maize and mono-cropped soybean, with similar time frames of 120 years for accumulation, for the mono-cropped wheat and the two double copping systems. Nickel had a similar response and rates of accumulation thresholds as cobalt (Co), with maize and soybean lengthening the threshold accumulation time by about 70 years.

The double cropping systems incorporating wheat into their rotations, have simulated that the soil trace element accumulation that get either worse than that predicted for Tier 1, or remains the same. The simulated results for wheat can suggest its attenuation, uptake, and usage

rates of Mn, Co, Ni and Cd are lower than that of soybean and maize, this however would need to be confirmed with field trials. As stated earlier (Section 3.2.3), time frames and levels for trace element soil accumulation thresholds should be reviewed on an individual site basis.

Table 4.1: Tier 1 and Tier 2 Fitness-for-use (FFU) comparison assessment of the five chosen cropping systems.

Suitability Parameters			Tier 1	Tier 2 - Cropping systems						
Soil Quality				Mono-crop maize	Monocrop wheat	Monocrop soybean	Maize-wheat rotation		Soybean-wheat rotation	
Soil profile salinity (%)	Ideal			91	64	89	33		33	
	Acceptable			9	36	11	64		64	
	Tolerable		535 mS/m				3		3	
	Unacceptable									
Soil Permeability (%)	Surface Infiltration	Ideal		80	79	82	89		89	
		Acceptable	Slight	20	21	18	11		11	
		Tolerable								
		Unacceptable								
	Soil Hydraulic Conductivity	Ideal	None	98	100	98	100		100	
		Acceptable		1		1				
		Tolerable		1		1				
		Unacceptable								
Trace elements - reaching soil accumulation threshold (in years)	Cadmium (Cd)		167	373	184	355	150		150	
	Cobalt (Co)		125	280	138	266	113		113	
	Manganese (Mn)		10	19	9	18	8		8	
	Nickel (Ni)		69	155	76	147	62		62	
Yield and Quality of crop			1000 mm/a	447 mm/a	906 mm/a	470 mm/a	Maize 309 mm/a	Wheat 799 mm/a	Soybean 310 mm/a	Wheat 799 mm/a
Relative crop yield (%)	Root zone Salinity (EC)	Ideal		100	100	100	69	100	100	100
		Acceptable					18			
		Tolerable					13			
		Unacceptable	0							
	Sodium (Na)		Ideal	Ideal	Ideal	Ideal	Acceptable		Ideal	
Degree of leaf scorching			Slight	Slight	Slight	No scorching	No scorching		No scorching	

Table 4.2 summarises the simulated water and salt balances for the chosen 5 cropping systems. The table states the yearly rainfall and precipitation, evapotranspiration and drainage flux the soil profile will experience, as well as the salt balance of the soil profile, how much salt is added, leached and precipitated.

Table 4.2: Summary of DSS seasonal salt and water balances for the five chosen cropping systems.

Cropping system	Irrigation + Precip.	Evap. + Transp.	Drainage	Salt added		Salt leached	Gypsum precip.
	mm/year			tons/ha per year			
Monocrop maize	1115	833	283	10		8.4	1.3
Monocrop wheat	1205	1086	107	21		4.7	8.4
Monocrop soybean	1142	859	282	11		8.7	1.6
Maize-wheat (M is maize and W is wheat)	1832	1529	302	M	7	15	0.1
				W	18	2	7.9
Soybean-wheat (S is soybean and W is wheat)	1833	1530	303	S	7.1	15	0.1
				W	18	2	7.9

Figure 4.1 indicates the seasonal changes in the salt balance for the maize-wheat double cropping system over a 45-year period. Appendix B presents seasonal salt balances for the remaining simulated 4 cropping systems. For all five cropping systems, no limestone ($CaCO_3$) precipitation occurred, this is in keeping with the irrigation quality, as calcium sulphate (Gypsiferous) is the dominant hydrofacies, with limited carbonates present.

Both maize and soybean summer monocropping systems, precipitate minimal gypsum in comparison to the amount of salts added, with greater levels of salt leaching. The DSS simulated gypsum precipitation amounts are confirmed by the in-field measurements of 1.8 – 2.2 tons/ha per year. An average of 3 tons/ha per year gypsum precipitation is predicted to occur over the 45-year simulation period per crop at the unmined trial site. The salt stress response and physiological adaptions to irrigation indicates, from the simulated outcomes, that soybean and maize have similar mechanisms of managing salt stress. The DSS simulations show a field with a crop stores more salt (tons/ha) than fallow land does. The discrepancy in simulated and actual measurements could be due to human error in sampling and laboratory work, uncontrollable sample contamination, and the basis that simulations are in a controlled environment, but the apparent deviation is deemed within normal limits.

For the maize-wheat rotation, the simulated gypsum precipitation under wheat will be 7.9 tons/ha/year, while maize will only precipitate 0.1 ton/ha/year. The two double crop rotation simulations have very similar output results. With wheat being a common crop between the two, it is seeing the majority of the salt addition to the soil, as well as the bulk of the gypsum precipitation, as can be expected as this crop is grown in the dry winter season. Using wheat as a monocrop or in a rotation will allow more salts to be attenuated in the soil, less available salts in solution, and the salt load entering ground and surface water is thus reduced. Both maize and soybeans have minimal gypsum precipitation in the double cropping system.

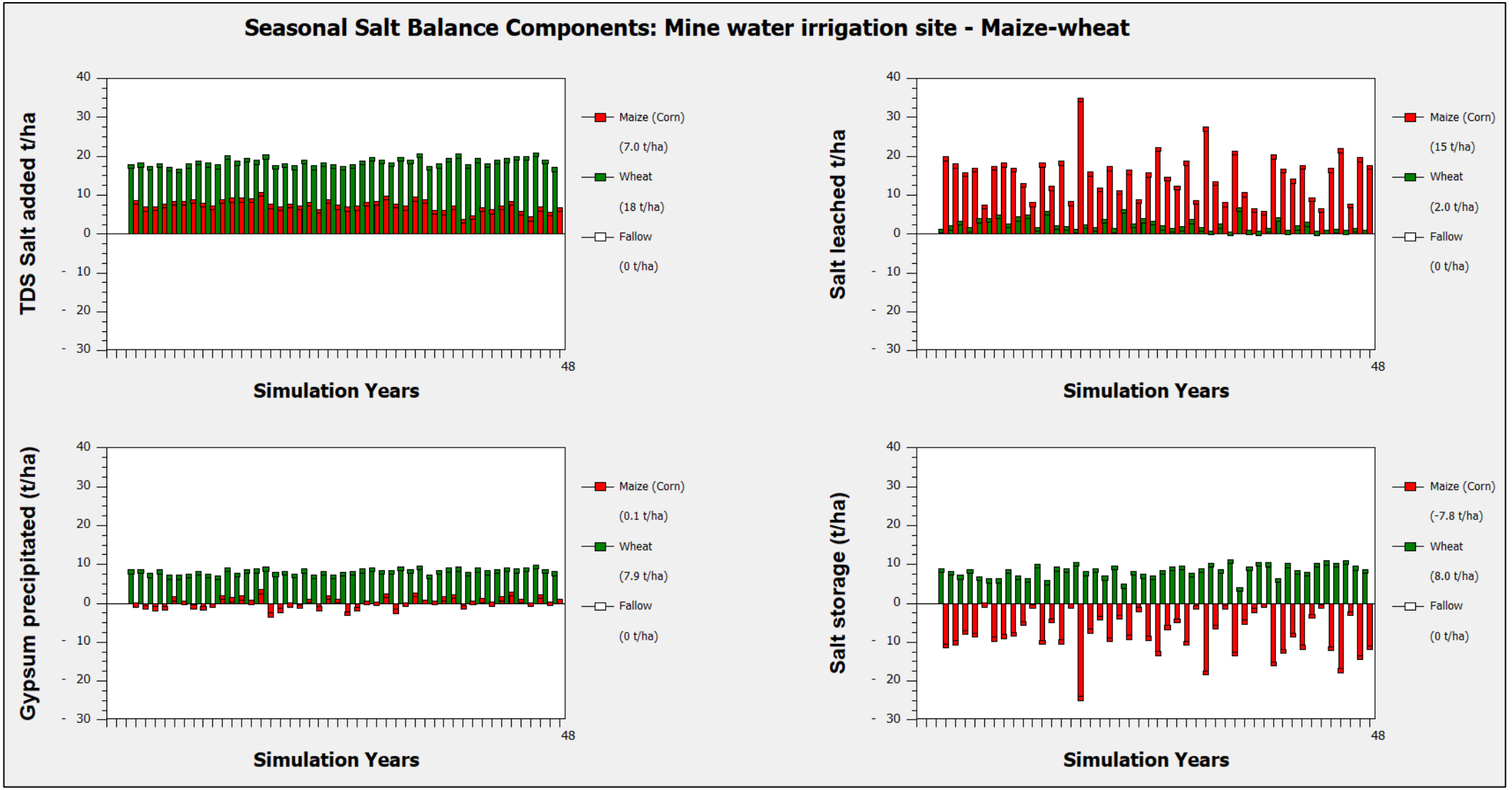


Figure 4.1: Maize-wheat seasonal salt balance for a 45-year DSS simulation.

A problem often associated with the use of mine water for irrigation is the effect on soil salinity. Soil salinization is known to negatively affect crop growth, development, and yields. Maas and Hoffmann (1977) compiled a ranking for various crop salinity thresholds and sensitivities. Maize is ranked at a soil salinity threshold of 180 mS/m (blue dotted line), as moderately sensitive, soybean is moderately tolerant at a threshold of 500 mS/m (orange dotted line), and wheat is tolerant, with a threshold level of 600 mS/m (grey dotted line) (Figures 4.2 and 4.3).

From the simulated ECe results, wheat and soybean as monocrops at the unmined trial site are suitable for irrigation with this mine-affected water, as soil salinity is not expected to be detrimental to crop performance, as it is remains below the published threshold for both crops. Although maize may still produce a reasonable yield with this mine water on this specific site, there may be reductions in maize performance and quality due to the lower salinity tolerance of maize. Over the period of 45 years, the simulated ECe for maize regularly goes above the threshold level (blue dotted line), making the possibility of maize yield reduction or suppression higher. The in-field measurement of the soil's ECe (Section 3.3.5), for the irrigated monocrop maize, is an average of 160 - 180 mS/m, which confirms the DSS simulated results, and no significant yield losses attributed to soil salinity have been noted over the three irrigated seasons (Section 3.3.3).

No measurable overall increase in ECe is observed over the continuous irrigation period of 45 years for all three monocropping systems and can therefore be classified in the medium- to long- term as sustainable from a crop production point of view, with limited detrimental effects on soil salinity.

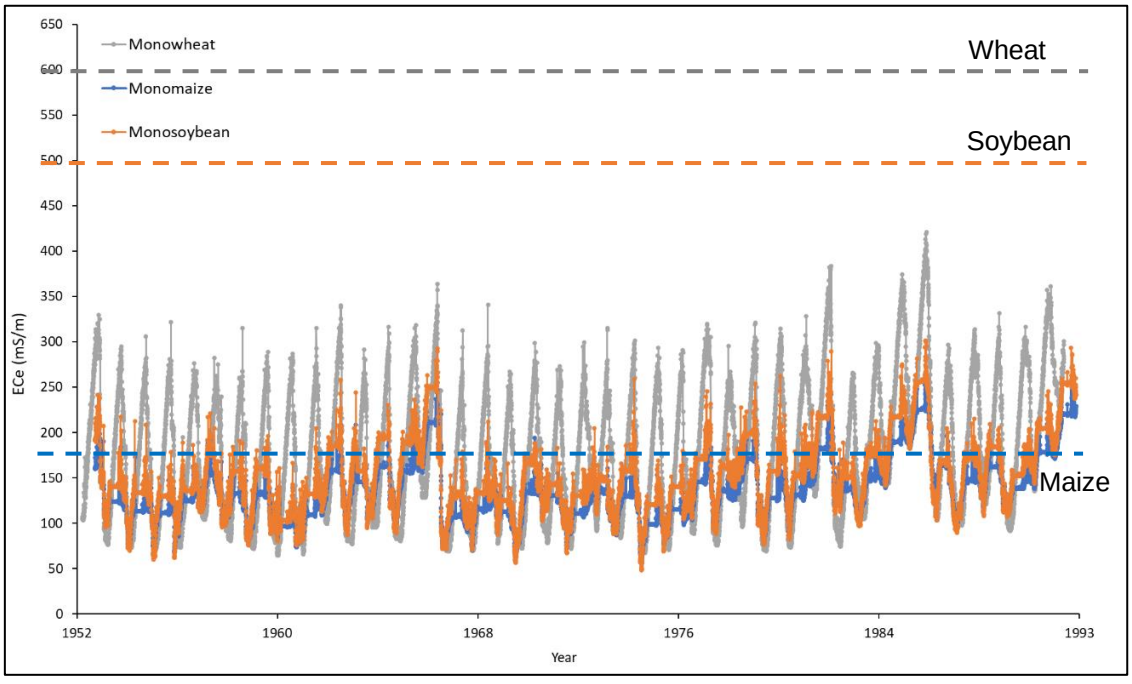


Figure 4.2: Simulated soil profile salinities (EC_e in mS/m) for an irrigation period of 45 years for three monocrops, including Maas and Hoffmann's (1977) salinity thresholds.

The similar ECe pattern, from both double cropping systems, shows the resilience, use and environmental response of this soil-crop system, to irrigating with this gypsiferous mine water. An initial increase (doubling of initial ECe) is seen in the first two years, with the subsequent peaks and troughs pattern on the ECe curves influenced by the crop rotation selection and the weather parameters (precipitation, evaporation, temperatures), with more leaching observed in wet summer months, and salt build up in dry winter seasons. The ECe ranges from an average high of 400 mS/m to an average low of 80 mS/m. A similar response of soybean and maize to this irrigation water is also noted; either of these crops paired with wheat in a rotation, yield similar ECe responses. Wheat raises the ECe, while during both maize and soybean seasons, the ECe lowers dramatically. During winter months, the crop's water requirements must be supplied by irrigation, so more salt is therefore added in winter. This is also a time when the leaching fraction is low, and salts tend to build up in the soil. In summer, less irrigation occurs because rain helps supply crop water needs, and exceeding field capacity helps to leach salts. The soybean-wheat rotation only exceeds the salinity threshold at one time period during the 45-year simulation. The soybean-wheat rotation generally has an ECe well below the stated salinity thresholds, with expected minimal effect on crop yield and quality, and therefore is expected to be a more economical crop selection under the specified site conditions, but of course this depends on actual yields attained, commodity prices, and input costs. The maize-wheat rotation exceeds the maize salinity threshold most of the time. These simulated slightly elevated soil salinity conditions may indicate growing conditions which are unfavourable for optimal and maximal crop performance. Although both double cropping systems have a similar soil ECe patterns over the 45 years, the soybean-wheat rotation is deemed a better cropping system choice than the maize-wheat rotation, for this specific trial site and mine-affected irrigation water.

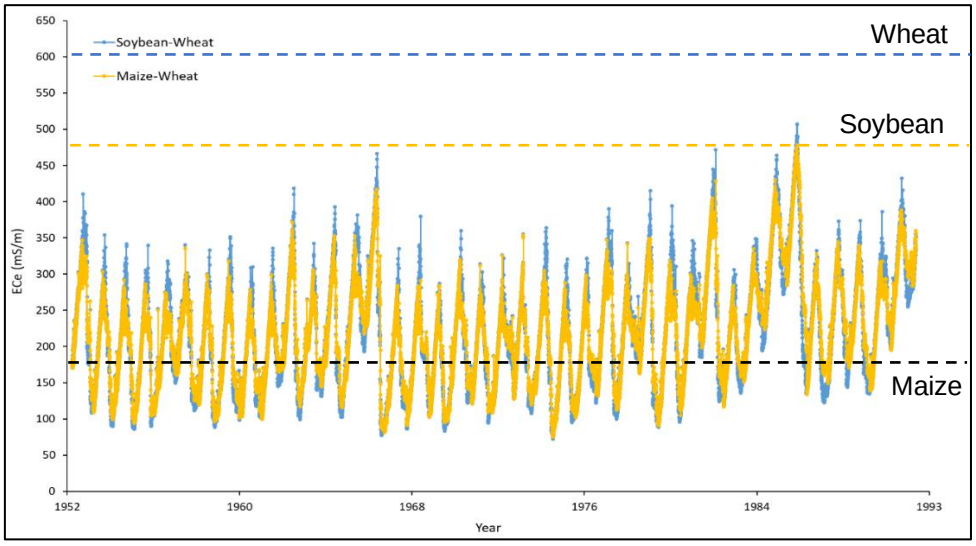


Figure 4.3: Simulated soil profile salinity (EC_e in mS/m) for an irrigation period of 45 years for two double cropping systems, including Maas and Hoffmann's (1977) salinity thresholds.

The DSS simulation results indicate the importance of site-specificity and crop selection. A one size fits all approach has limitations when looking into irrigation with mine-affected waters. Soil and crop criteria need to be detailed and suited according to the area and site conditions where irrigation will occur. The response of crops to different water qualities varies, and through trial and error, the best suited cropping and irrigation system can be chosen and assistance given by using the DSS (du Plessis et al. 2017).

4.4 Conclusion

Detailed weather, soil and irrigation data from the field trial carried out at the trial site (Chapter 3), were used in the DSS model, and simulations were performed to validate the crop growth and water balances. The DSS indicated that the gypsiferous mine-affected water, used at the trial site, was suitable for irrigation under certain conditions.

Depending on what factors are chosen as the best performance indicators, either the monocropped maize or the soybean-wheat rotation had the best overall simulated results of the five cropping systems. The soybean-wheat rotation precipitated the most gypsum per year, 7.9 tons/ha, which is deemed favourable, as well as ideal classification for relative crop yield (%) as affected by root zone salinity, yet doesn't exceed the salinity threshold, which is significant for crop performance. The monocropped maize had the greatest improvement in each respective suitability class in the Tier 2 simulations (Table 4.1), although it had the lowest gypsum precipitation at only 1.3 tons/ha and is sensitive to soil salinity conditions.

The DSS simulations provide insight into which water constituents may be of concern for the predetermined suitability factors. Having a decision-making tool is valuable for planning and management when irrigating with mine-affected waters. Modelling mine-affected water irrigation suitability and environmental effects in the short and long term, have proved to be crucial in determining project sustainability, inception and development, and continuous monitoring required to maintain an irrigation practice of this nature.

CHAPTER 5: TECHNICAL GUIDELINES FOR IRRIGATING WITH MINE-AFFECTED WATERS

The literature, reviewed in Chapter 2, demonstrates the extensive research and success of mine water irrigation in South Africa and globally. Furthermore, it illustrates the gap and need for the development of a standardised framework and technical guideline as a tool for beneficially using suitable mine-affected waters within the South African agricultural environment. The concepts presented in this chapter have been published in a WRC Technology Transfer Report (Heuer et al 2020).

5.1 Introduction

The mining and agricultural industries can be amongst the most lucrative in South Africa, but both are resource input intensive (Ighalo et al. 2022). As both industries use a large amount of water, sustainable use and good governance of this scare resource is crucial. The mining industry is notorious for negatively affecting large volumes of water, and these need to be treated before productive use or deemed safe for discharge. With agriculture requiring large water inputs to improve and optimise yields of crops, a noteworthy opportunity arises (Ronquest 2019). Using mine-affected water of appropriate quality for irrigation should reduce water treatment costs incurred by mines and taxpayers, and an additional and supplemented water supply should contribute to increased agricultural production (Pretorius et al. 1999). However, not all mine-affected waters are suitable for irrigation purposes, thus risk-based approaches and long-term monitoring are imperative for ensuring sustainable irrigation with acceptable environmental impact (Annandale et al. 2006).

Both irrigated environments and mine-affected water management are complex systems (Kunz et al. 2013). Each potential irrigation scenario has an accompanying level of complexity, whether environmental or institutional, and requires a tailored approach and management response. A guideline to irrigation with mine-affected waters proposes a framework to improve governance, and lessen the challenges faced when making operational and technical decisions about irrigation with mine-affected waters.

The primary aim with the development of a Technical Guideline is to provide a framework for beneficially using suitable mine-affected waters and soil resources within the agricultural environment, to produce crops sustainably, while limiting environmental impact. All potential risk factors associated with soils, waters and crops irrigated with mine waters should be assessed, to indicate monitoring requirements and to identify means of setting thresholds for action, to respond when monitoring indicates constituents of concern are outside acceptable

limits. This proposed Technical Guideline is intended to be a practical reference for all stakeholders, including prospective irrigation water users, and policy and decision makers.

Site-specificity is fundamental when planning, structuring, and developing an irrigation scheme of this nature. Mine-affected water suitability for irrigation first needs to be determined, as the long-term viability of irrigation hinges on this fitness-for-use determination. Using a locally developed Irrigation Water Quality Decision Support System (DSS) (Du Plessis et al. 2017), it is possible to model the effect of irrigation management practices with a specific mine-affected water on a specific crop's performance, soil properties and irrigation equipment, thereby indicating whether or not there are conditions under which the proposed irrigation project is likely to be sustainable in the long-term. The DSS will also facilitate the identification of potential constituents of concern (CoC) in the irrigation water.

Once a water is deemed fit for use for irrigation, an assessment of the proposed irrigated site should be completed. Site selection is essential for ensuring the long-term productivity and environmental sustainability of the irrigation project.

An integrated environmental monitoring programme tailored to the specific site is required to maintain the integrity of the irrigated environment. Monitoring procedures should be chosen according to the identified constituents of concern and their potential impact on environmental receptors (crop, soil, and water resources).

Setting constituent thresholds for action ensures that identified constituents of concern, in the three receptors of the irrigation site, can be controlled before unacceptable environmental harm is caused.

The success of irrigation with mine-affected waters (MAW's), will depend on effective communication between MAW users and relevant authorities; a continuous, assured mine-water supply (quality and quantity); and regular strategic monitoring of water, soils and crops. It is highly recommended to refer to the mining sector resource protection and waste management strategy and operational Best Practice Guidelines (BPG) (DWAF, 2006) to ensure the mine-affected water irrigation activities are carried out according to the principles set out in these documents. The Technical Guidelines developed in this dissertation assumes that stakeholders looking to irrigate with mine-affected waters will engage with specialists who are competent, and who have the relevant and applicable knowledge to provide technical support for a project of this nature.

The purpose of this proposed Technical Guideline (TG) is:

- To provide a standardised framework for the establishment and stewardship of irrigation with certain mine-affected waters in South Africa;
- To advise on the use of the Irrigation Water Quality Decision Support System (DSS) to provide site-specific, risk-based assessments of the fitness-for-use of mine waters for irrigation;
- To provide appropriate site irrigability characterisation procedures to identify an irrigation landscape capable of sustainably supporting a mine water irrigated cropping system;
- To provide a risk assessment framework that will identify potential key unwanted events that may occur as a result of irrigation with mine water;
- To provide a methodology for identifying constituents of potential concern and determining thresholds for action;
- To provide an integrated monitoring regime to ensure that qualities of soils, waters and crops fall within acceptable environmental thresholds; and
- In the event that monitoring identifies constituents of concern exceeding acceptable levels, to recommend adaptive management strategies to remedy the situation.

5.2 Standardised Framework

The goal is sustainable use of irrigation with MAW. Effective collaboration, planning, adaptation, and management of resources is necessary to attain irrigation sustainability (Figure 5.1). Identified competent, independent professionals who have the necessary academic qualifications, vocational experience, and professional registration within the related field, should advise on the technical aspects of an irrigation environment (Dippenaar et al. 2014). Engaging with relevant authorities (DWS, DEA, DALRRD) ensures compliance with South Africa's environmental and agricultural laws and are followed throughout the irrigation project's lifecycle (Pocock & Coetzee, 2021). Site-specific environmental risk assessments identify possible hazards and their associated impacts within the irrigation environment. Using the Decision Support System (DSS), in conjunction with site selection procedures, an irrigation environment's suitability can be characterized (du Plessis et al. 2017; LaRSSA, 2019). Adaptive management and flexibility are required to ensure the irrigation strategy changes according to the needs of the specific irrigation environment. If followed, these listed factors will assist in the development of a sustainable irrigation with MAW project.

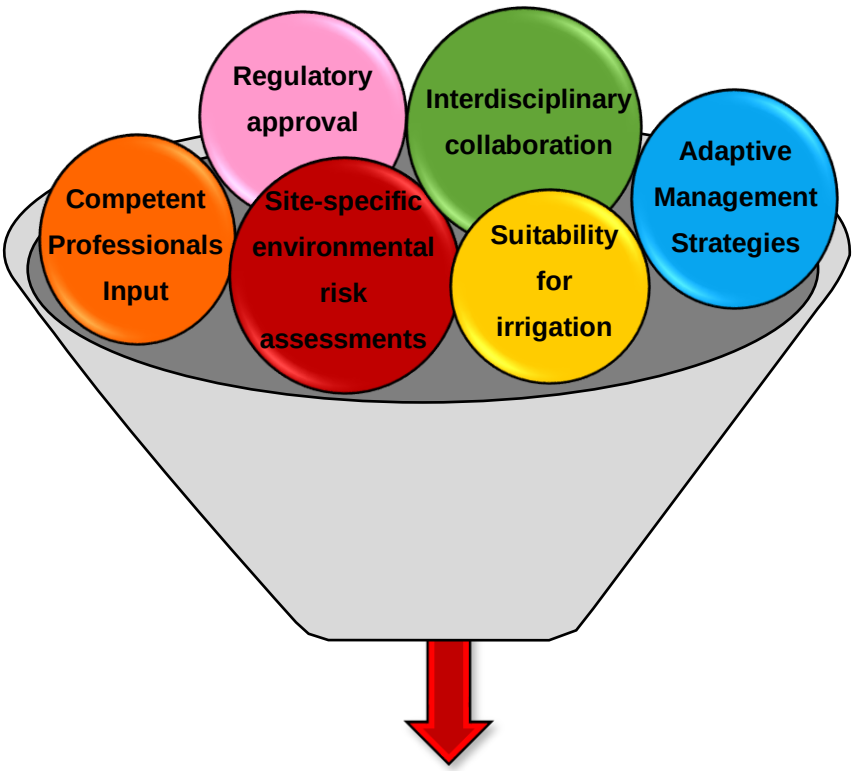


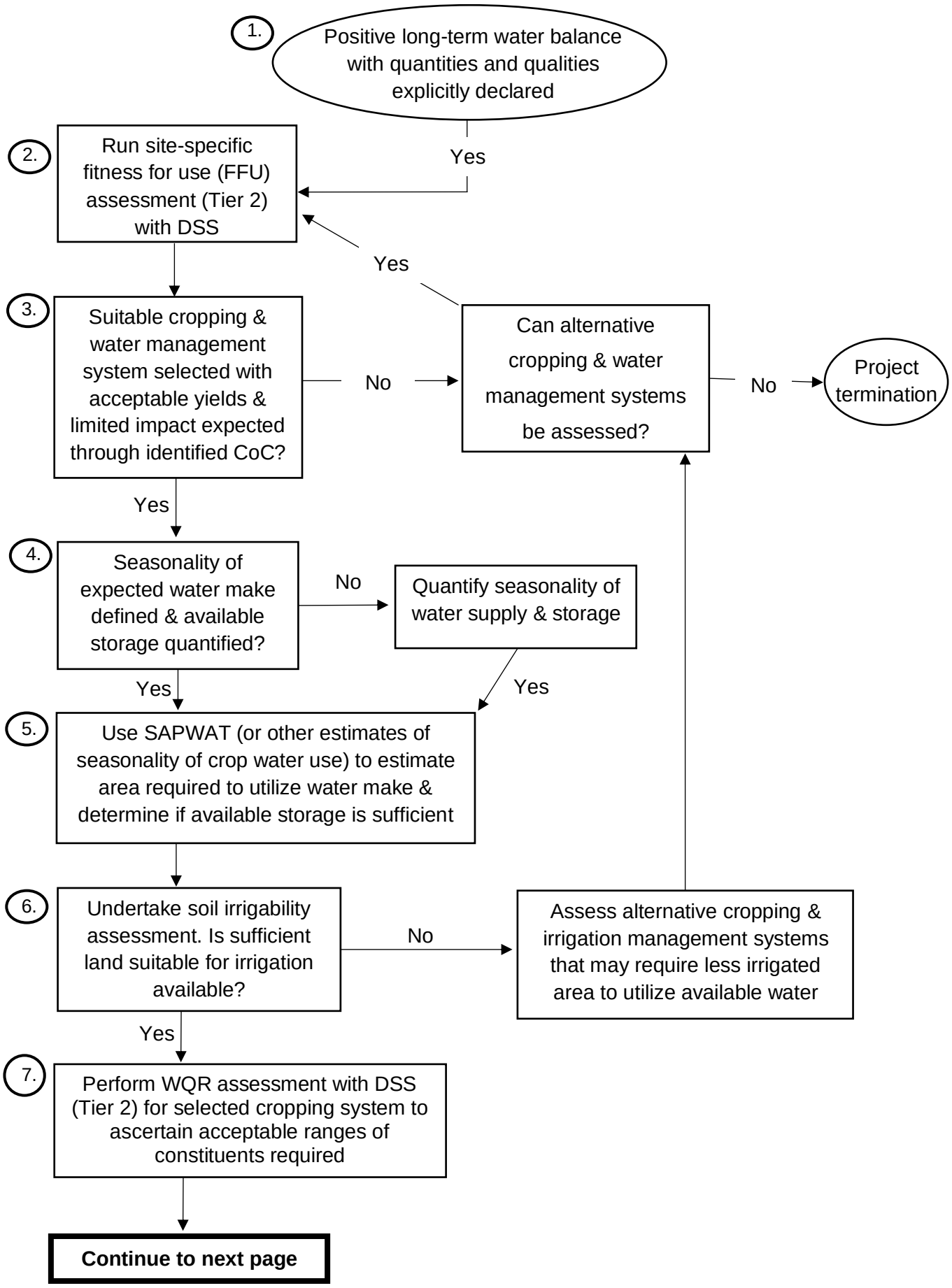
Figure 5.1: Factors pivotal to project success and sustainable irrigation practices with mine-affected waters.

This Technical Guideline assumes that stakeholders looking to irrigate with MAW's will engage with specialists who are familiar with South African agricultural, mining and environmental legislation applicable to this practice. A separate set of guidelines that focus on attaining regulatory approval for mine water irrigation have been developed, WRC (TT report 837/20) (Pocock & Coetzee, 2021), and this framework should be consulted for policies and regulations surrounding the permitting of irrigation with MAW. Competent, independent professionals should be engaged throughout the feasibility study and decision-making processes of a mine water irrigation project. Identifying and understanding risks and predicting long, medium and short-term impacts, as well as any suitable mitigation practices, should provide the necessary assurance for project lifespan success. Regardless of geographical region, the resource mined, the mine-affected irrigation water quality and quantity, an integrated framework is required for evaluating an irrigation project using mine-affected waters. Using a risk-based management approach should ensure appropriate scientific methods and oversight are employed throughout the irrigation project.

The following key points summarised, are suggested considerations (Figure 5.2 – Decision Tree) to be used as a guide for using mine-affected water for irrigation:

1. Determine a mine's long-term water balance with the expected quantities (seasonality) and qualities stated for the lifespan of the intended irrigation period
2. Assess the suitability of the mine water for irrigation - Run Fitness-for-Use (FFU) assessment with Decision Support System (DSS) and note the identified Constituents of Concern (CoC)
3. Undertake soil irrigability assessments to ascertain if sufficient irrigable land is available for mine water irrigation
4. Establishment of suitable cropping and water management system with acceptable yields and limited environmental impact expected through identified CoC
5. Environmental risk assessment is performed for the identified CoC, and monitoring programs and thresholds for action are determined thereafter
6. With expert recommendations, an adaptive management approach will be required to ensure project sustainability

These steps can be used as a guide on the sequence of considerations to take in assessing if mine-water irrigation in a specific setting is feasible.


1.
Positive long-term water balance with quantities and qualities explicitly declared
Yes
2.
Run site-specific fitness for use (FFU) assessment (Tier 2) with DSS
Yes
3.
Suitable cropping & water management system selected with acceptable yields & limited impact expected through identified CoC?
No
Can alternative cropping & water management systems be assessed?
No
Project termination
Yes
4.
Seasonality of expected water make defined & available storage quantified?
No
Quantify seasonality of water supply & storage
Yes
Yes
5.
Use SAPWAT (or other estimates of seasonality of crop water use) to estimate area required to utilize water make & determine if available storage is sufficient
6.
Undertake soil irrigability assessment. Is sufficient land suitable for irrigation available?
No
Assess alternative cropping & irrigation management systems that may require less irrigated area to utilize available water
Yes
7.
Perform WQR assessment with DSS (Tier 2) for selected cropping system to ascertain acceptable ranges of constituents required
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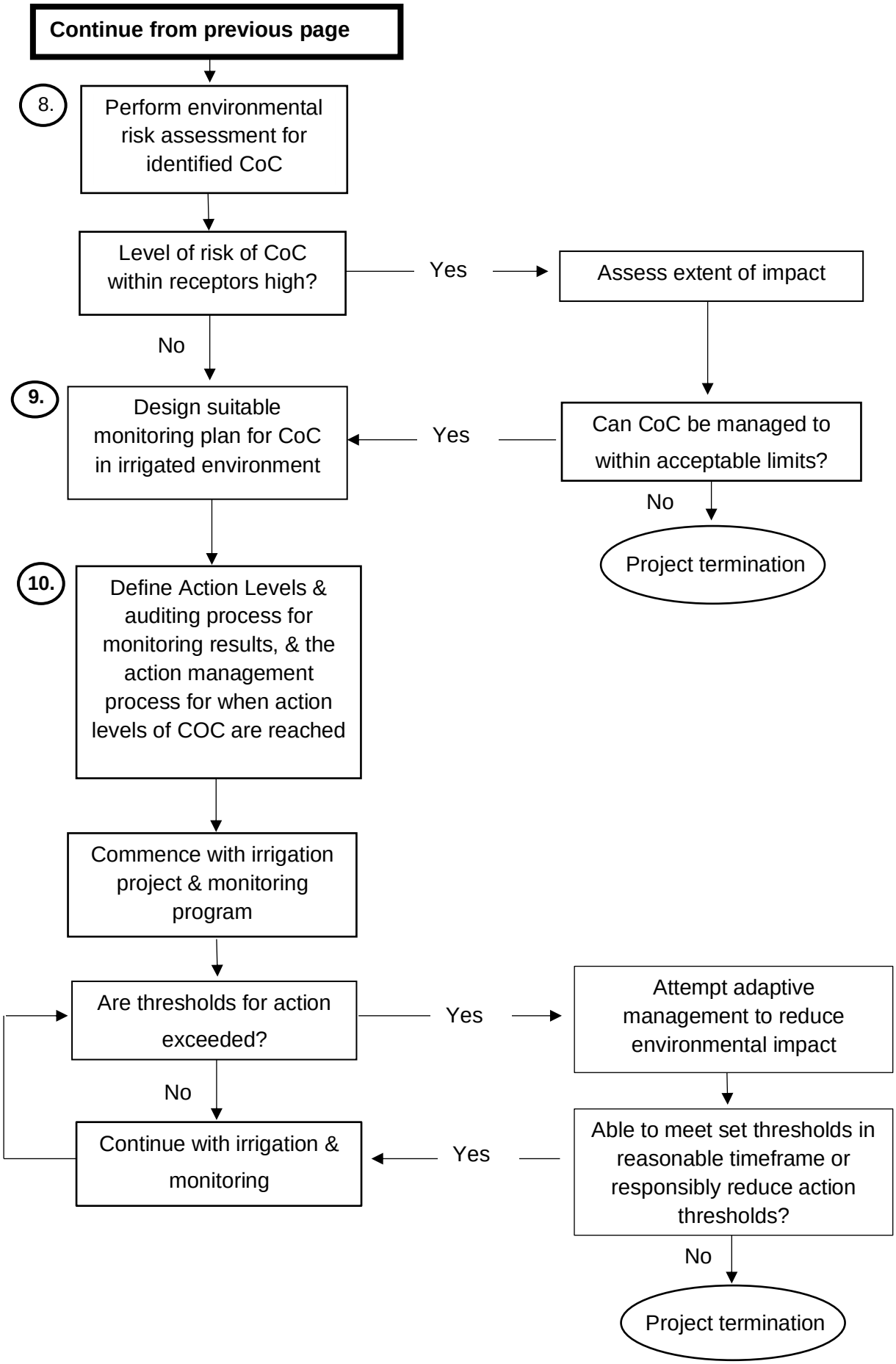

Figure 5.2: Decision tree for assessing if mine-water irrigation in a specific setting is feasible and accompanying action steps.

The subsequent sections describe the detail behind the relevant branches within the proposed decision tree.

5.3 Mine-Affected Waters

5.3.1 Water Balance, Quality and Quantity

Mine water characterisation requires the determination of the water chemistry and production volumes a mine is likely to generate over its lifetime and post-closure (Figure 5.3) (Wolkersdorfer et al. 2020). Quantifying the characteristics of mine water intended for irrigation use, enables scientifically sound decisions to be made (Reddy et al. 2014). Geochemical modelling can attempt to predict the long-term water chemistry, and a hydrological model can simulate long-term affected water production volumes. These studies can therefore attempt to predict the magnitude and temporal nature of a mine's potential impact on its proximal receiving environment.

A mine's water balance quantitatively defines hydrological inflow and outflow of a geological unit. Mines with a water surplus or positive water balance are ideal to investigate the potential for irrigation with mine-affected water, as irrigation is a consumptive use of water. Quantifying the volume of water produced, its seasonality and available storage capacity, ensures that a cropping system is selected to best suit the mine's water balance. Knowing the rate of mine water supply, constant or intermittent, in conjunction with an area's rainfall regime, appropriate irrigation scheduling can be recommended to ensure water delivery is tailored to a specific crop's water use (Pretorius et al. 1999). Constant re-evaluation of a mine's water balance is required to ensure water production is well predicted, updated, and managed, and sufficient water is available for crop production. Many mines do not have accurate or reliable predictions of the volume of water "make" that will emanate from the mine post-closure, and expert assistance is essential to determine this key factor. The selection of crops for tolerance to water quality constituents must be harmonised with crop water requirement and water availability. Provisions must be made for years with above or below average rainfall, with additional irrigable land area for cropping or water storage catered for.

Characterising mine water quality for irrigation entails quantifying major and minor anions and cations present in the water, as well as any other constituents that may affect the success of an irrigation project. Continuously assessing the quality of mine water ensures predictions can be made of the response of the crops, soil and irrigation equipment to irrigation (Reddy et al. 2014). It is imperative that mines characterise their water quantities and qualities as accurately as possible, as all proposed cropping and irrigation management actions are determined using this data in the DSS simulations (du Plessis et al. 2017). The DSS should also be used to ascertain appropriate Water Quality Requirements (WQR) of the selected site-specific

cropping system (Tier 2 simulation), as these represent the ranges of constituents within which the water quality must remain for the selected irrigation project to remain viable.

Irrigation system design procedures appropriate for irrigated area and cropping requirements should be followed. Consultation with competent irrigation professionals will ensure the irrigation equipment is designed and implemented according to industry standards (SABI, 2017). Specific attention needs to be paid to the effect of the water quality on irrigation equipment, as mine waters could be scaling or corrosive.

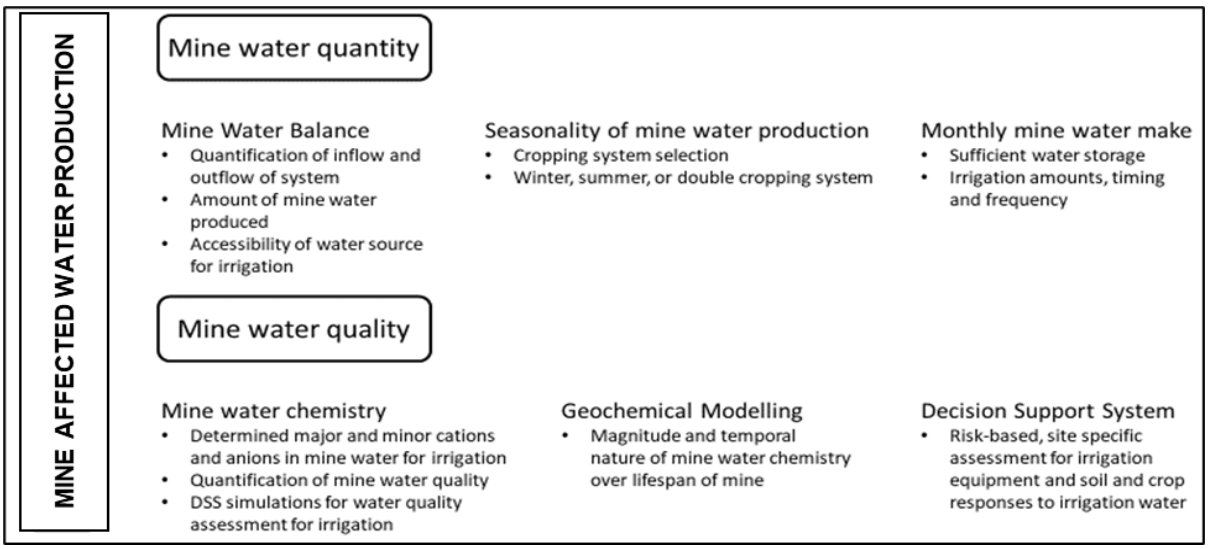

Figure 5.3: Summary of water and solute balances to consider for mine water irrigation planning (Heuer et al. 2021).

5.3.2 Decision Support System

A locally developed, software-based, Irrigation Water Quality Decision Support System (DSS), provides site-specific, risk-based guidance on the fitness-for-use for irrigation of water sources, as well as determining water quality requirements for a specific cropping system and water management approach. The DSS provides irrigation water users with information about the associated risks of using a specific water quality for irrigation, under specific site conditions (climate, soil, crop, water management options), including associated risks for irrigation equipment and soil and crop resources.

As discussed in Chapters 3 and 4, the DSS is structured into three tiers. Tier 1 encompasses the generic and conservative 1996 South African Water Quality Guidelines that are likely to be of limited use for poorer quality mine-affected waters. The fitness-for-use (FFU) assessment categorises water constituents into different levels of acceptability and implied risk.

The decision tree below will guide the water user through the options available in the DSS. Firstly, the user would assess the fitness-for-use of a particular water. For this, water quality data are required, and to take site-specifics into account, a Tier 2 simulation is required. Once a suitable cropping system and irrigation management strategy has been decided upon based on the FFU simulation, the user can run a Water Quality Requirements simulation for these specific conditions, to generate output on the range of water qualities that should be acceptable for this intended use. Tier 2 FFU evaluation and outcome reports indicate the fitness-for-use and the expected impact of a specific water quality on crop yield and quality, soil quality, and irrigation equipment, for a specific location. The DSS can also supply additional information if required.

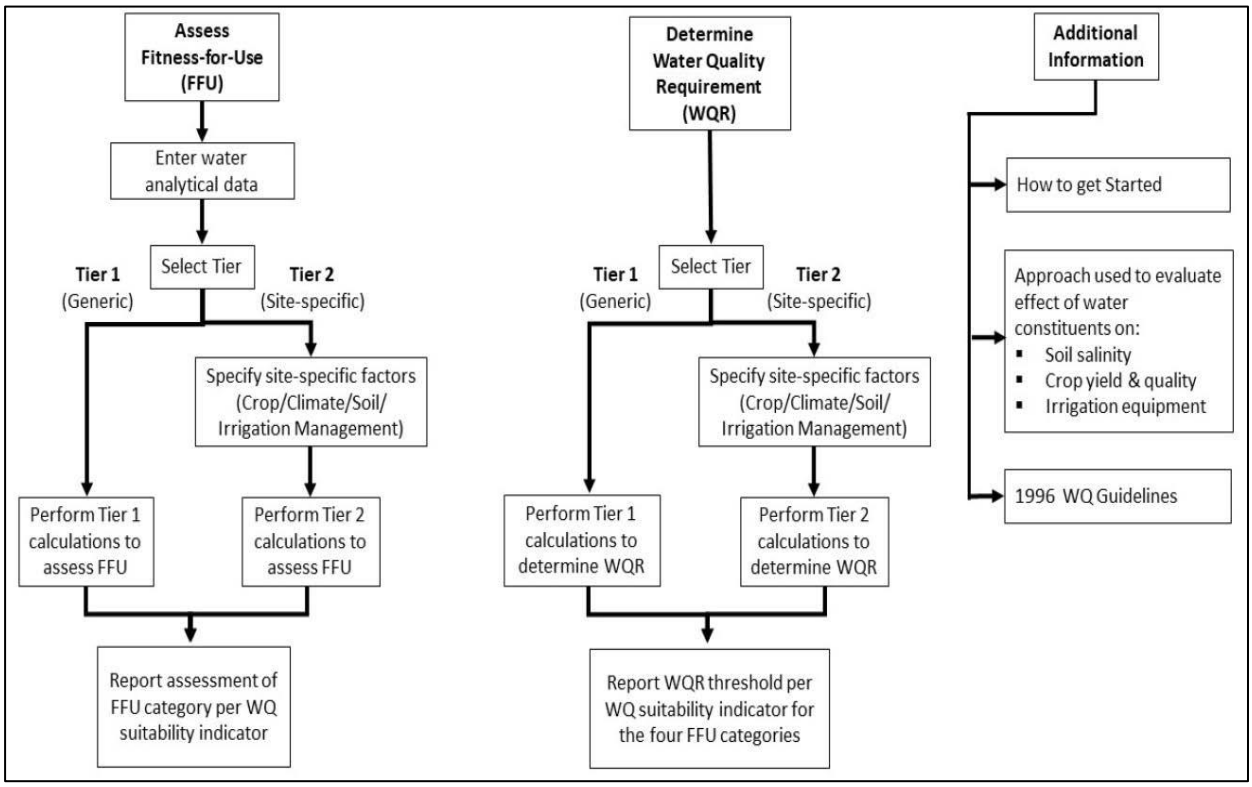

Figure 5.4: The structure of the Decision Support System (DSS) when assessing the suitability of water for irrigation (du Plessis et al, 2017).

The water input screen (Figure 5.5) requires the minimum user-defined records indicated as the major cations and anions, as well as pH and electrical conductivity (EC). For mine water, it will also be essential to enter key trace elements present in the water, and possibly nutrients, this assists in the identification of potential constituents of concern. The site-specific input screen (Figure 5.6) requires the user defined conditions, stating all site, weather, soil and irrigation management applicable to a potential irrigation site.

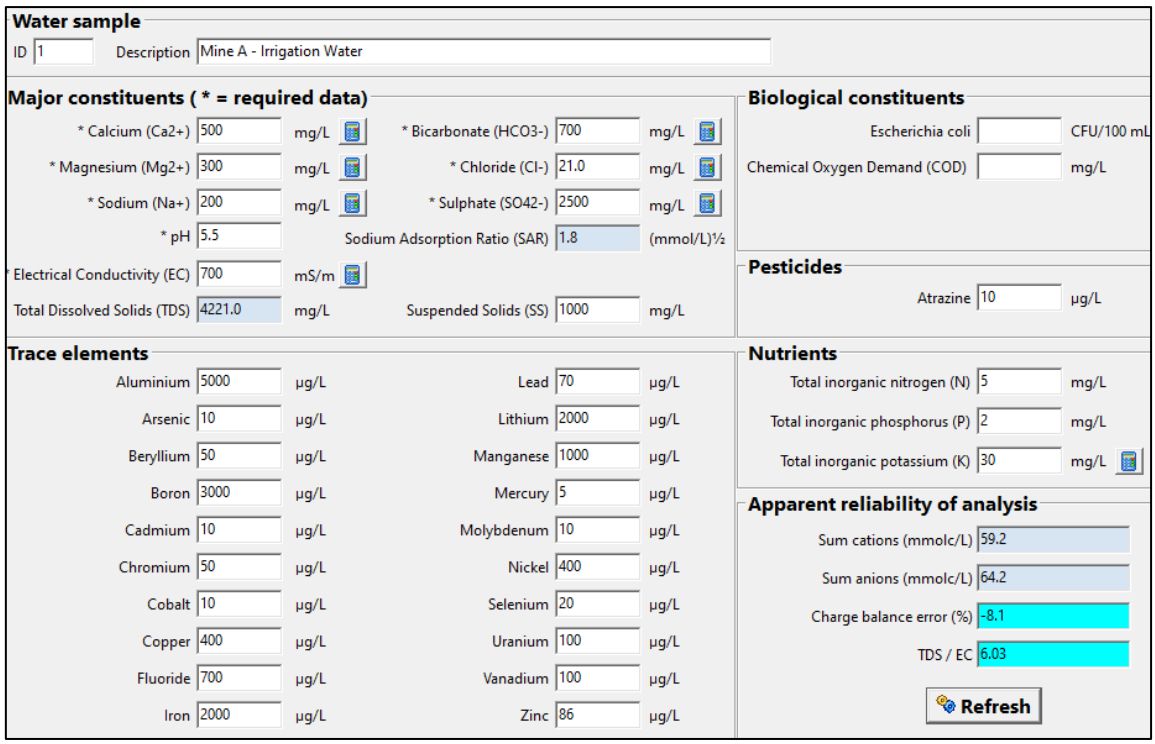

Figure 5.5: The water quality input screen as seen in the DSS.

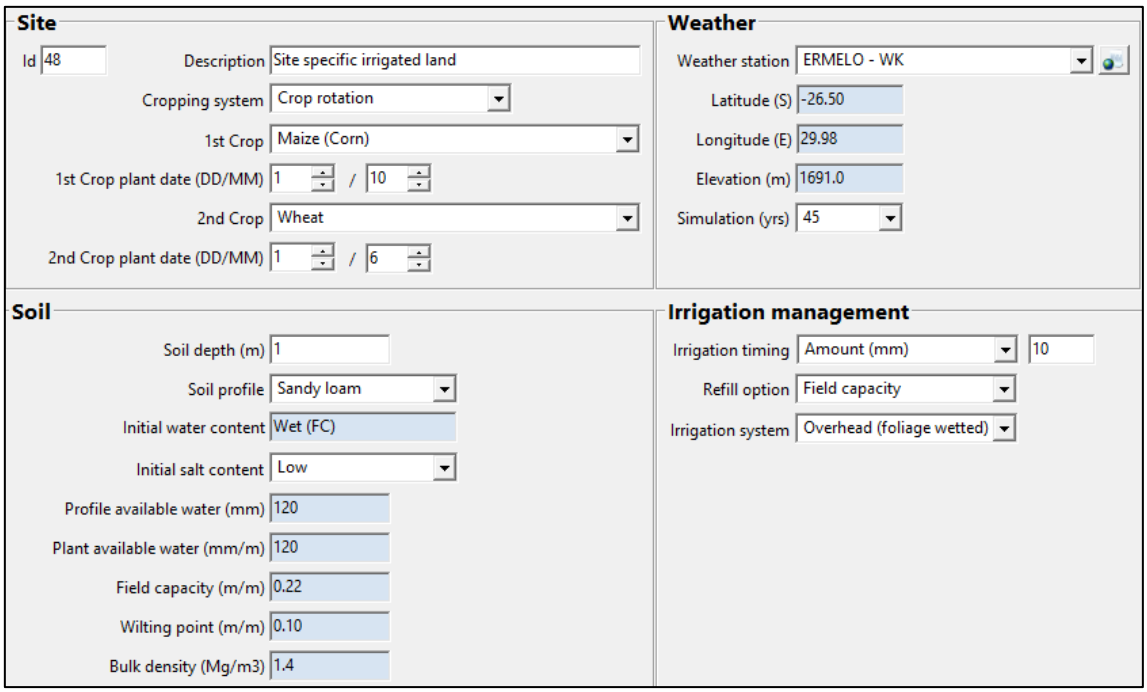

Figure 5.6: The input screen where site-specific details are selected.

Colour-coded classification of the water quality categorises the fitness-for-use into four classes, corresponding to the increased level of risk (Table 5.1). These four FFU suitability categories and their accompanying colour schemes, are consistently used throughout the DSS.

Table 5.1: A general description of the DSS fitness-for-use categories for water quality (du Plessis et al, 2017).

Fitness-for-use category	Description
Ideal	A water quality that would not normally impair the fitness of the water for its intended use
Acceptable	A water quality that would exhibit some impairment to the fitness of the water for its intended use
Tolerable	A water quality that would exhibit increasingly unacceptable impairment to the fitness of the water for its intended use
Unacceptable	A water quality that would exhibit unacceptable impairment to the fitness of the water for its intended use

The DSS reports the following suitability indicators to assess the impact a water quality may have on the soil quality, crop yield and quality, and irrigation equipment:

- Soil quality – Soil Profile Salinity, Soil Permeability, Oxidisable Carbon Loading, and Trace Element Accumulation
- Crop Yield and Quality – Root Zone Effects on Yield, Leaf Scorching when wetted, Contribution to NPK Removal, Microbial Contamination and Qualitative Atrazine Damage
- Irrigation Equipment – Corrosion or Scaling, and Clogging of Drippers

5.4 Site Selection

5.4.1 Introduction

South Africa's irrigation footprint is limited by water scarcity (DWA, 2013), making alternative water sources such as mine-affected water an invaluable and viable irrigation water source. Dryland unmined fields and appropriately rehabilitated fields in close proximity to mine water sources could use this additional water in the rain-fed growing season, as well as to produce crops in the dry season (Hattingh, 2016; Frost & Sullivan, 2011). The yield potential of such areas is thereby expected to increase dramatically, with subsequent growth in the local economy, and benefit water users and the surrounding community.

When identifying areas for irrigation with mine water, an integrated and multi-disciplinary approach to site selection is required. Not only does the soil profile need to be irrigable, but the position in the landscape and proximal environment is important when selecting a suitable site. Although many mine waters suitable for irrigation are gypsiferous in nature, not all of the salt in the irrigation water will precipitate as gypsum in the soil profile. For irrigation to be sustainable, salts not precipitating need to be leached from the root zone. The fate of solutes passing through the soil profile should be predicted and the impact determined to be acceptable for the project to continue. For irrigation with mine-affected waters, the water logging and salinization risk also determines the suitability of an area of land for this type of

water use. Areas that are susceptible to salinization and have a high potential for salts to affect the surrounding natural environment should be identified and excluded from consideration. Alternatively, proven effective mitigation measures must be put in place for improved drainage, and, if necessary the interception and management of solutes leaving the field.

Identifying risks and conducting a comprehensive site risk assessment should ensure the selection of an environmentally sustainable irrigation site, if sufficient detail and insight is acquired during the execution of the site selection considerations listed below (Fairman et al. 1998).

Determining the agricultural potential of land and ensuring on-site conditions and positioning within the surrounding environment are appropriate for irrigation, provides a scientifically sound basis for site selection. A source - pathway - receptor (SPR) analysis (Hasanuzzaman et al. 2018; Sayers et al. 2005) should be employed to assess the risks, susceptibility, and capacity of an environment to receive mine-affected water through irrigation.

5.4.2 Soil Irrigability

Not all soils are suitable for irrigation, and characterising the soil is essential for determining irrigability. It is highly recommended that a qualified professional soil scientist be consulted when determining the suitability of land for irrigation. The following factors can be used to determine land suitability for irrigation (Adapted from Scherer 2018 and USBR 2005).:

- Effective soil depth
- Internal soil profile drainage
- Surface drainage

Effective Soil Depth

Determining the potential rooting depth of the soil profile throughout the irrigated area ensures sufficient soil is available for root development, nutrient uptake, water storage capacity and adequate drainage.

Soil Profile Internal Drainage

Many mine waters are gypsiferous, and this presents the opportunity to precipitate gypsum in the soil profile, thereby reducing soluble salt load on the water environment. However, irrigation is not sustainable if excess soluble salts cannot be leached from the profile. A number of considerations are involved in assessing the internal drainage ability of a soil profile:

- Identifying if there are any limiting layers present in the soil profile throughout the irrigated area.
- Identifying whether such limiting layer(s) would inhibit root growth and development

and limit crop production.

- Identifying the extent to which limiting layer(s) restrict drainage and whether the soil profile is at risk of water logging or salinisation.
- Determining the soil's infiltrability and permeability to indicate if drainage problems are likely to arise, and if any mitigation measures should be implemented.

Surface Drainage

Determining the uniformity of the slope of the land allows for inferences to be made on potentially problematic ponding areas, run-off, recharge, and erosion rates, as well as assisting with irrigation system design. This is important for planning for mitigation measures, if applicable, to be implemented to lower the risk of soil material losses, water logging, and salinization of the irrigated land. Developing a site-, local- and regional-specific hydrological model can be complex, but using existing guidelines, tools and data, as well as onsite characterisation, an extensive understanding of the ground and surface flow regimes can be determined (Diamond et al. 2019; Dippenaar et al. 2019; Gomo & Vermeulen 2017).

An irrigable soil classification (Table 5.2) broadly groups soils into three irrigation categories, irrigable, conditionally irrigable, and non-irrigable. Irrigable soils can generally be irrigated under most conditions. Conditionally irrigable soils may have some limitations, require a higher degree of management, and introduction of supplemental surface or subsurface drainage may be necessary. This can be judged on an individual, site-specific basis. Irrigation of non-irrigable soils may cause further soil or environmental degradation and soil productivity loss, and mitigation measures would have little to no effect. Irrigation of 'Non-Irrigable' soils is strongly discouraged, as these environmental conditions are not conducive for the beneficial use of mine-affected waters.

Table 5.2: Irrigable soil classification (Adapted from Scherer 2018 and USBR 2005)**.**

	Irrigable	**Conditionally irrigable**	**Non-irrigable**
Soil depth	> 750 mm	500 – 750 mm	< 500 mm
Soil profile drainage			
Limiting layer occurrence	Little to none	Slight	Dominant
Restriction to root growth	Low to none	Slight restriction	Severe
Risk of water logging	Low to none	Possible	Severe
Risk of salinization	Low to none	Possible	Severe
Surface drainage			
Slope	Little to none	Gentle	Steep and/or undulating
Risk of surface ponding	Low to none	Slight	Severe

Site considerations where irrigation with mine-affected waters may not be permissible:

- Environmentally sensitive areas which are susceptible to water pollution (below 1:100-year flood line, wetlands, vleis, pans and flood plains)
- Areas where groundwater recharge is great and shallow water tables exist
- Areas of steep slopes where slope stability, run-off and soil erosion are problematic
- Areas of consistent or intermittent ponding or water logging
- Protected areas or proclaimed national parks (natural habitats of endangered plant or animal species)
- Areas of instability (dolomitic or karst areas where subsidence or sinkholes are prevalent, seismic or fault zones)

Although irrigation in these areas is normally strongly discouraged or legally impeded, an open dialogue with the relevant environmental departments is imperative for further assessments and re-evaluations of such sites, where applicable. Irrigation with mine-affected waters in some areas may be reconsidered if the water user could scientifically prove there are adequate mitigation measures in place to alleviate any unacceptable, potentially negative effects.

Some spatial analysis tools or publications that can be used to assist in assessing site suitability for irrigation follow:

- Land capability assessment (DAFF, 2016)
- Digital elevation models (DEM)
- National hydrogeological overview map series (DWAF, 2003)
- National web-based environmental screening tool (DEA, 2017)
- National Freshwater Ecosystem Priority Areas (NFEPA) (SANBI, 2011)

It is recommended that if specialised studies are to be performed, professional hydrogeologists, soil scientists, agriculturists and environmental practitioners should be consulted (Pocock & Coetzee, 2021; Dippenaar et al. 2014). Should there be any environmental concerns raised during site selection, it is the responsibility of the water user to consult with the appropriate authorities and to put measures in place to ensure sustainability of the irrigation project, before implementation.

5.5 Environmental Risk Assessment

5.5.1 Introduction

The risk assessment process should follow the International Standard (ISO 31000:2018) Risk Management Principles (ISO, 2018). Risk assessments should be regularly revised and updated as the project progresses to ensure stated risks are continuously reviewed as more data is received to validate the models used to predict impacts. The international standard recognises five steps to be undertaken in the risk management process. These are:

1. Setting the context;
2. Risk identification;
3. Risk analysis;
4. Risk evaluation; and
5. Risk treatment.

These five steps are linked by monitoring of the context, and setting boundaries, requiring a continuously repeating cycle of determining risk levels and identifying appropriate risk mitigation strategies. Undertaking a risk assessment requires the assembly of an appropriately skilled technical team, with representatives of the irrigation project management team and the use of a trained facilitator, in order to ensure that the outcome accurately reflects the true "unwanted events" (risks) that face the project over its lifespan, and identifies appropriate control measures that are simple, measurable and implementable (Cosma & Hopcroft, 2019).

In addition to the evaluation of internal risks associated with soil, water and crop variables, the risk assessment must also focus on risks posed by management and external issues. Competency of irrigation project staff, availability of long-term expert supervision, risks associated with climatic damage, crop harvesting, marketing, crime and the socio-economic status of surrounding communities, will all be factors which should be fully evaluated in the risk assessment process for any irrigation project. Although the formal risk assessment process for a proposed irrigation project should encompass all the above issues, this should be effectively managed by carefully following ISO 31000 (2018) principles, and accordingly, the detail of this will not be covered further in this guideline.

The remainder of this section on risk assessment will focus on the requirements to identify unwanted events related to the impacts of particular constituents of concern in the irrigation water, and how they can be expected to interact with the site environment. Effective environmental risk assessment for mine water irrigation is essential when looking to determine an acceptable impact level a constituent may have on the receiving environment (soil, crop, and water resources) (Fairman et al. 1998). Categorising and prioritising on-site irrigation

constituent risks ensures that applicable mitigation strategies can be developed and employed (Reddy et al. 2014).

The following steps can be used when determining potential constituents of concern, their impact, and whether a monitoring plan and threshold levels for action are necessary:

- Using some form of a water footprint assessment (Reddy et al. 214), quantify the geochemical and water production volumes of the mining and irrigation environment
- From DSS output reports, identify which constituent(s) have been highlighted as tolerable or of an unacceptable level
- Distinguish which constituents identified are mobile, and which receptor(s) (soil, crop and water resources) could be impacted (environmental risk matrix)
- Characterise the constituents which would have greater impacts on the receptors, and devise monitoring requirements and a plan to observe and detect changes in the receptors
- Define logical threshold levels and monitoring locations based on identified CoC environmental mobility and site-specificity

5.5.2 Constituents of Concern (COC)

As part of the risk identification, analysis, and evaluation process, the following three steps are recommended when looking at the potential impact a constituent has on the irrigated environment. Firstly, identification of CoC, secondly, the potentially affected receptor of the CoC, and finally, the characterisation of the risk the CoC poses to the receiving environment.

Identification of CoC

Constituents of concern (CoC) can be identified in the soil quality, and crop yield and quality outcome reports obtained from the DSS simulations (du Plessis et al. 2017). Constituents of concern can be identified as higher risk if highlighted as tolerable or unacceptable fitness-for-use in the DSS reports. At the discretion of a competent agriculturist, soil scientist or environmentalist, with relevant expertise, some constituents that are deemed tolerable or unacceptable in the DSS reports, may be deemed of low risk on site, with sufficient justification (Tier 3 assessment). Once a list of constituents of concern has been made, the risk to the receptors can then be determined and characterised.

Receptor(s) of CoC

The source-pathway-receptor (SPR) system describes the movement of constituents from the irrigation water (source) through pathways (surface runoff, infiltration and percolation) to the receiving environments (soil, crops, and water resources) (DWS, 2017). Identifying in which realm (crop, soil or water) a specific CoC may have its greatest impact and effect, assists in determining the risk a constituent may pose to receiving environments (Figure 5.7).

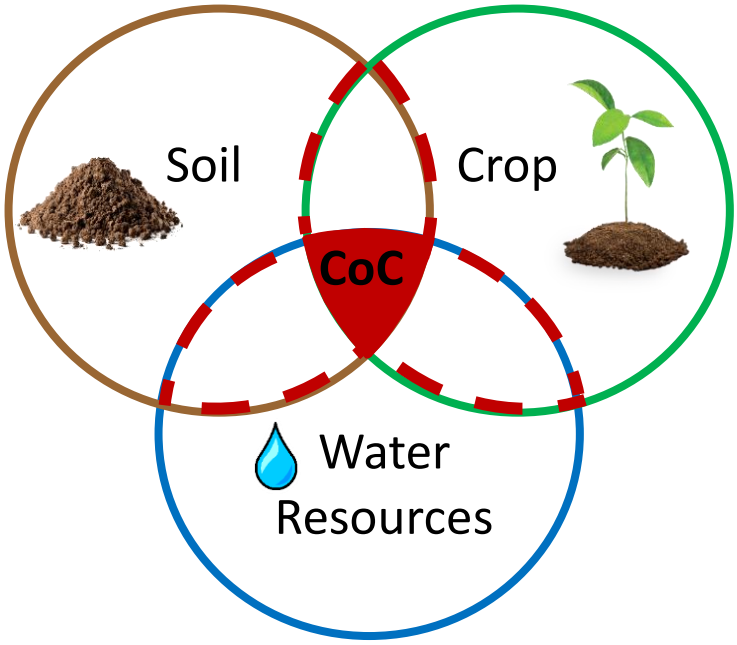

Figure 5.7: Three potential receptors of a constituent of concern CoC, in an irrigated environment.

Characterisation of CoC

Characterising the risk a constituent may pose to each receptor will guide the water user, consultants, and relevant authorities, with regard to necessary monitoring plans or thresholds for action that should be put in place. Appropriate techniques for impact prediction on water resources can be found in DWAF's Best Practice Guideline (G4) (DWAF, 2008). Characterising risk requires determining the mobility, the expected extent of the impact on the soil, crops, and water resources, and then level of risk associated with each constituent. Tables 5.3 and 5.4 provide a characterisation of the mobility and impact of a constituent and Table 5.5 provides an example of how this risk characterisation for the receiving environments may materialise.

Table 5.3: Levels of mobility of constituents in the receiving environment.

Mobility	
Mobile	Constituent is **present** in the receptor
Considerably mobile	Constituent is **likely** to be present in the receptor
Marginally mobile	Constituent is **unlikely** to be present in the receptor
Immobile	Constituent is **not present** in the receptor

Table 5.4: Levels of impact constituents may have on the receiving environment.

Impact	
Severe	Presence of constituent causes **permanent** damage to receptor
High	Presence of constituent causes **impairment** to receptor
Medium	Presence of constituent causes **slight changes** to receptor
Low	Presence of constituent causes **little** damage to receptor

Table 5.5: Example of how to characterise a constituent's risk to receiving environments.

Example: Iron	Soil	Crop	Water resources
Mobility	Immobile	Marginally mobile	Marginally mobile
Impact	Low	Low to medium	Low
Risk level	Low	Medium	Low

Constituents deemed as low risk to the receptors (soil, crop, and water resources) can be seen as being of an acceptable impact and should not require additional monitoring. Constituents deemed as medium to high risk may require further investigation as to the extent of impact, and appropriate monitoring regimes and thresholds for action must be determined on a site-specific basis.

Applying environmental risk matrices and assessments to the irrigated environment ensures risk 'treatment' and mitigation and reduction measures can be implemented to ensure the irrigation practices are beneficial and sustainable in all environmental realms.

5.5.3 Monitoring plan

A plan should be set up to monitor any constituents of concern, and other potential "unwanted events" that have been identified in the risk assessment. Constituents of concern may affect one, two or all of the receptors in an irrigated environment. The level of risk a constituent of concern may have on a receptor will determine the intensity and frequency of monitoring required. Using the standards set out in ISO 14001 (ISO, 2015), these principles can be used for continual improvement of the environmental management system. The following is a recommended approach to designing and implementing an environmental monitoring plan for constituents of concern when irrigating with mine-affected waters (adapted from ISO, 2015):

1. **Design** - State constituents of concern to be monitored.
   Define correct chemical state of constituent to be monitored (e.g. U(IV), U(VI), Total U)
   Questions to be asked in order to establish a representative monitoring plan are*:
   What receptors (soil, crop, water resources) need to be monitored on-site?
   How often and for how long do these receptors need to be monitored?
   What monitoring or sampling method will be employed for this specific receptor?
   *(dependent on constituents' mobility, impact, and risk level it imposes on receptors).

   This stage entails identification of the locations and density of the monitoring stations, as well as the frequency and timing of sampling of on-site soil, crop and water resource receptors.

2. **Appraisal** – Relevant interested and affected parties should have an opportunity to review the final monitoring plan design.

3. **Implementation –** Persons responsible for each aspect of the monitoring plan should be identified and have the necessary qualifications to perform the monitoring task. Necessary equipment should be acquired and made freely available to the persons tasked with monitoring. Easy access to the irrigation site for data collection by monitoring personnel must be ensured.

4. **Data collection** - Correct sampling strategies should be followed in order for the data to be accurate and representative of the potentially affected receptor and CoC. The frequency and timing of sampling should be strictly adhered to, to ensure compliance with set monitoring requirements. Monitoring quality control measures should be applied continuously to ensure the integrity of the dataset.

5. **Data analyses** – Samples collected from the irrigated fields and the environment in close proximity to the site need to be analysed, correctly evaluated and interpreted. Data should be presented in a form that allows decision makers to easily understand and interpret the monitoring results.

6. **Continual review of monitoring system** - The monitoring plan and the quality of the results obtained should be audited regularly to ensure that the irrigation plan has been implemented and is achieving the set objectives. The audit should identify any limitations to current monitoring protocols or opportunities for improvement to the monitoring system or to the irrigation.

7. **Auditing** - The audit report should be sent to the person directly responsible for the implementation of the irrigation project, and to the responsible government departments, so that informed decisions can be made regarding the continuation of the project. The information and trends documented on the state of the irrigated area and surrounding environment, as obtained from the monitoring data, can be used to refine site-specific thresholds for action. Communication of the information to relevant water resource managers and decision makers should ensure a sound and continuous strategy is employed on a general and site-specific level, for on-going, sustainable irrigation.

The environment is dynamic and in a constant state of flux, therefore the applicability of an irrigation project plan and its monitoring protocol, needs to be constantly reviewed, Life Cycle Analysis, a primary tool used to support decision-making for sustainable development. (Azapagic, 2011). Developing a monitoring plan is highly dependent on site-specificities. As South Africa's geology, soils, hydrology, and climate vary greatly, there is no one size fits all approach to implementing a monitoring plan. More information regarding water management monitoring plans can be found in DWAF's Best Practice Guideline (G3) (DWAF, 2006). Competent persons should be employed to carefully develop and evaluate the design and applicability of any monitoring plan to be implemented on an irrigation site.

5.5.4 Action levels

Thresholds for action are upper limits or tolerance levels set for an environment to ensure the water use activity does not unacceptably degrade the physical, chemical, or biological status of the irrigated area and its surrounding environment. As previously mentioned, due to the complex geological and hydrological landscape of South Africa, a tailored action plan should follow the carefully determined and reviewed monitoring plan.

Water and Soil Trace Element Thresholds

The 1996 South African Irrigation Water Quality Guideline (SAWQG, 1996) set out maximum concentrations and threshold levels for irrigation water qualities and irrigated soils, with these being conservative and protective levels to ensure limited environmental degradation would occur (Table 5.6). These can be used to develop initial guidelines for action levels; however, they are likely to result in an excessively conservative approach. Ongoing research should permit a better understanding of soil, crop and drainage waters' ability to tolerate higher loadings of certain key elements (Fe, Mn, Al in particular) than is currently postulated in the 1996 guidelines.

Table 5.6: The maximum acceptable trace element content of irrigation water for short (20 years) and long (100 years) term use, and corresponding concentrations and loads of trace elements in soil.

Trace element	1996 SA Irrigation Water Quality Guidelines		Concentration in irrigated soil		Load applied to irrigated soil	
	100 years	20 years	100 years	20 years	100 years	20 years
	mg/L		mg/kg		kg/ha	
Aluminium	5.0	20.0	2500	2000	5000	4000
Arsenic	0.1	2.0	50	200	100	400
Beryllium	0.1	0.5	50	50	100	100
Boron	0.5	Vary	250	-	500	-
Cadmium	0.01	0.05	5	5	10	10
Chromium (VI)	0.1	1.0	50	100	100	200
Cobalt	0.05	5.0	25	500	50	1000
Copper	0.2	5.0	100	500	200	1000
Fluoride	2.0	15.0	1000	1500	2000	3000
Iron	5.0	20.0	2500	2000	5000	4000
Lead	0.2	2.0	100	200	200	400
Lithium	2.5	-	1250	-	2500	-
Manganese	0.2	10	100	1000	200	2000
Mercury	0.002	-	1	-	2	0.4
Molybdenum	0.01	0.05	5	5	10	10
Nickel	0.2	2.0	100	200	200	400
Selenium	0.02	0.05	10	5	20	10
Uranium	0.01	0.1	5	10	10	20
Vanadium	0.1	1.0	50	100	100	200
Zinc	1.0	5.0	500	500	1000	1000

As trace element loading is of concern in a large majority of mine-affected waters in South Africa, it is currently deemed appropriate to develop thresholds for action for trace elements when irrigating with waters rich in these. The 1996 South African Irrigation Water Quality Guidelines used a very similar approach, with minor modifications made to guidelines developed by the United States Environmental Protection Agency (US EPA, 1973), for deriving irrigation water quality and soil accumulation thresholds for trace elements. The maximum acceptable soil trace element accumulation concentrations set in the 1996 South African Irrigation Water Quality Guidelines, were calculated assuming soils are irrigated for 100 years at an irrigation application rate of 1000 mm p.a., at an effective soil depth of accumulation of 150 mm and a soil bulk density of 1333 kg/m^3. A more lenient short-term standard was derived by assuming irrigation of up to 20 years on “forgiving soils”, fine-textured calcareous or neutral to alkaline soils.

Tier 1 DSS simulations consider exceedance of the maximum acceptable soil trace element accumulation concentrations set in the 1996 South African Irrigation Water Quality Guidelines over a period of irrigation for 100 years or less, as unacceptable, and accumulation over a period of 200 years or more as the ideal. It does not provide for the more lenient short-term standard for periods up to 20 years (Table 5.6). Tier 2 DSS simulations use the same criteria as Tier 1, but Tier 2 provides considerations for a soil's background trace element concentration and calculating the trace element accumulation from the actual irrigation application and a soil bulk density derived from the chosen soil texture.

Site-specific threshold for action limits should be investigated and determined by competent professionals using specialised Tier 3 investigations if Tier 2 output appears to be overly conservative. This is especially likely in the case of mine waters rich in the trace elements Al, Fe and Mn, as these trace elements are abundant in natural soils in South Africa, and unlikely to be of concern in limed and well-aerated soils that will be encountered with productive irrigated systems, as such environments will typically render these elements insoluble. For these reasons, excluded Al and Mn from their list of recommended maximum concentrations of trace elements in irrigation waters.

With the wide range of geologies, soils and hydrological regimes present throughout South Africa, and the corresponding wide differences in natural background levels of inorganic constituents in soils and waters, the environments receiving irrigation waters will vary greatly, and applying a rigid blanket approach to trace element thresholds for action seems inappropriate. Quantifying the load a specific irrigation environment can receive will assist in setting site-specific threshold levels for on-site soil and water resources.

Site-specific thresholds should be determined for each site because each has different abilities to sequester CoC. For instance, the quaternary sands of the Sandveld, West Coast region of South Africa and the high potential clay-loam soils of the Mpumalanga region would exhibit radically different responses to certain metals of concern. Setting the same threshold limits for both these regions would be inappropriate, as the irrigated environments would manage the load from irrigation waters in completely different ways due to their unique soil properties. It is recommended that revised irrigation water quality guidelines be developed which account for the natural background soil and water concentration levels found in different South African environments.

Soil properties influence the solubility of trace elements and are important indicators of their plant-availability. Total trace element concentration is not the best indicator of trace element plant-availability due to numerous factors. These factors include, but are not limited to, pH,

adsorption-desorption reactions, chemical complexation, redox reactions, presence or absence of organic and inorganic ligands, humic and fulvic acids, root exudates, and microbial metabolites (Violante et al. 2010). Due to the large number of factors influencing element availability, and their considerable spatial and temporal variability in field conditions throughout South Africa, the set threshold limits are tentative and should be assessed on a site-specific basis, by competent agricultural professionals.

Thresholds for action for trace elements in soil irrigated with mine-affected waters have been adapted from the 1996 Irrigation Water Quality Guidelines and the Guidelines for the Utilisation and Disposal of Wastewater Sludge (Snyman & Herselman, 2006). The method presented in the Wastewater Sludge Guidelines, is to define a Total Investigative Level (TIL), which is a 30% reduction in the concentration of the Total Maximum Threshold (TMT) of trace elements in the soil. A conservative estimate of 2.5% of the Total Maximum Threshold (TMT) is assumed to determine the Maximum Available Threshold (MAT) (in mg/kg) of trace elements in the soil. This approach has been adapted and extended here to include elements in the published irrigation water quality guidelines (Table 5.7).

Table 5.7: Suggested trace element limits for soils irrigated with mine-affected waters (Adapted from Snyman & Herselman, 2006 and du Plessis et al. 2017).

Element	Total Investigative Level (TIL) (Aqua Regia)	Total Maximum Threshold (TMT) (Aqua Regia)	Maximum Available Threshold (MAT) (NH_4NO_3)
	mg/kg		
Aluminium	1610	2300	57.5
Arsenic	85	120	3
Beryllium	35	50	1.25
Boron	175	250	6.25
Cadmium	3.5	5	0.125
Chromium (VI)	53	75	1.9
Cobalt	193	275	6.9
Copper	200	300	7.5
Fluoride	875	1250	31.25
Iron	1750	2500	62.5
Lead	105	150	3.75
Lithium	455	650	16.25
Manganese	700	1000	25
Mercury	0.7	1	0.025
Molybdenum	3.5	5	0.125
Nickel	105	150	3.75
Selenium	5.6	8	0.2
Uranium	5.6	8	0.2
Vanadium	53	75	1.9
Zinc	350	500	12.5

The following procedure can be followed when evaluating trace element concentrations in soils irrigated with mine-affected waters:

1. The Total Metal Content (TMC) of the soil should first be determined using the aqua regia extraction method (Appendix 1). Compare these results with Table 5.7 values.
2. If the TMC is less than the Total Investigative Level (TIL) then irrigation can continue with soil analyses required after 5 years.
3. If the TMC is above the Total Maximum Threshold (TMT) then irrigation should be terminated.
4. If the TMC is above the TIL but below TMT, the mobility and plant available portion of the trace element(s) in the soil needs to be assessed. The available metal content of the soil is determined using the NH_4NO_3 extraction method (Appendix C).
5. If the available trace metal content of the soil is less than the Maximum Available Threshold (MAT), then irrigation can continue with soil analyses required after 2 years. This 2-year soil monitoring period ensures the available trace metal content remains below the MAT.
6. If the available trace metal concentration in the soil exceeds the TMT or the MAT, then irrigation with mine-affected waters should cease.

These soil thresholds and suggested monitoring programmes can be used as a reference when determining maximum permissible concentrations in soils irrigated with mine-affected waters. With the application and adjustment of these thresholds and monitoring regime on a site-specific basis, a database of the applicability of these stipulated thresholds for action can be established in South Africa, and a local knowledge base developed. Again, it is noted that due to the wide range of geologies, soils and hydrological regimes present throughout South Africa, these thresholds should therefore be adapted on a site-specific basis (Tier 3 evaluations).

With the generation of new information regarding the capacity of South African soils to receive constituent loading, thresholds for action and monitoring regimes for soils should be updated The decision tree (Figure 5.8) can be used as a guide for determining the thresholds for action, and soil monitoring regime for trace elements in a soil irrigated with mine-affected waters.

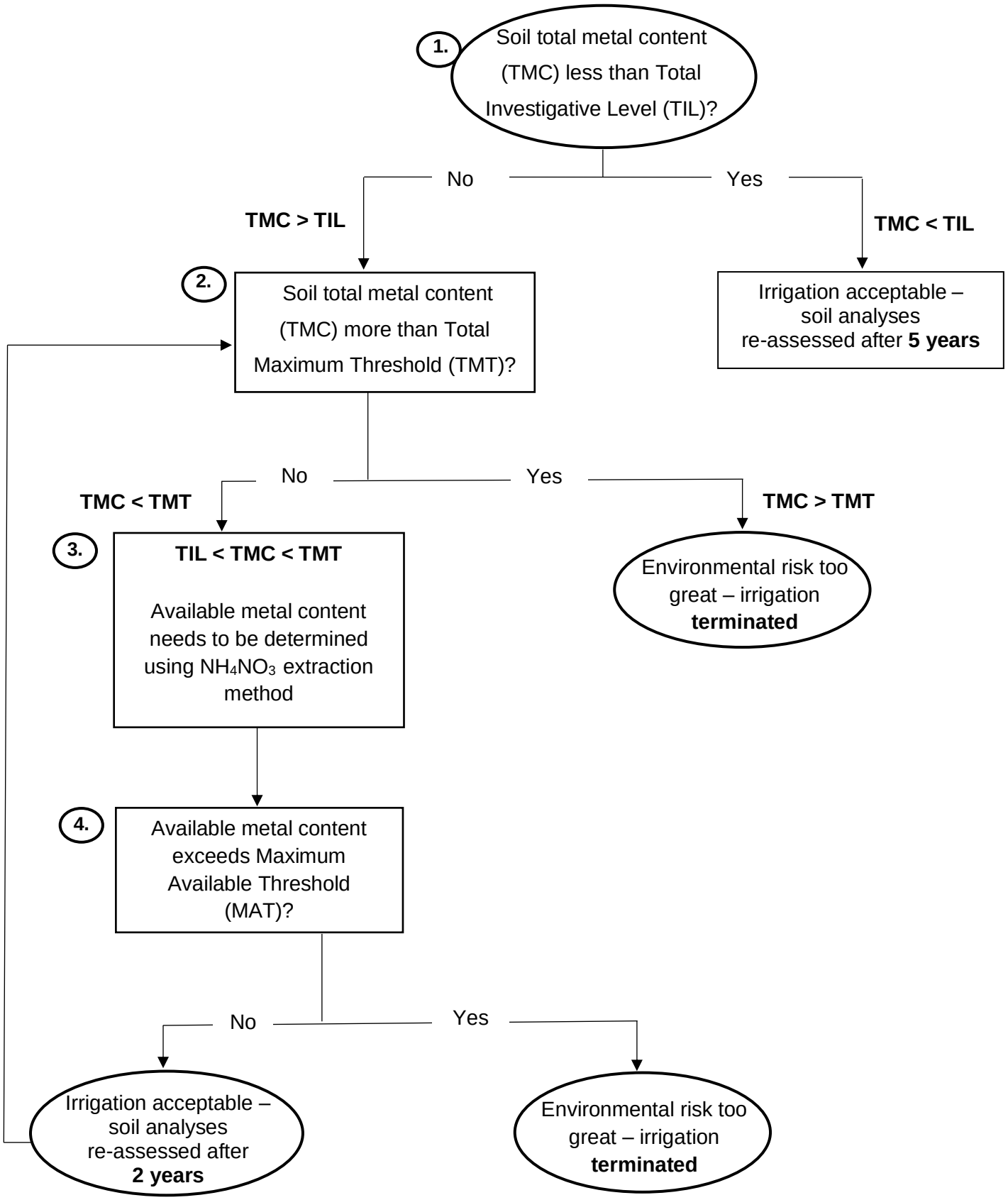

Figure 5.8: Decision Tree for determining thresholds for action for soil trace elements in a soil irrigated with mine-affected waters.

Water Resource Thresholds

The Decision Support System (DSS) models the fitness-for-use and effect of a specific water quality on irrigation equipment and soil and crop resources. The DSS does not model the impact an irrigation water has on the water quality of proximal ground and surface water resources.

The Department of Water and Sanitation (DWS) has developed a catchment and resource directed approach to water quality, with the sole goal being the sustainable use and responsible management of surface and ground water resources (Violante et al. 2010; DWS, 2016). DWS has generated classes and resource quality objectives (RQO) of significant water resources (rivers, dams, estuaries, and groundwater) within several catchments throughout South Africa. Integrated Units of Analysis (IUA) have been delineated within various Water Management Areas (WMA), that classify the extent of permissible utilization and protection of water resources. RQOs have been defined for each IUA in terms of water quantity, quality, habitat and biota (DWS, 2016). Various indicators and RQO metrics are set out for the respective water resources within each quaternary catchment and IUA, with these values deemed critical to ensure the protection and maintenance of aquatic ecosystems.

Water use licence water quality threshold levels are set in accordance to the specific IUA Resource Quality Objectives. On a site-specific basis, the potential impact of mine water irrigation on ground and surface waters differs, dependent on the location of the irrigation site within South Africa, the resource proximity to the irrigated area and the position of the resource within the landscape (Vermeulen et al. 2008). The natural physical and chemical characteristics and environmental roles of ground and surface waters provide a baseline for which site-specific thresholds can be set within the IUA's RQO.

According to the Resource Quality Objectives (RQO) for groundwater, long-term trends should not show negative quality deviation from natural levels. However, it may be unreasonable to expect there will be no impact on water quality from large-scale mine water irrigation. Therefore, the amount and quality of leachate from irrigated fields needs to be quantified in order to determine the solute input from irrigation to groundwater resources. Acceptable threshold levels for the site-specific groundwater body can then be determined, compared and verified. If surface water runoff is of potential concern for the irrigated site, the amount and quality of runoff water should be determined. Acceptable threshold levels for the site-specific surface water can then be determined, compared, and verified.

The following methodology can be employed when investigating thresholds for water resources in the vicinity of fields irrigated with mine-affected waters:

1. Identify and prioritise potential water resource(s) of concern;
2. Delineate sphere of influence of irrigated land;
3. Quantify natural water resource(s) quality;
4. Define IUA and RQO water quality limits for irrigated site location, and
5. Negotiate an acceptable level of impact from mine water irrigation below the established, reasonable RQO threshold level.

The decision tree (Figure 5.9) can be used as a guide for determining the thresholds for action for potential water resource(s) of concern.

Of the 19 Water Management Areas in South Africa, Resource Quality Objectives have been established for only some catchments (Olifants-Doorn, Berg, Olifants, Mokolo, Matlabas, Crocodile (West) and Marico, Upper, Middle and Lower Vaal, Mzimvubu). Although there is a staggered roll out, with various risks associated with this RQO approach to water quality in South Africa (DWS, 2016) and with some RQOs still under development, this is a first practical step towards quantifying water resource quality management in South Africa. This can be used as a basis from which thresholds for action can be set for water resources in the proximity of land irrigated with mine-affected waters.

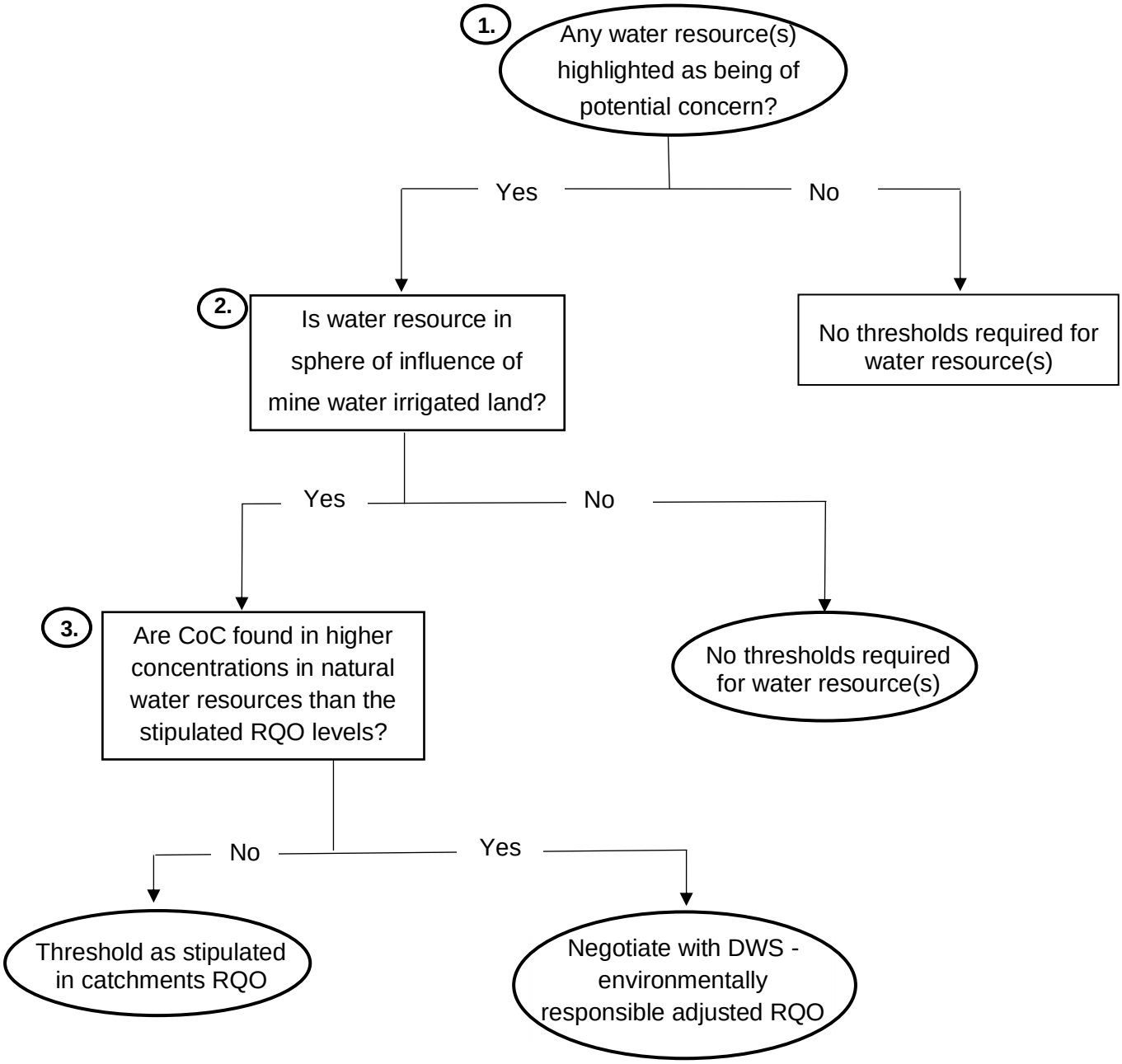

Figure 5.9: Decision Tree for determining thresholds for action for potential water resource(s) of concern.

Food and Feed Safety

Determining the elemental composition of the edible portions of a crop and comparing this to the South African food and fodder safety guidelines (Forster, 1991) ensures crops are safe to consume. It is noted that the South African guidelines are based on the European food safety guidelines. The South African food safety guidelines include the following potential elements of concern from a food safety perspective; arsenic (As), cadmium (Cd), chromium (Cr), zinc (Zn), lead (Pb) and mercury (Hg). An acid digestion of milled plant parts should be undertaken, at the end of each growing season, and comparisons to current food and fodder safety thresholds should be made for elements present in the irrigation water and highlighted as potentially of concern by the DSS. Table 5.8 provides the threshold values of selected elements for grain food and feed safety.

Table 5.8: Food and feed safety thresholds for selected elements in grain.

Element	FAO – General Standard for contaminants & toxins in food & feed (CODEX 1995)	SA food safety thresholds (Act 54 of 1972)	SA feed safety thresholds (Act No. 36 of 1947)
	ppm or mg/kg		
Arsenic (As)	-	-	2
Cadmium (Cd)	0,1	0,1	1
Zinc (Zn)	-	-	150
Lead (Pb)	0,2	0,2	10
Mercury (Hg)	-	-	0,1
Chromium (Cr)	-	-	-

Grains are one of the most widespread crops cultivated in South Africa and are therefore most likely the crops to be irrigated with mine-affected waters. This is the logic behind suggesting these crop threshold specifications. If a value in the above table has no threshold value, the corresponding national act or guideline has no stated maximum level for grain. If crops irrigated with mine-affected waters produce grain with potentially toxic elements above the stated safety thresholds, then the irrigation practice and crop or site selection should be reviewed. Food and fodder safety analyses should be undertaken by competent food and feed quality professionals to ensure grain quality meets local and international safety standards.

The DSS technical support, Volume 2 guidelines (du Plessis et al. 2017b), discuss the risks posed for food safety for microbial contamination. If microbial populations are highlighted as constituents of potential concern in the DSS simulations, the risk assessment and health-based approach set out should be followed to ensure there are no human or animal health risks associated with the crop produced.

5.6 Conclusion

The anisotropic and heterogeneous nature of irrigated environments make it difficult to follow a ‘one size fits all’ approach to selection criteria, environmental thresholds, monitoring and responses threshold exceedance. The proposed guideline presents key factors to assess when considering irrigating with mine-affected waters. The tools and methods proposed are developed to assist in identifying potential unwanted risks that irrigation may pose to environmental receptors, and a unified and cross-disciplinary approach to ensure sustainable resource management. The proposed guideline borrows many principles and strategies from existing guidelines, and has adapted them to suit mine-affected water irrigation, with the cradle to grave approach being fundamental to success. The strategy set out in this guideline is derived from field-tested and laboratory research studies of irrigation with mine-affected waters over a 30-year period in South Africa.

The threshold criteria of a mine-affected water irrigation project are dependent on adequate and reliable baseline data of the irrigation site, without which limited action and threshold levels can be applied. Although the proposed threshold for action levels may not be fullproof, i.e., deemed appropriate in some areas and not appropriate in others, it is an initial proposal for using currently available information and guidelines, for forging a structured framework site-specific threshold for action.

Future research should include the development of site- or region-specific frameworks and threshold and monitoring criteria in South Africa. Amalgamating regions of similar agro-ecological properties and behaviours can result in accurate and unique compartments with their own subset of operational and monitoring frameworks, applicable and valid to the specific region. These types of local water catchment or management area standards for mine-affected water irrigation, permits targeted and easier MAW usage, as well as accountability for misuse.

Use of this guideline by competent irrigation and agricultural professionals should significantly assist the relevant authorities to grant regulatory approval for irrigation with mine-affected waters.

CHAPTER 6: CONCLUSION

6.1 Study Conclusions

The increase in availability of suitable mine water sources for irrigation is of benefit to both the mining and agricultural industries. Large areas of agricultural land are located near mines in South Africa, so there is a great opportunity for mine-water irrigated cropping to occur. Owing to the substantial treatment costs mines face, this alternative and consumptive water utilisation option can reduce water treatment cost, creating employment and empowering local communities through the production of mine-water irrigated crops.

This irrigation project using mine-affected water has shown that at least in the short term, this untreated, circum-neutral mine water can be profitable, and has insignificant and temporary environmental influences, if any at all. This ongoing research demonstrates the sustainability of irrigating with mine-affected water, and the opportunities presented by mine water irrigation practices. As is evident in the preceding chapters, approximately one third of applied salts were immobilised in the soil profile over the irrigation period. It is important to monitor salt levels in the irrigation environment and to stop or adaptively manage irrigation if any unacceptable impacts are encountered. The grain produced at the unmined pivot site is safe for human consumption, which makes grain production for human and animal consumption with this mine-affected water feasible. If the food and forage thresholds are not met, a biofuel or fibre crop can be considered. An average yearly profit of R10 000/ha was achieved for irrigating with this gypsiferous mine water.

The demonstration pivot site has validated a cost-effective and productive utilisation of untreated, circum-neutral mine water. This is a valuable demonstration for prospective mine water irrigators and the regulators who will be approached to approve such projects. On a larger scale than this demonstration trial, such irrigation projects are expected to contribute to job creation and stimulate local economies. The success of this project has clearly shown that productive mine water irrigation is possible, and with further long-term studies, stakeholders such as the Department of Human Settlements, Water and Sanitation, the Department of Agriculture, Land Reform and Rural Development, mines and farmers can more confidently enter into the utilisation of mine-impacted waters for irrigation.

One way to estimate the long-term viability is by using crop modelling to simulate effects on crop yield, soil quality, and the irrigation water's fitness-for-use. The DSS scenario simulations indicate which performance indicators an irrigation water may influence. The soybean-wheat rotation had the best simulation results. The simulated gypsum precipitation was 7.9 tons/ha, which is deemed favourable, as well as giving an ideal classification for relative crop yield (%)

as affected by root zone salinity, as neither crop's published salinity threshold as exceeded, which is significant for crop performance.

The proposed Technical Guideline for Irrigation with Mine-Affected Waters, provides a standardised framework by which a water user can assess whether or not they can successfully irrigate specific crops with a specific mine water, on a specific site. It can also assist key decision makers to reduce risks when considering irrigation with mine-affected waters and assist in identifying potential unwanted events that may pose risk to environmental receptors. Assessing the use of mine-affected waters for irrigation requires a unified and cross-disciplinary approach to ensure sustainable resource management. Use of this guideline by competent irrigation and agricultural professionals should greatly assist the relevant authorities in granting regulatory approval for irrigation with mine-affected waters.

Not all mine-affected waters are suitable for irrigation purposes, thus risk-based approaches and long-term monitoring are imperative for ensuring sustainable irrigation with acceptable environmental impact. Irrigation with mine water over the short to medium term can be viable, sustainable, and feasible if the appropriate management practices are in place.

6.2 Recommendations

Recommendations which can aid in further investigation of irrigation with mine-affected waters are as follows:

- More sites with different water qualities, soil, and crops could be established at a commercial scale and monitored to expand our understanding and demonstration of conditions under which irrigation with mine-affected waters is sustainable;
- Introduction and monitoring of a winter crop into the crop rotation plan of the current irrigated unmined trial site. An increase in irrigation volumes of mine-affected water, within normal plant requirement ranges, assists in investigating and modelling the longer-term effects of irrigation on the environmental receptors;
- A larger and longer historic soil and groundwater monitoring record before irrigation commences ensures a verified data baseline of the irrigation environment is known, so it can be used as a reference platform;
- Considering the great spatial distribution over the 19 ha trial site, non-destructive approaches like satellite or drone imagery can be used to verify crop growth field measurements and enhance crop canopy response quantification;
- Encourage peer review and industry usage of this proposed guideline for irrigation with mine waters to receive constructive feedback on its usefulness and coverage when stakeholders are investigating an irrigation project of this nature. This will be invaluable in updating and improving these suggested guidelines.

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APPENDIX A

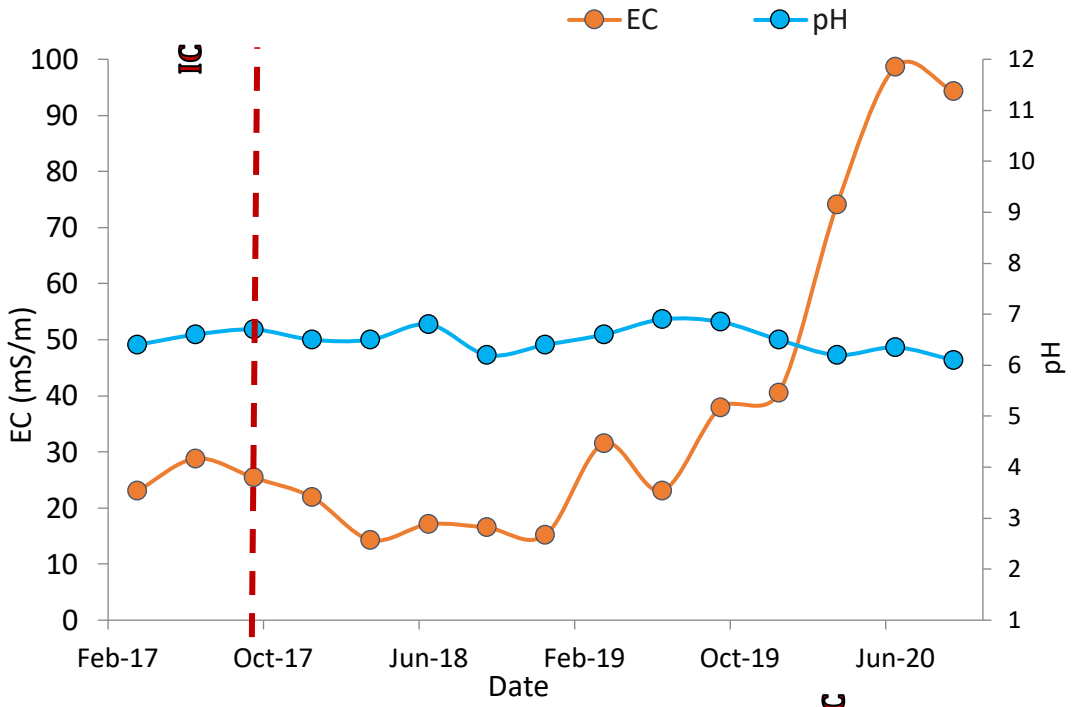
Table A.1: Summary of elemental concentrations of the mine supplied irrigation water quality at the unmined trial site.

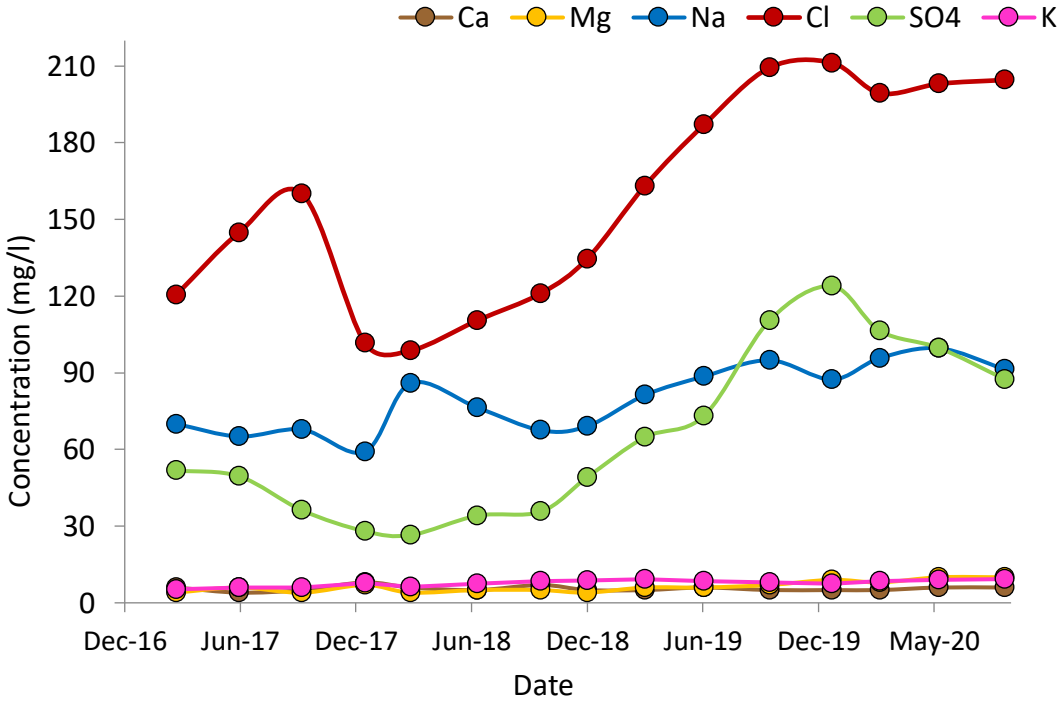
Variable	Jan 17	Feb 17	Mrz 17	Apr 17	Jun 17	Jul 17	Aug 17	Sep 17	Okt 17	Nov 17	Dez 17	Jan 18	Feb 18	Mrz 18	Apr 18	Mai 18	Jun 18	Jul 18	Aug 18	Sep 18	Okt 18	Nov 18	Dez 18	Jan 19	Feb 19	Mrz 19	Apr 19	Mai 19	Jun 19	Jul 19	Aug 19	Sep 19	Okt 19	Dez 19	Jan 20	Feb 20	Mrz 20	Mai 20	Jun 20	Jul 20	Aug 20
pH	7.2	8.1	7	7.3	7	7.3	7.1	7.2	8.2	8	7.7	7.6	7.3	7.8	7.9	7.4	8.1	8	7.9	7.7	7.7	7.6	7.98	8.16	8.01	7.81	7.75	8.18	8.25	8.09	7.82	7.59	7.65	8.33	8.08	8.14	8.12	7.92	8.11	8.18	8.10
EC	197	194	190	244	218	224	227	219	220	209	202	187	199	209	193	207	206	212	212	444	222	139	217	196	180	174	183	203	199	205	252	196	189	208	135	216	243	247	249	253	260
TDS	1858	1836	1826	1902	2092	2104	1990	2062	2094	1956	1872	1734	1984	1886	1746	1840	1984	1966	1994	2022	2058	1178	1520	1365	1179	972	1212	1660	768	1624	1588	2080	1984	1365	915	1936	1656	1856	1532	1768	2236
Ca^{2+}	80	245	228	240	275	317	275	270	268	282	236	232	249	222	248	251	259	264	248	268	244	146	240	196	133	129	211	213	203	133	223	195	143	209	128	187	231	264	189	249	238
Mg^{2+}	133	140	128	139	157	168	150	139	135	153	137	131	143	124	138	144	151	159	132	155	143	90	154	112	81	78	132	119	108	106	97	74	103	95	81	122	146	162	150	158	136
Na^{+}	51	57	48	52	56	56	61	59	57	55	49	48	51	62	54	55	55	59	55	58	56	34	57	53	54	46	47	58	52	73	71	47	72	56	9	49	48	56	60	73	59
K^{+}	28	29	27	29	32	32	32	32	32	31	28	27	28	32	29	30	33	31	30	35	31	22	31	28	28	24	26	34	29	34	10	28	34	5	7	16	30	33	31	35	31
T-Alkalinity as CaCO3	280	280	272	260	264	288	292	260	280	264	240	220	264	224	200	268	252	276	256	260	260	112	237	198	290	288	226	218	157	230	158	162	298	118	140	214	248	368	220	222	252
Cl^{-}	20	20	18	19	20	22	24	23	26	23	21	19	23	23	21	23	27	24	23	23	25	15	24	21	19	18	19	20	20	20	17	20	23	20	10	22	22	23	27	16	27
SO_4^{2-}	1051	987	996	972	1088	1122	1187	1106	1177	1153	1043	1044	1081	1004	945	1037	1151	1113	1184	1157	1094	612	1126	870	558	498	1013	982	916	735	913	745	658	899	549	888	1094	1082	998	1313	1055
Total P	0.2	1.7	0.2	0.2	3.1	0.2	0.2	1	0.2	0.2	0.2	0.2	0.5	0.2	0.2	0.2	0.7	0.2	0.2	0.2	6.7	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

| | | |

Table A.2: Summary of elemental concentrations of verification samples taken of the irrigation water at the trial site.

Unit	Parameter	October 2017	November 2018	December 2018	October 2019	January 2020
	pH	7.6	7.2	7.5	7.8	7.4
	EC (mS/m)	205	189	225	326	265
mg/L	**K**	42	34	38	46	39
	Mg	135	148	154	248	236
	Ca	185	220	242	315	266
	SO_4	1132	1280	1326	1650	1452
	Na	64	66	55	74	69
	Cl	33	45	29	53	41
	Fe	0.02	0.05	0.04	0.05	0.08
	Al	0.05	0.03	0.25	0.5	0.35
	Mn	0.5	0.7	0.45	0.25	0.1
	Pb	0	0.02	0.05	0.02	0.02
	Zn	0	0.02	0.02	0.02	0.02





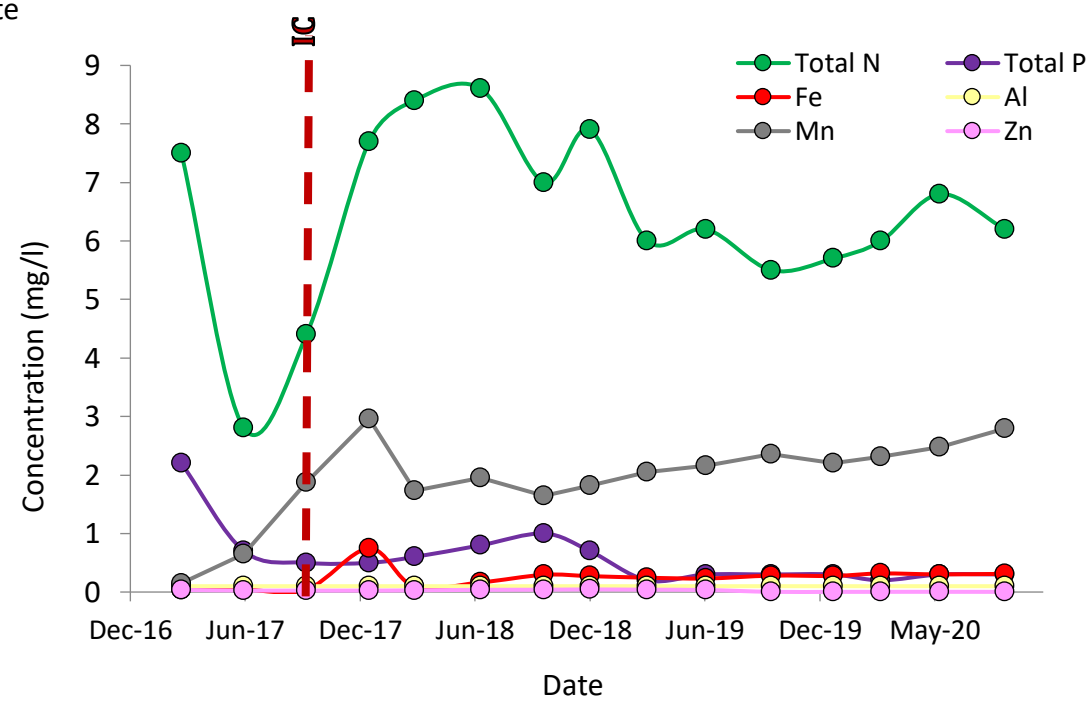
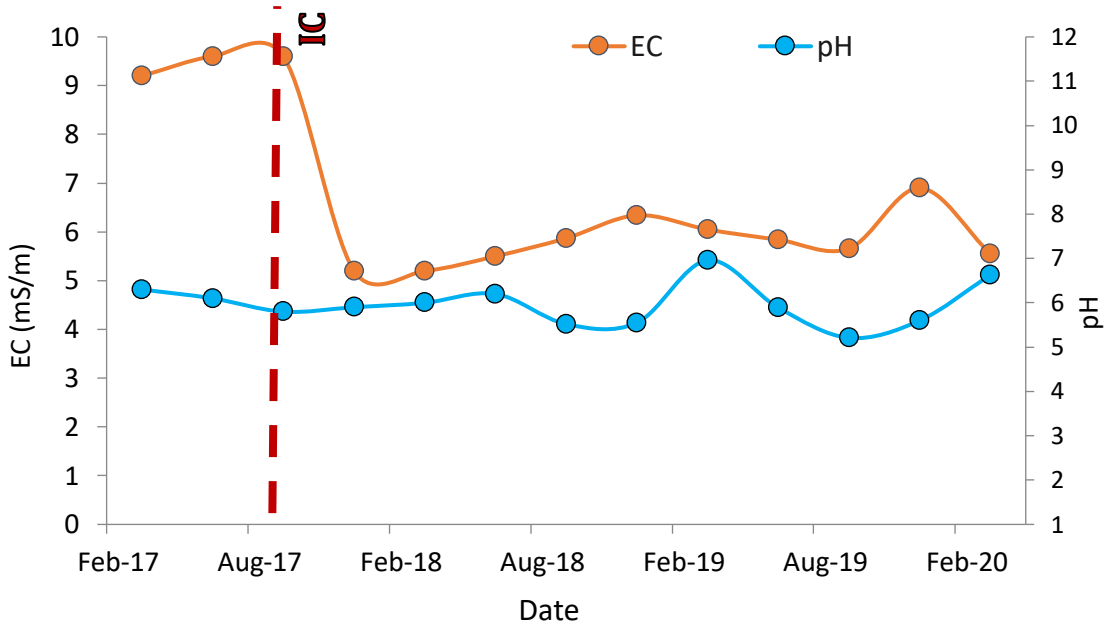
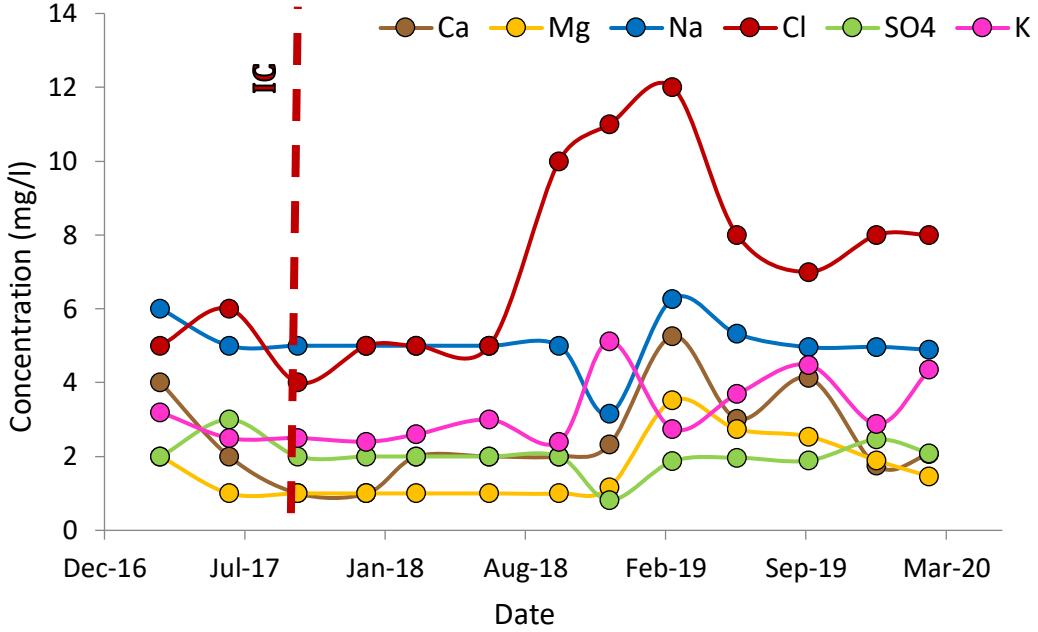


Figure A.1: Temporal water quality graphs for the onsite borehole, BH01.





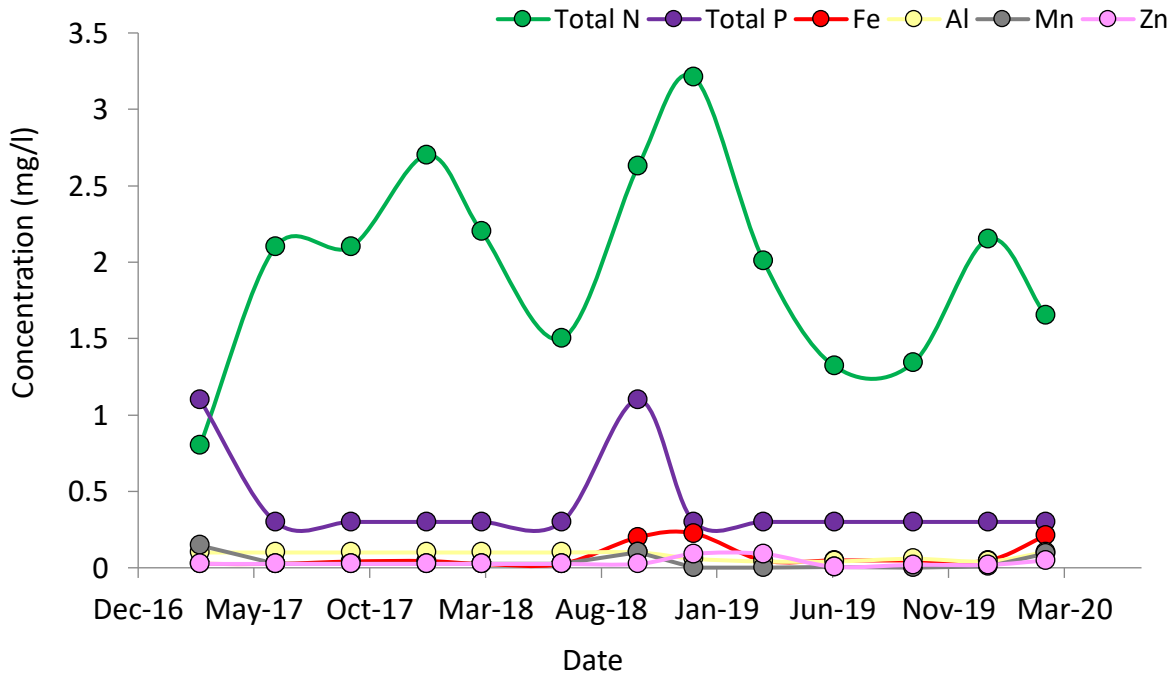
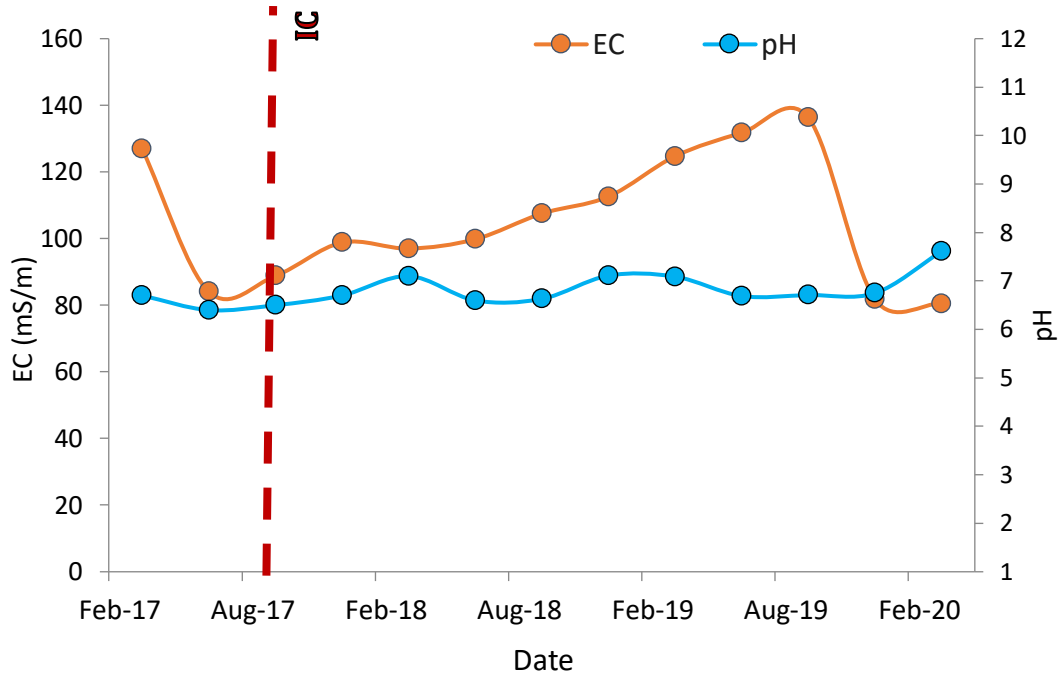
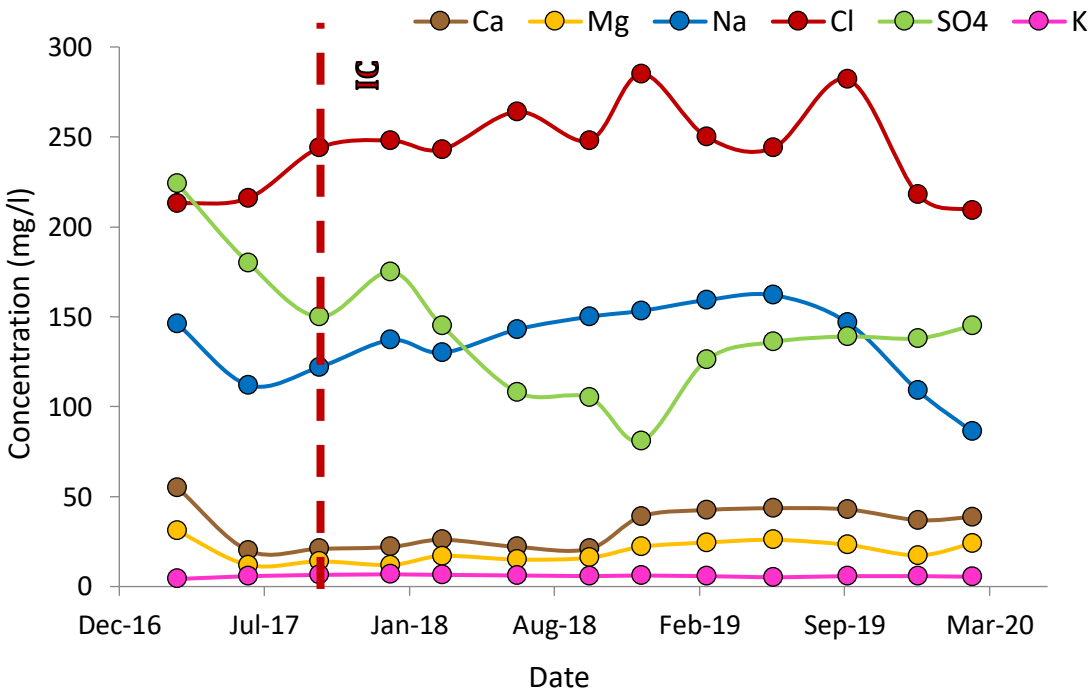


Figure A.2: Temporal water quality graphs for the onsite borehole, BH02.





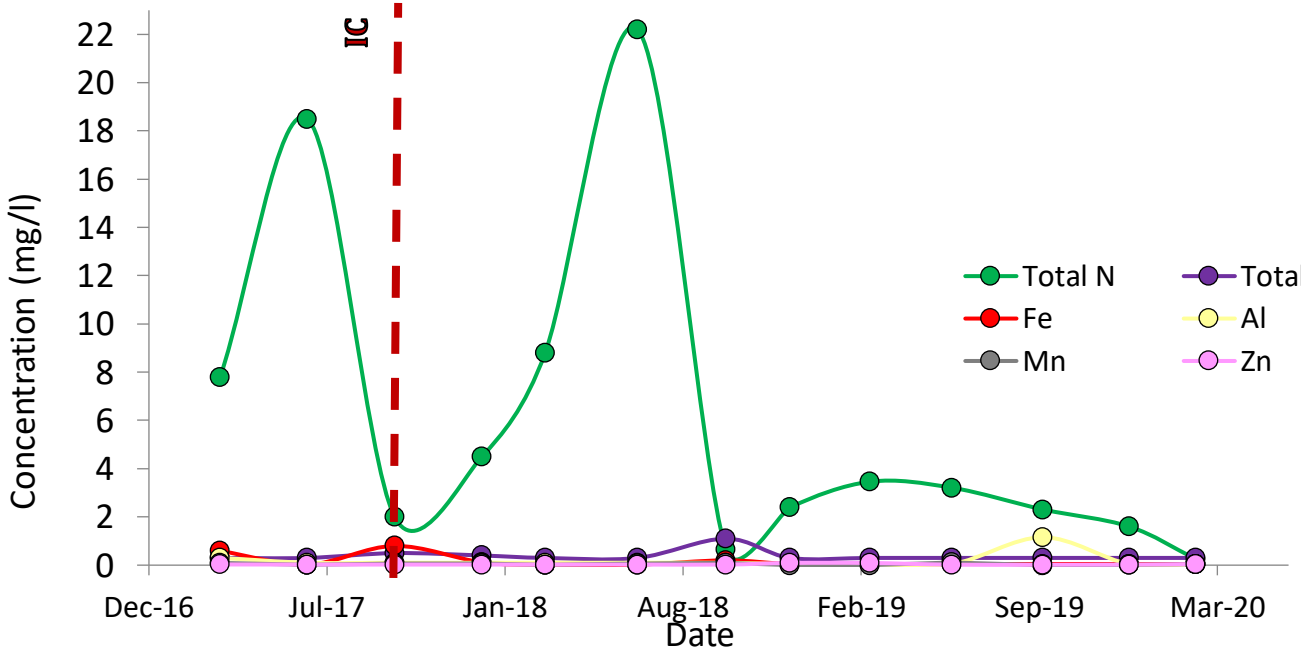


Figure A.3: Temporal water quality graphs for the onsite borehole, BH03.

Table A.3: Summary of the fertilizer regime and costs, applied to the unmined trial site each year.

Fertilizer type	Details	N (kg/ha)	P (kg/ha)	K (kg/ha)	S (kg/ha)	Cost (R per ha)
Pre-plant broadcast	9.1.2 (38) 0.5% Zn @ 500 kg ha^{-1}	161.3	17.9	35.8	-	R2 572,59
Planting fertilizer	3.2.1 (38) 0.5% Zn @ 200 kg ha^{-1}	38	25.3	12.7	-	R1 343,00
Top dressing	None	-	-	-	-	R0,00
Total cost for 2016/17 season						**R3 915,59**
Pre-plant broadcast	9.1.2 (38) 0.5% Zn @ 500 kg ha^{-1}	142.5	15.8	31.6	-	R2 526,00
Planting fertilizer	4.3.4 (36) 0.4% Zn + 3.9% S @ 250 kg ha^{-1}	32.7	24.5	32.7	9.75	R1 400,00
Top dressing	Urea 46% @ 250 kg ha^{-1}	115	-	-	-	R1 088,75
Total cost for 2017/18 season						**R5 014,75**
Pre-plant broadcast	9.1.2 (38) 0.5% Zn @ 500 kg ha^{-1}	142.5	15.8	31.6	-	R2 580,00
Planting fertilizer	4.3.4 (36) 0.4% Zn + 3.9% S @ 250 kg ha^{-1}	32.7	24.5	32.7	9.75	R1 490,00
Top dressing	Urea 46% @ 250 kg ha^{-1}	115	-	-	-	R1 150,50
Total cost for 2018/19 season						**R5 220,50**
Pre-plant broadcast	9.1.2 (38) 0.5% Zn @ 500 kg ha^{-1}	142.5	15.8	31.6	-	R2 640,00
Planting fertilizer	4.3.4 (36) 0.4% Zn + 3.9% S @ 250 kg ha^{-1}	32.7	24.5	32.7	9.75	R1 520,00
Top dressing	Urea 46% @ 250 kg ha^{-1}	115	-	-	-	R1 210,00
Total cost for 2019/2020 season						**R5 370,00**

Table A.4: Summary of the pre-planting herbicide sprays at the unmined trial site.

Herbicide/insecticide	Quantity	Cost per hectare
Eptam Super (EPTC)	2 ℓ ha^{-1}	R196,00
Guardian S (840 EC)	700 mℓ ha^{-1}	R62,89
Insectido (50 g L-1)	200 mℓ ha^{-1}	R13,40
Allbuff	2 ℓ per 2 000 ℓ water	R2,90
Boron (10%)	2 ℓ ha^{-1}	R51,00
Total cost for 2016/17 season		**R 326,19**
Galago (480)	256 mℓ ha^{-1}	R52,47
Guardian S (840 EC)	1.2 ℓ ha^{-1}	R98,40
Atrazine 500 (Atraflo)	2 ℓ ha^{-1}	R73,80
Lamda (5EC)	100 mℓ ha^{-1}	R6,30
Correcto	100 mℓ ha^{-1}	R3,40
Liquibor (10%)	2 ℓ ha^{-1}	R56,00
Total cost for 2017/18 season		**R 290,38**
Galago (480)	260 mℓ ha^{-1}	R55,00
Guardian S (840 EC)	1.2 ℓ ha^{-1}	R104,40
Atrazine 500 (Atraflo)	2 ℓ ha^{-1}	R76,50
Lamda (5EC)	100 mℓ ha^{-1}	R6,80
Correcto	100 mℓ ha^{-1}	R3,60
Liquibor (10%)	2 ℓ ha^{-1}	R58,00
Total cost for 2018/19 season		**R 304,30**
Galago (480)	280 mℓ ha^{-1}	R59,50
Guardian S (840 EC)	1.2 ℓ ha^{-1}	R105,00
Atrazine 500 (Atraflo)	2 ℓ ha^{-1}	R78,60
Lamda (5EC)	100 mℓ ha^{-1}	R7,00
Correcto	100 mℓ ha^{-1}	R3,80
Liquibor (10%)	2 ℓ ha^{-1}	R59,50
Total cost for 2019/20 season		**R 313,40**

Table A.5: Summary of the post-planting herbicide sprays at the unmined trial site.

Herbicide	Quantity	Cost per hectare
Terbuzine	2.5 ℓ ha^{-1}	R196,00
Acetochlor (900EC)	682 mℓ ha^{-1}	R62,89
Campertop (225)	800 mℓ ha^{-1}	R13,40
Allbuff	2 ℓ per 2 000 ℓ water	R2,90
Total cost for 2016/17 season		**R 326,19**
Galago (480)	200 mℓ ha^{-1}	R52,47
Acetochlor (900EC) no safener	682 mℓ ha^{-1}	R98,40
Terbuzine/Cheetah 600	2 ℓ ha^{-1}	R73,80
Lamda (5EC)	100 mℓ ha^{-1}	R6,30
Correcto	100 mℓ ha^{-1}	R3,40
Total cost for 2017/18 season		**R 290,38**
Galago (480)	200 mℓ ha^{-1}	R55,00
Acetochlor (900EC) no safener	690 mℓ ha^{-1}	R104,40
Terbuzine/Cheetah 600	2 ℓ ha^{-1}	R76,50
Lamda (5EC)	120 mℓ ha^{-1}	R6,80
Correcto	100 mℓ ha^{-1}	R3,60
Total cost for 2018/19 season		**R 304,30**
Galago (480)	210 mℓ ha^{-1}	R59,50
Acetochlor (900EC) no safener	690 mℓ ha^{-1}	R105,00
Terbuzine/Cheetah 600	2 ℓ ha^{-1}	R78,60
Lamda (5EC)	120 mℓ ha^{-1}	R7,00
Correcto	100 mℓ ha^{-1}	R3,80
Total cost for 2019/20 season		**R 313,40**

Table A.6: Summary of the post-planting fungicide sprays at the unmined trial site.

Fungicide	Quantity	Cost per hectare
Spanta S.C.	500 mℓ ha^{-1}	R107,75
Performer	500 mℓ ha^{-1}	R14,25
Total cost for 2016/17 season		**R 326,19**

Table A.7: Summary of the yearly costing report as supplied by the partnering commercial farmer at the unmined trial site.

Direct input costs	2016/17 Dryland	2017/18		2018/19		2019/20	
		Dryland	Irrigated	Dryland	Irrigated	Dryland	Irrigated
	R per ha						
Fertilizer and minerals	3 915,59	2 200,00	5 014,75	4 358,00	5 265,5	4 663,10	5 634,10
Herbicides and insecticides	556,63	394,05	394,05	399,20	399,20	427,15	427,15
Fungicides	122,00	-	-	-	-	-	-
Seeds	1 727,68	1 745,30	2 706,30	1 776,00	2 841,62	1 882,60	2 983,70
Fuel	1 441.59	1 528,09	1 528,09	1 604,45	1 604,45	1 716,76	1 716,76
Repairs and maintenance	1 577,65	1 672,31	1 672,31	1 755,95	1 755,95	1 878,90	1 878,90
Rent	450,00	477,00	477,00	500,85	500,85	535,90	535,90
Depreciation	1 625,43	1 722,96	1 722,96	1 809,11	1 809,11	1 935,75	1 935,75
Fixed improvements	74,01	78,45	78,45	82,40	82,40	86,50	86,50
Wages (temporary staff)	367,27	389,31	389,31	408,78	408,78	429,22	429,22
Indirect fixed costs	**2016/17**	**2017/18**		**2018/19**		**2019/20**	
	Dryland	**Dryland**	**Irrigated**	**Dryland**	**Irrigated**	**Dryland**	**Irrigated**
Salaries (permanent staff)	2 675,83	2 836,38	2 836,38	2 978,20	2 978,20	3 196,30	3 196,30
Medical aid (Provident Fund)	209,37	221,93	221,93	233,03	233,03	247,02	247,02
Electricity	326,97	346,59	346,59	363,92	363,92	382,12	382,12
Transport for contractors	80,88	85,73	85,73	90,00	90,00	94,50	94,50
Insurance and licences	85,68	90,82	90,82	95,36	95,36	102,04	102,04
Silo cost and packaging	3,67	3,89	3,89	4,09	4,09	4,30	4,30
Telephones	24,86	26,35	26,35	27,70	27,70	29,70	29,70
Statutory levies and WCC	130,86	138,71	138,71	145.65	145,65	155,85	155,85
Sundry operating expenses	118,45	125,56	125,56	131,88	131,88	138,50	138,50
Total cost per hectare	**R15 514,42**	**R15 980,09**	**R17 859,17**	**R16 779,10**	**R18 752,15**	**R17 906,20**	**R19 978,30**

Note: Irrigation and pumping costs (estimated at R5 000 per ha) are covered by the neighbouring Colliery.

Table A.8: Summary of the chemical constituents of the plant parts of white maize at the unmined trial site.

	Dryland	Year			Irrigated	Year		
		2017/18	2018/19	2019/20		2017/18	2018/19	2019/20
Grain (mg/kg)	K	18,3	14,5	12,92	K	17,3	21,5	18,3
	Mg	8,9	9,63	9,11	Mg	9,8	9,5	10,1
	Ca	0,4	0,61	0,68	Ca	0,3	0,6	0,85
	Na	0,022	0,009	0,01	Na	0,024	0,029	0,03
	S	9,5	8,2	8,9	S	9,9	8,3	9,1
	P	32,3	24	27,5	P	31,2	26,8	29,7
	B	0,015	0,066	0,04	B	0,017	0,03	0,01
	Fe	0,112	0,12	0,15	Fe	0,142	0,12	0,163
	Mn	0,044	0	0,013	Mn	0,045	0,055	0,053
	Al	0,01	0,011	0,015	Al	0,01	0,03	0,021
	Cu	0,008	0,005	0,003	Cu	0,008	0,004	0,004
	Zn	0,143	0,125	0,2	Zn	0,157	0,17	0,26
	Hg	0,001	0,001	0,001	Hg	0,001	0,001	0,001
	Cd	0,001	0,001	0,001	Cd	0,001	0,001	0,001
	Cr	0,0009	0,0004	0,0007	Cr	0,0004	0,0006	0,0003
	Pb	0,006	0,006	0,006	Pb	0,006	0,006	0,006

	Dryland	Year			Irrigated	Year		
		2017/18	2018/19	2019/20		2017/18	2018/19	2019/20
Stem	K	11870	12405	12655	K	12350	14840	15890
	Mg	2620	2450	2905	Mg	2510	2423	2630
	Ca	1895	2120	2230	Ca	2000	1975	2015
	Na	85	92	95	Na	31	30	33
	S	445	425	450	S	775	763	790
	P	350	355	341	P	419	433	421
	B	3,9	3,3	4,5	B	3,5	4,7	3,8
	Fe	2,6	2	2,4	Fe	3,5	3,2	3,3
	Mn	3	2,7	3,1	Mn	6,9	5	6,5
	Al	43	42	58	Al	43	36	49
	Zn	12	6,8	14	Zn	19	12	15

	Dryland	Year			Irrigated	Year		
		2017/18	2018/19	2019/20		2017/18	2018/19	2019/20
Leaves	K	12630	10895	11210	K	13780	12105	13345
	Mg	4015	3928	4210	Mg	4650	4380	4515
	Ca	6200	6110	6450	Ca	6430	6085	6570
	Na	8,9	8,7	9,2	Na	67	65	70
	S	1080	880	1230	S	1870	1633	1950
	P	980	850	1100	P	1810	1440	1750
	B	6,2	5,9	7	B	9,7	10,3	10,1
	Fe	20	22	18	Fe	11	15	13
	Mn	41	45	38	Mn	51	55	48
	Al	497	519	489	Al	396	385	401
	Cu	2,4	2,6	2,3	Cu	2,8	3	2,9
	Zn	27	29	28	Zn	29	25	27

Table A.9: Summary of the soil texture of the soil samples at the unmined trial site.

Sample	Sand%	Silt%	Clay%	Soil texture Classification
S01	44	28	28	Clay loam
S02	41	34	25	Loam
S03	43	33	24	Loam
S04	46	34	20	Loam
S05	40	37	23	Loam
S06	45	33	22	Loam
S07	43	36	21	Loam
S08	49	30	21	Loam
S09	50	30	20	Loam
S10	52	25	23	Sandy clay loam
S11	50	31	19	Loam
S12	54	29	17	Sandy loam
S13	51	30	19	Loam
S14	47	33	20	Loam
S15	56	28	16	Sandy loam
S16	52	29	19	Loam
S17	45	29	26	Loam
S18	42	33	25	Loam
S19	41	30	29	Clay loam
S20	54	29	17	Sandy loam

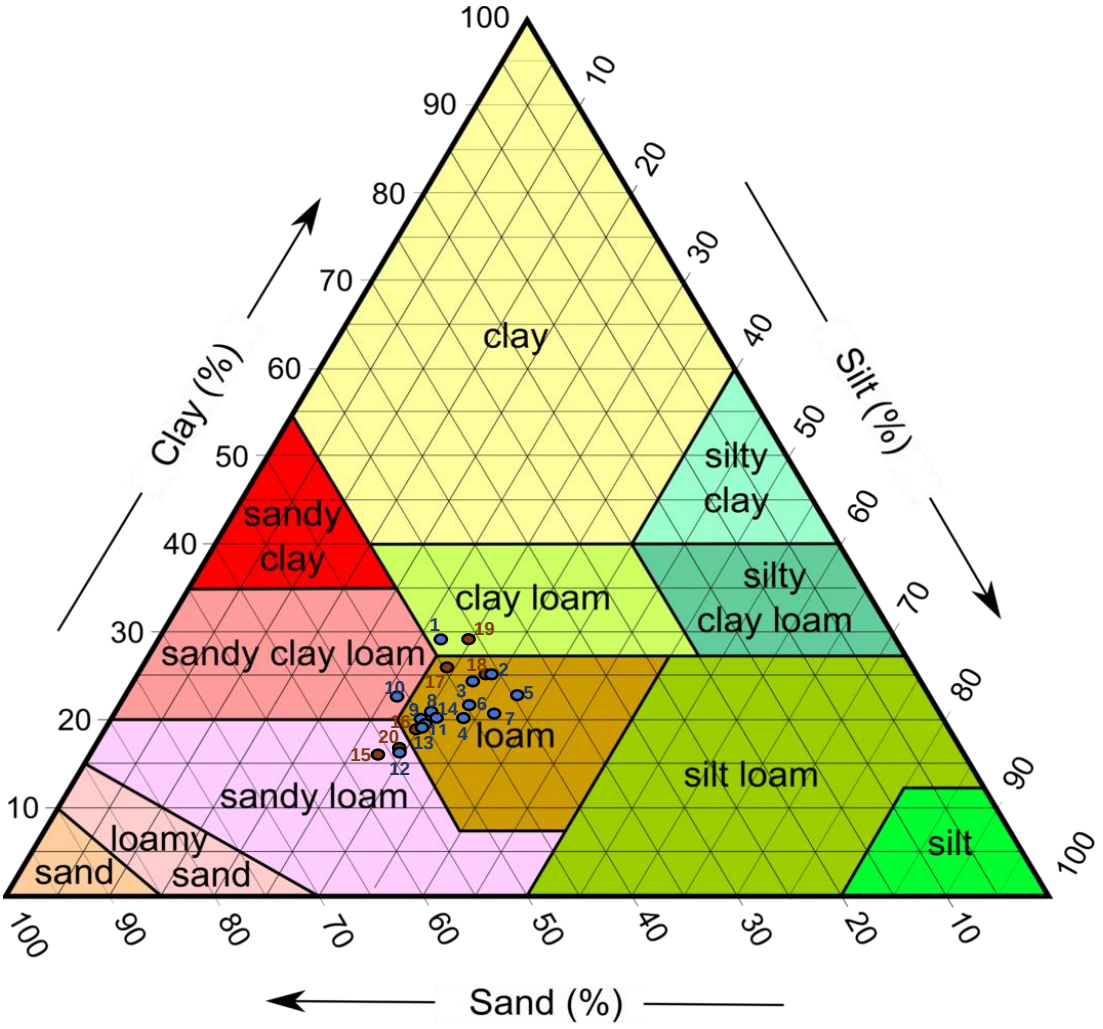


Figure A.4: A soil texture curve for the irrigated and dryland samples, taken in 2019.

Table A.10: Summary of laboratory analyses for the soil sampling sites (0–30 cm depth).

Year	Point	Depth	Chemical Constituents (mg/L)												
			pH	EC	Na	K	Ca	Mg	SO_4	P	Fe	Mn	Al	Cu	Zn
2017-2018	S01	0 - 30cm	5,8	181	24	62	632	201	223	48	80	18	812	2	4
	S02		5,7	213	27	69	627	191	250	56	91	23	893	3	4
	S03		6,1	173	22	79	623	176	211	45	76	16	798	2	3
	S04		6,3	166	19	71	642	169	204	39	74	14	801	3	3
	S05		5,6	201	26	78	622	186	243	63	82	26	876	3	3
	S06		6,4	142	17	70	639	181	210	41	72	15	810	3	3
	S07		6,4	170	19	67	631	189	202	43	70	16	809	3	3
	S08		6,5	145	17	59	639	181	197	38	66	17	778	2	3
	S09		6,3	134	15	57	626	176	200	41	65	13	766	2	3
	S10		6,4	122	17	55	640	160	189	46	63	14	793	2	3
	S11		6,5	130	14	61	597	133	161	39	60	11	763	1	2
	S12		6,4	126	16	59	602	151	152	43	59	10	770	2	2
	S13		6,6	133	17	56	589	146	176	48	68	13	781	2	3
	S14		6,5	126	18	61	578	161	185	58	74	14	759	2	3
	S15		6,4	112	13	64	567	146	117	48	63	13	743	2	3
	S16		6,2	108	15	71	574	170	106	55	61	14	756	2	3
	S17		5,8	180	21	84	563	183	239	69	71	25	887	3	4
	S18		5,5	191	23	81	613	195	248	71	77	29	912	3	4
	S19		5,4	220	29	96	619	198	251	69	83	31	956	3	4
	S20		5,3	231	26	101	626	203	261	74	88	34	970	4	5
	S21		6,5	134	17	68	580	172	133	41	59	13	734	2	3

Year	Point	Depth	Chemical Constituents (mg/L)												
			pH	EC	Na	K	Ca	Mg	SO_4	P	Fe	Mn	Al	Cu	Zn
2018-2019	S01	0 - 30cm	5,9	190	26	59	643	197	230	41	85	20	841	2,5	3
	S02		5,9	211	28	74	624	181	262	52	81	25	905	2,5	3,5
	S03		6,2	190	18	80	630	185	226	52	61	18	812	2,5	2,5
	S04		6,2	175	22	65	637	176	197	43	68	15	826	3	3
	S05		5,8	212	29	74	631	199	251	57	77	24	887	2,5	3
	S06		6,2	136	18	80	626	190	218	43	60	16	823	2,5	2,5
	S07		6,2	181	21	63	614	199	220	38	67	18	813	2,5	3,5
	S08		6,3	151	18	62	627	195	213	42	73	14	801	2,5	3
	S09		6,3	141	16	67	620	187	212	37	65	12	794	2	3
	S10		6,3	130	14	63	631	173	196	48	60	16	802	2	3,5
	S11		6,5	125	16	60	607	141	170	42	51	12	778	1,5	2,5
	S12		6,6	120	14	69	619	155	155	41	48	9	784	2	2
	S13		6,6	141	18	47	599	142	173	50	43	12	795	1,5	2,5
	S14		6,5	136	19	60	563	172	190	56	52	14	765	2,5	3
	S15		6,3	123	14	60	577	150	123	45	59	16	730	2	3
	S16		6,1	91	13	65	589	174	113	53	54	18	745	2,5	3,5
	S17		5,7	185	25	74	614	191	240	70	69	29	901	3,5	4,5
	S18		5,4	203	26	79	631	193	250	68	76	32	923	3	4,5
	S19		5,5	216	31	99	623	206	243	70	86	30	1003	3	4,5
	S20		5,4	246	28	97	616	200	254	76	93	36	998	3,5	5,5
	S21		6,4	141	19	71	564	189	141	46	52	15	745	2,5	3,5

Year	Point	Depth	Chemical Constituents (mg/L)												
			pH	EC	Na	K	Ca	Mg	SO_4	P	Fe	Mn	Al	Cu	Zn
2019-2020	S01	0 - 30cm	5,8	202	29	68	650	210	245	55	90	23	856	2,5	3,5
	S02		5,8	220	30	75	634	197	267	59	78	30	912	3	4
	S03		6,3	201	19	84	641	191	232	62	65	22	826	1,5	3,5
	S04		6,3	183	25	62	649	184	209	57	73	16	839	2,5	3,5
	S05		5,7	210	26	78	650	206	260	69	83	22	897	2,5	3,5
	S06		6,3	131	22	85	639	198	225	58	64	17	839	3	3,5
	S07		6,3	178	28	70	627	208	231	49	78	20	840	3	3
	S08		6,2	161	20	68	630	212	229	54	72	15	821	1,5	3,5
	S09		6,3	145	19	74	635	193	227	49	78	15	804	1,5	3
	S10		6,2	128	21	69	625	188	212	60	62	17	810	2	3,5
	S11		6,4	130	22	71	621	165	191	63	56	14	791	1,5	2
	S12		6,5	116	20	78	626	161	161	65	55	11	799	2	2,5
	S13		6,6	135	25	59	610	155	187	70	50	13	807	1,5	3
	S14		6,3	128	24	67	580	180	204	71	58	15	778	2	3
	S15		6,2	117	18	65	591	162	139	58	64	18	745	2,5	2,5
	S16		6	121	16	70	576	180	125	66	60	17	756	2,5	3,5
	S17		5,6	171	26	75	623	200	253	78	80	26	918	3	3,5
	S18		5,3	210	29	84	636	199	261	84	84	34	930	3	3,5
	S19		5,1	204	33	102	630	212	258	80	92	32	1019	3	4
	S20		5	232	29	106	629	206	250	88	97	40	1008	3,5	4,5
	S21		6,3	157	21	83	587	194	146	56	60	20	756	2,5	3,5

Table A.11: Summary of laboratory analyses for the soil sampling sites (30–60 cm depth).

Year	Point	Depth	Chemical Constituents (mg/L)												
			pH	EC	Na	K	Ca	Mg	SO_4	P	Fe	Mn	Al	Cu	Zn
2017-2018	S01	30 - 60cm	5,8	176	22	58	645	205	260	37	74	16	854	2	3,5
	S02		5,8	232	24	62	650	190	287	45	83	21	906	2,5	3
	S03		6,2	186	16	70	641	174	236	26	71	15	816	2	2,5
	S04		6,5	171	12	65	669	175	235	22	68	12	843	2,5	2
	S05		5,9	221	22	72	635	190	270	44	75	22	899	2,5	1
	S06		6,6	146	10	60	651	176	246	29	62	13	843	2,5	2
	S07		6,5	165	13	59	659	188	236	30	59	12	829	2	3
	S08		6,6	149	15	55	664	183	229	28	53	14	805	2,5	2,5
	S09		6,4	140	12	53	671	178	231	32	50	12	798	2,5	3
	S10		6,5	136	13	52	673	161	207	39	59	11	816	2	2,5
	S11		6,5	136	11	57	623	134	186	30	57	10	785	1,5	2
	S12		6,5	131	8	55	630	147	196	31	45	12	794	1,5	2
	S13		6,7	139	10	50	619	149	208	37	57	15	796	2	3
	S14		6,6	140	12	58	615	163	219	37	61	13	774	2	3
	S15		6,5	120	10	60	591	150	143	34	52	13	765	1,5	2,5
	S16		6,4	118	11	65	598	168	136	41	58	12	769	1,5	2,5
	S17		6	189	18	74	588	181	289	55	70	26	923	2,5	4
	S18		5,7	206	20	76	630	197	299	59	70	27	936	3	4,5
	S19		5,8	229	27	83	628	199	288	56	77	30	1012	2,5	4
	S20		5,6	249	23	105	643	205	306	50	75	31	998	3,5	4,5
	S21		6,6	139	14	59	601	170	156	20	54	13	754	2,5	3

Year	Point	Depth	Chemical Constituents (mg/L)												
			pH	EC	Na	K	Ca	Mg	SO4	P	Fe	Mn	Al	Cu	Zn
2018-2019	S01	30 - 60cm	5,8	211	30	63	655	192	239	39	80	17	855	2,5	3
	S02		5,9	220	24	84	639	183	257	43	77	21	912	2,5	3,5
	S03		6,1	199	24	86	632	174	237	23	58	14	826	2,5	2,5
	S04		6,2	184	23	77	645	166	206	26	62	12	834	3	3
	S05		6,4	219	31	87	649	203	267	46	69	17	899	2,5	3
	S06		6,1	161	20	89	636	188	221	32	55	10	834	2,5	2,5
	S07		6,1	170	20	68	630	190	228	34	63	11	833	2,5	3,5
	S08		6,2	155	16	70	637	197	231	30	68	12	826	2,5	3
	S09		6,1	153	18	73	645	184	226	35	62	11	810	2	3
	S10		6,2	144	20	69	640	170	209	42	55	11	816	2	3,5
	S11		6,4	140	14	62	630	143	182	35	48	9	791	1,5	2,5
	S12		6,5	150	11	71	640	151	167	28	44	6	806	2	2
	S13		6,5	157	15	53	633	148	182	40	41	10	816	1,5	2,5
	S14		6,4	153	21	65	587	179	201	38	47	12	789	2,5	3
	S15		6,3	131	16	67	594	156	134	32	50	14	746	2	3
	S16		6	122	19	75	606	171	120	46	48	16	758	2,5	3,5
	S17		5,6	199	27	81	625	196	256	58	66	21	913	3,5	4,5
	S18		5,3	221	32	84	641	187	263	56	71	22	930	3	4,5
	S19		5,4	232	36	106	638	201	254	64	81	24	1010	3	4,5
	S20		5,3	255	34	102	629	196	269	61	93	27	1009	3,5	5,5
	S21		6	163	20	80	587	181	167	26	48	13	756	2,5	3,5

Year	Point	Depth	Chemical Constituents (mg/L)												
			pH	EC	Na	K	Ca	Mg	SO_4	P	Fe	Mn	Al	Cu	Zn
2019-2020	S01	30 - 60cm	5,9	218	26	72	666	212	252	51	86	20	863	3	3,5
	S02		6	236	29	73	647	200	273	54	71	27	926	2,5	3,5
	S03		6,4	225	18	89	658	189	241	57	62	20	840	3	3
	S04		6,3	209	22	66	650	196	216	50	71	15	851	2,5	3
	S05		5,8	229	21	72	659	210	271	63	84	20	906	3	2,5
	S06		6,1	231	20	81	647	205	234	52	65	13	856	3	3
	S07		6,1	155	23	76	639	216	240	45	73	14	851	3	4
	S08		6	141	16	70	641	220	245	50	70	12	843	2,5	3
	S09		6,2	146	15	78	650	195	236	44	66	11	819	2,5	3,5
	S10		6,1	150	17	82	638	197	229	49	60	14	823	2	3,5
	S11		6,1	169	16	80	643	173	210	51	55	10	812	2	3
	S12		6,2	139	17	85	641	174	189	56	51	8	809	2,5	2,5
	S13		6,4	145	20	66	635	164	201	62	49	11	821	2	3
	S14		6	163	16	74	597	194	211	63	51	13	798	2	2,5
	S15		6	146	15	70	604	170	151	50	62	14	761	2,5	3,5
	S16		6,1	131	15	78	589	186	149	61	55	16	765	2	4
	S17		5,8	209	22	80	631	195	261	69	74	22	926	3	4,5
	S18		5,5	229	24	88	648	208	278	74	81	24	947	3,5	4,5
	S19		5,2	239	27	112	641	223	260	72	79	28	1029	3,5	4
	S20		5,3	256	25	110	637	217	267	80	81	34	1016	3	5
	S21		6,2	169	16	90	591	206	159	45	53	16	768	3	4

Table A.12: Summary of laboratory analyses for the soil sampling sites (60–90 cm depth).

Year	Point	Depth	Chemical Constituents (mg/L)												
			pH	EC	Na	K	Ca	Mg	SO_4	P	Fe	Mn	Al	Cu	Zn
2017-2018	S01	60 - 90cm	5,9	185	18	53	649	209	270	41	79	20	860	2	3
	S02		5,8	240	12	51	663	193	302	52	86	26	910	2	2,5
	S03		6	199	10	66	671	170	245	34	74	23	820	1,5	2
	S04		6,3	180	8	56	689	171	251	28	78	20	855	2	2
	S05		6	245	16	67	654	189	286	46	80	26	907	2,5	1,5
	S06		6,4	165	7	45	673	182	261	37	67	24	856	2,5	2
	S07		6,5	189	12	51	698	197	249	41	63	23	831	1,5	2,5
	S08		6,5	161	14	49	645	190	241	36	58	18	812	2	2
	S09		6,4	152	11	56	683	175	257	40	59	20	809	2	2,5
	S10		6,5	149	10	59	691	163	229	42	64	19	822	1,5	2
	S11		6,5	142	8	45	647	137	200	34	62	16	795	1,5	2,5
	S12		6,4	140	5	41	626	151	224	37	50	17	806	1,5	2,5
	S13		6,5	151	8	43	627	155	226	40	63	18	810	2	2,5
	S14		6,3	163	11	47	632	169	230	42	67	16	789	2	3
	S15		6,4	143	9	53	605	147	160	38	60	17	770	1,5	2
	S16		6,3	127	8	47	609	170	151	46	64	20	754	2	2,5
	S17		6,1	199	16	62	601	188	307	59	74	30	936	2,5	3,5
	S18		5,8	212	15	68	645	195	321	63	76	30	947	3	5
	S19		5,8	239	13	65	633	203	306	64	83	36	1023	2	3,5
	S20		5,5	264	15	89	651	201	329	54	81	37	1005	3,5	4
	S21		6,4	151	11	49	612	178	179	30	62	16	764	2	3,5
Year	Point	Depth	Chemical Constituents (mg/L)												
			pH	EC	Na	K	Ca	Mg	SO_4	P	Fe	Mn	Al	Cu	Zn
2018-2019	S01	60 - 90cm	5,7	206	26	60	662	202	243	36	74	16	862	2,5	3
	S02		5,8	229	22	76	647	186	263	40	71	17	923	2,5	2,5
	S03		6	213	20	82	640	175	247	26	60	13	843	2	2
	S04		6,1	201	22	75	652	171	211	22	56	10	851	2,5	2
	S05		6,3	236	25	81	657	206	273	45	61	14	906	2,5	1,5
	S06		6,2	172	19	84	643	191	230	33	52	8	854	3	2
	S07		6,2	197	21	63	633	193	233	31	60	9	850	2	2,5
	S08		6,3	153	14	62	641	201	237	27	61	10	841	2	2
	S09		6,2	165	16	67	650	187	236	31	55	10	822	2	2,5
	S10		6,3	159	19	61	645	174	216	40	52	11	829	2	2
	S11		6,6	167	15	56	640	150	199	33	46	10	803	1,5	2,5
	S12		6,6	162	12	66	649	155	175	26	40	7	814	1,5	2,5
	S13		6,4	155	13	50	644	157	189	36	36	10	825	1,5	2,5
	S14		6,4	163	19	61	602	186	212	35	40	11	791	1,5	3
	S15		6,3	143	15	60	603	164	142	30	42	12	753	1,5	2,5
	S16		6,3	126	17	67	614	180	129	44	46	14	769	2	3
	S17		6	223	24	74	632	207	266	51	61	18	932	3	3
	S18		5,7	239	30	80	649	192	273	50	65	20	956	2,5	4,5
	S19		5,8	261	32	100	649	206	260	53	73	22	1023	2,5	4
	S20		5,6	251	35	94	636	200	273	55	85	24	1020	3	4,5
	S21		6,1	172	15	76	599	183	179	17	41	14	767	2	3
Year	Point	Depth	Chemical Constituents (mg/L)												
			pH	EC	Na	K	Ca	Mg	SO_4	P	Fe	Mn	Al	Cu	Zn
2019-2020	S01	60 - 90cm	5,7	223	22	76	658	216	248	49	82	16	271	2,5	3
	S02		5,9	226	24	79	640	197	271	50	66	20	940	2	3
	S03		6,2	231	16	90	659	184	243	51	57	14	862	1,5	3
	S04		6,4	211	20	71	654	189	218	46	64	11	867	2	3
	S05		6	225	18	75	661	215	268	55	73	13	923	2	2
	S06		5,9	236	16	84	652	212	241	46	59	9	874	2,5	3
	S07		6	159	18	80	648	226	246	40	61	10	869	2	3
	S08		6,2	147	14	78	651	237	251	44	60	8	851	2	2,5
	S09		6,1	152	12	86	649	209	240	39	58	7	832	2,5	3
	S10		6,4	159	13	90	636	210	231	41	50	12	830	1,5	2,5
	S11		6,3	173	12	85	647	189	218	43	49	8	826	2	2
	S12		6,5	141	11	87	653	178	194	51	46	8	827	1,5	2
	S13		6,2	149	14	70	648	170	214	57	41	10	834	1,5	2,5
	S14		6,1	179	12	73	603	204	226	61	50	11	809	2	2,5
	S15		5,9	151	12	69	610	181	160	47	56	12	777	2	3
	S16		6	139	11	80	697	193	153	56	51	11	779	1,5	2,5
	S17		6	216	15	83	647	204	270	76	66	15	936	2,5	2,5
	S18		5,8	235	17	90	655	216	281	69	70	17	957	2,5	4
	S19		5,4	257	18	120	658	236	269	62	64	21	1039	2,5	3,5
	S20		5,5	261	19	113	649	228	271	76	75	27	1025	2	4
	S21		6	170	11	92	609	212	170	42	43	13	779	2,5	3

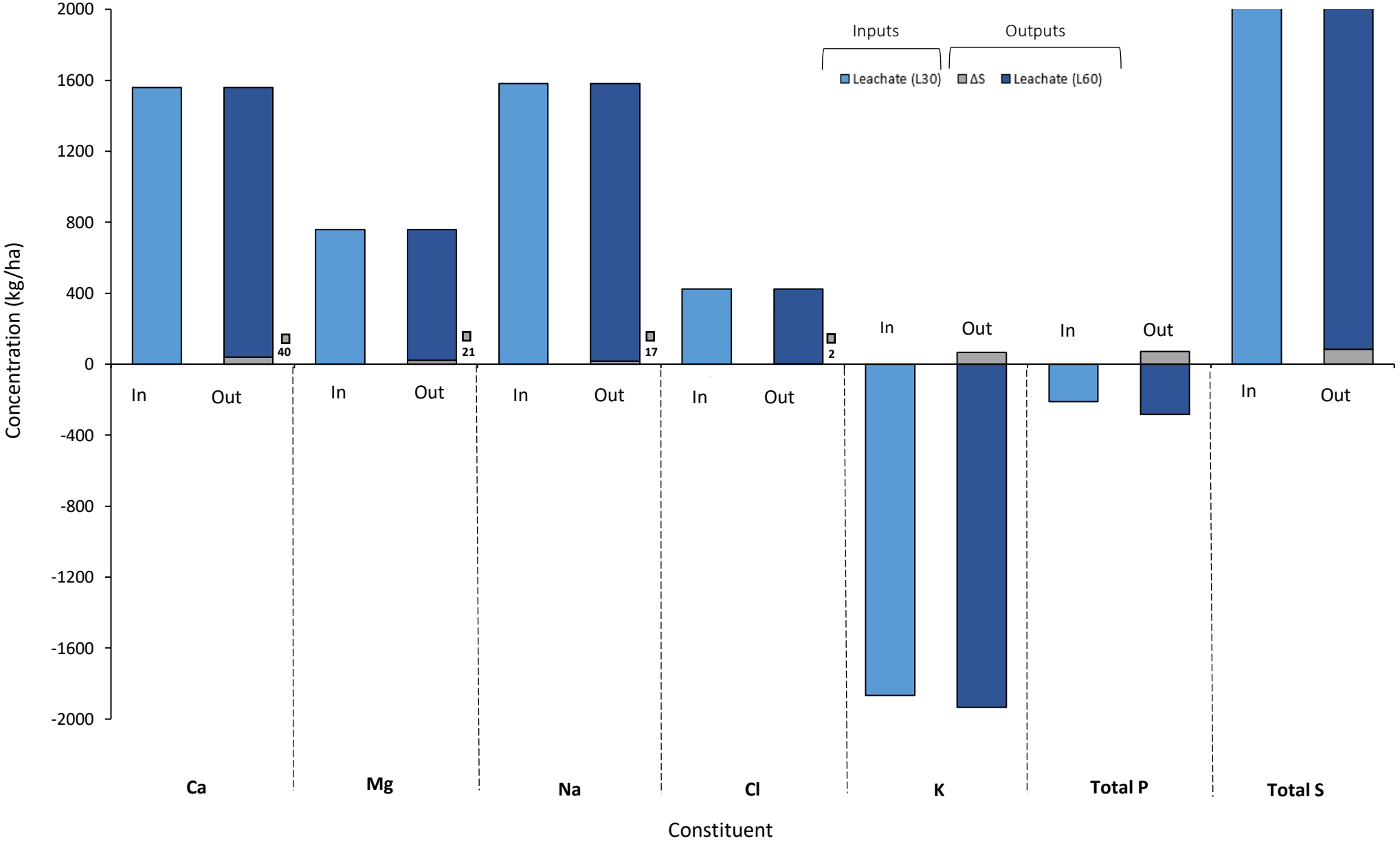


Figure A.5: Partial nutrient mass balance: Each constituent broken down into Input (L_{30}) and Output ($\Delta S + L_{60}$) in kg/ha for the 30 – 60cm depth.

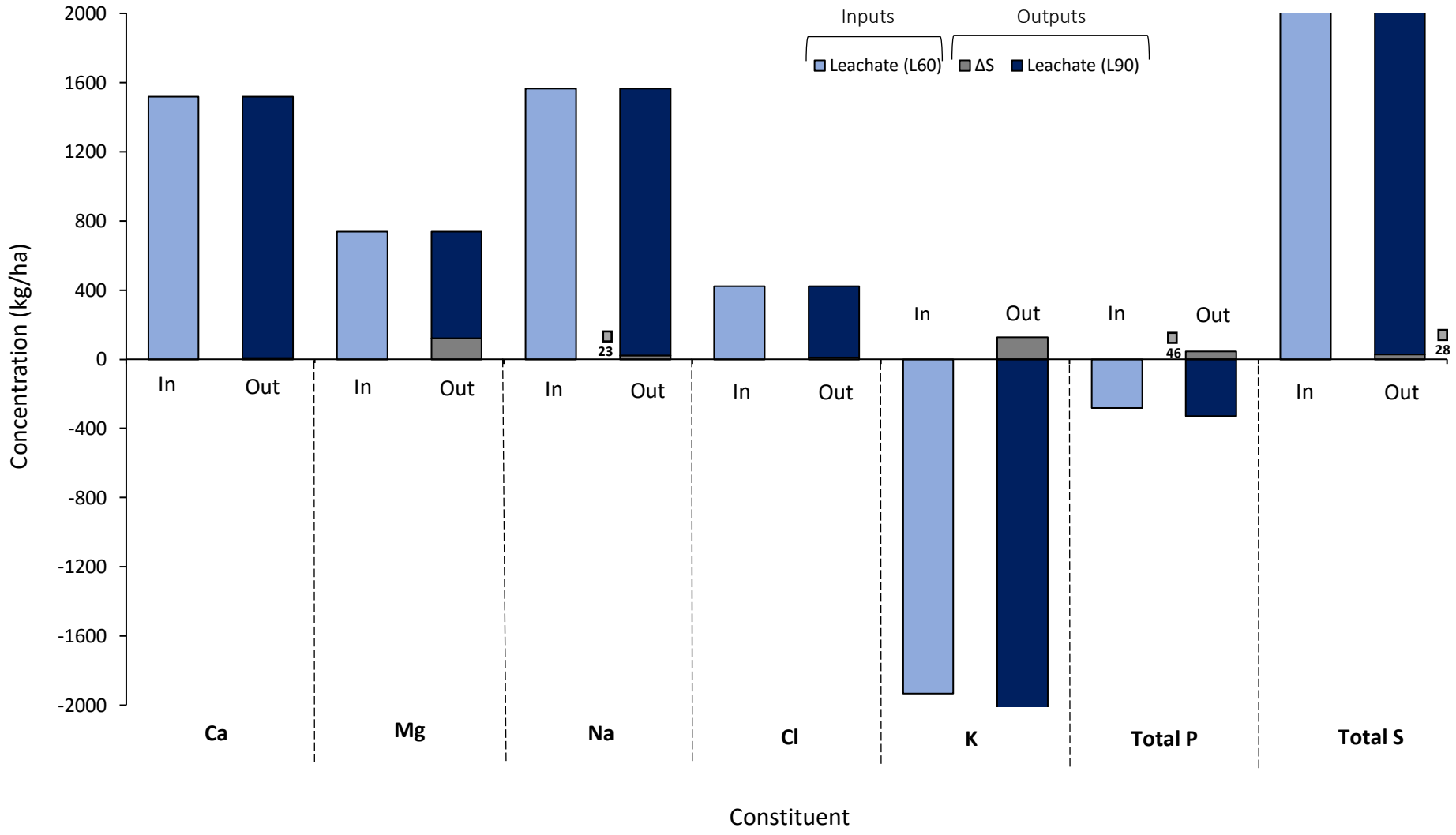


Figure A.6: Partial nutrient mass balance: Each constituent broken down into Input (L_{60}) and Output ($\Delta S + L_{90}$) in kg/ha for the 60 –90cm depth.

APPENDIX B

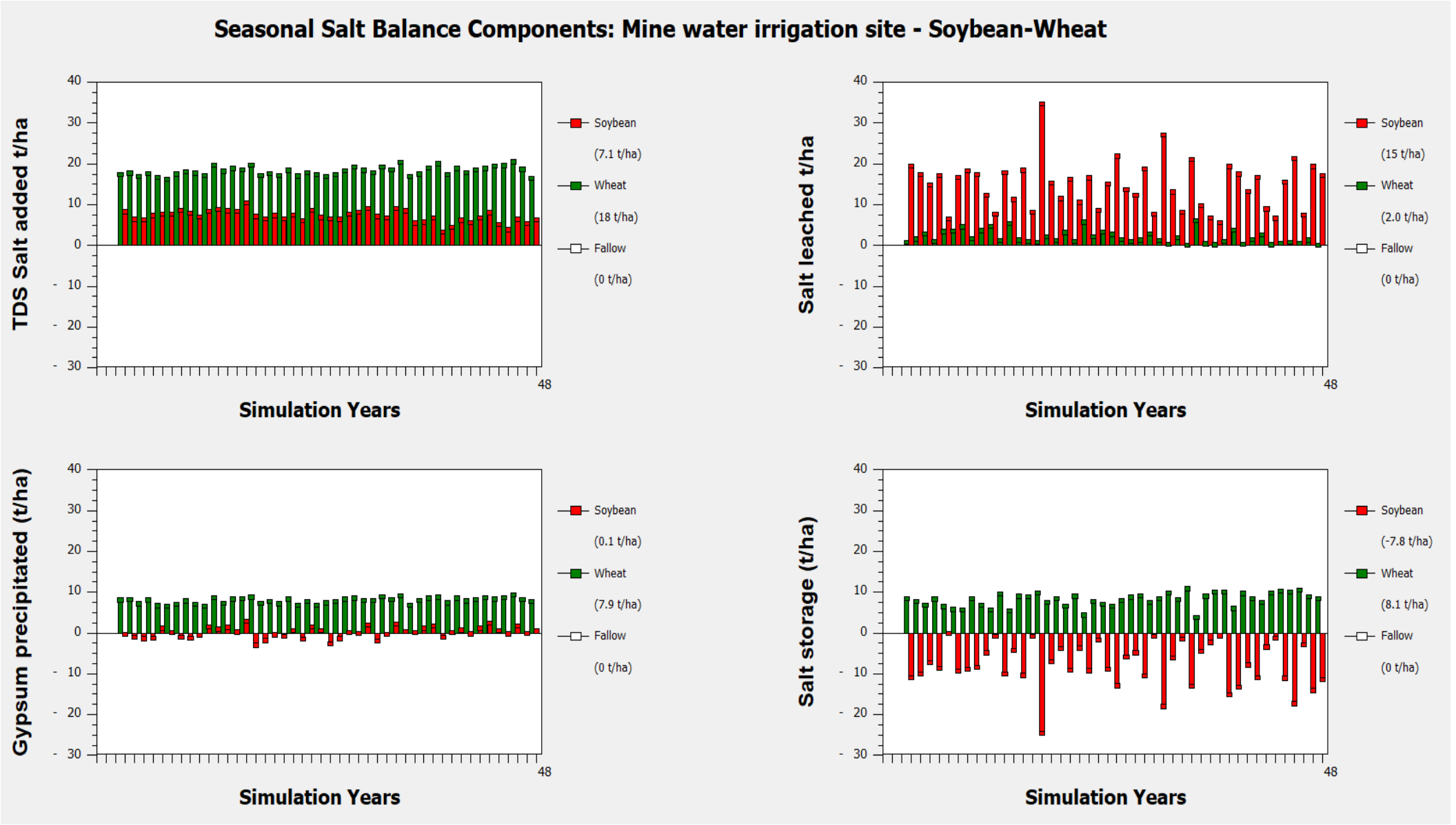


Figure B.1: Soybean-wheat seasonal salt balance for a 45-year DSS simulation.

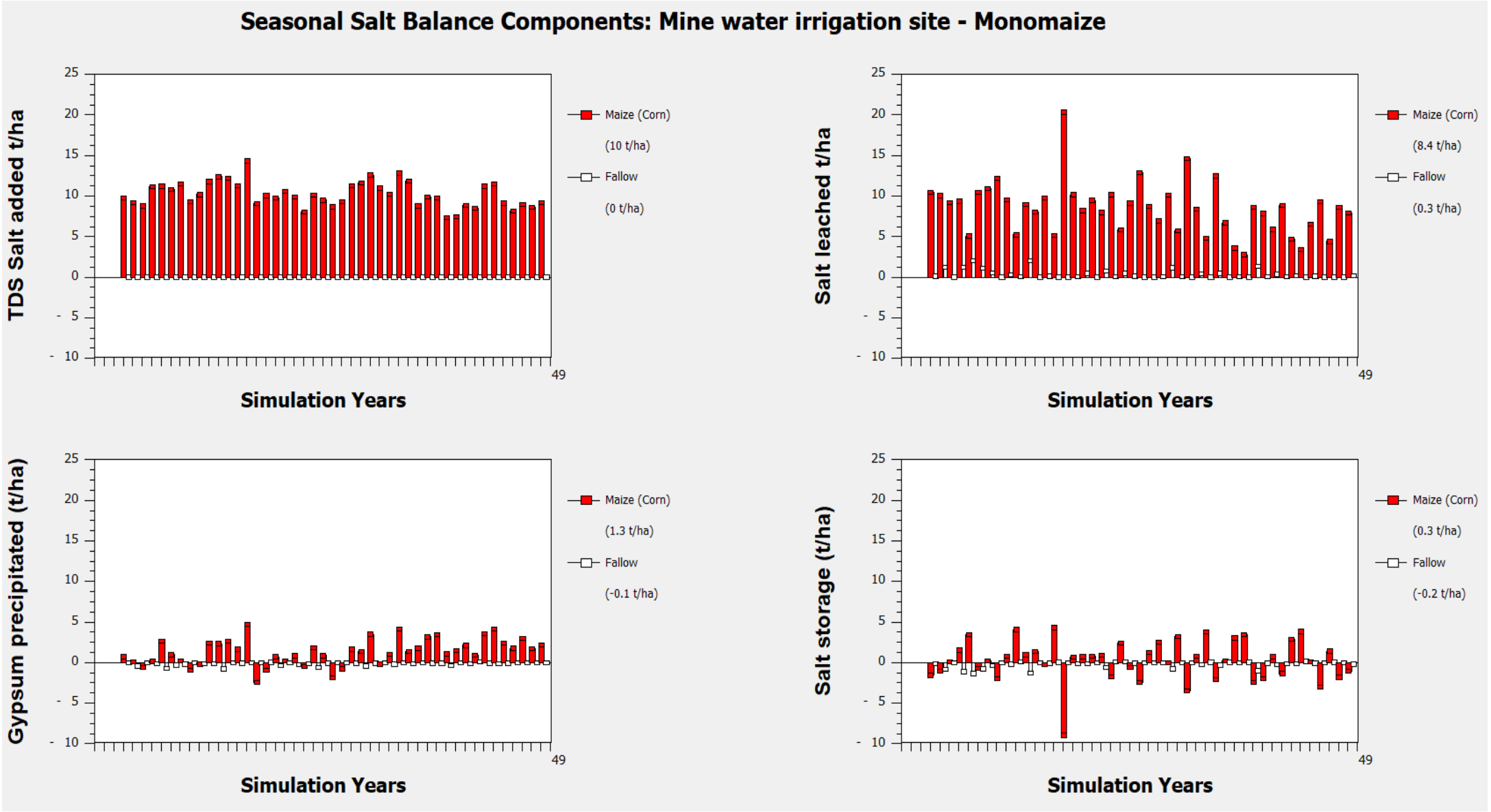


Figure B.2: Monomaize seasonal salt balance for a 45-year DSS simulation.

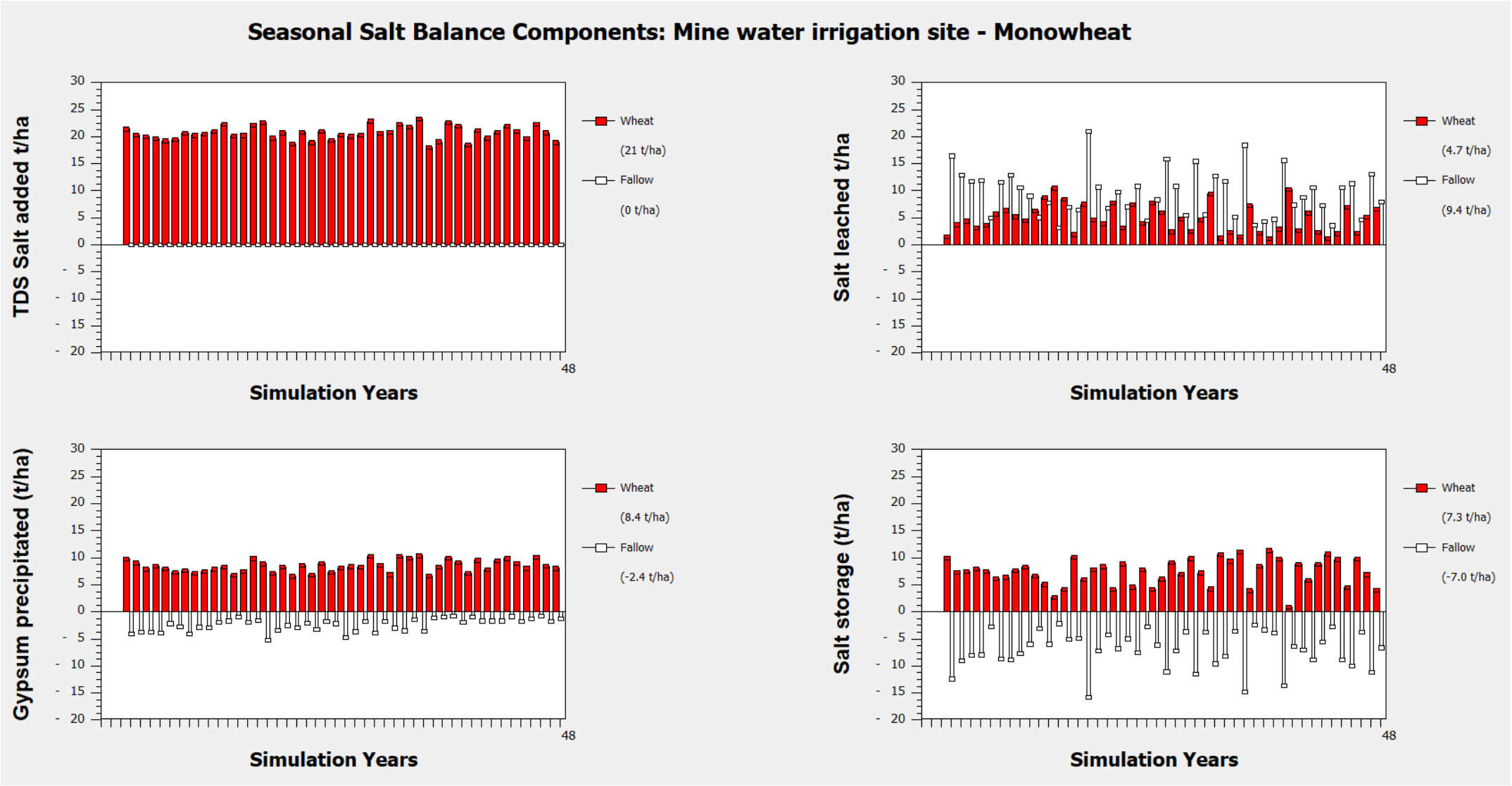


Figure B.3: Monowheat seasonal salt balance for a 45-year DSS simulation.

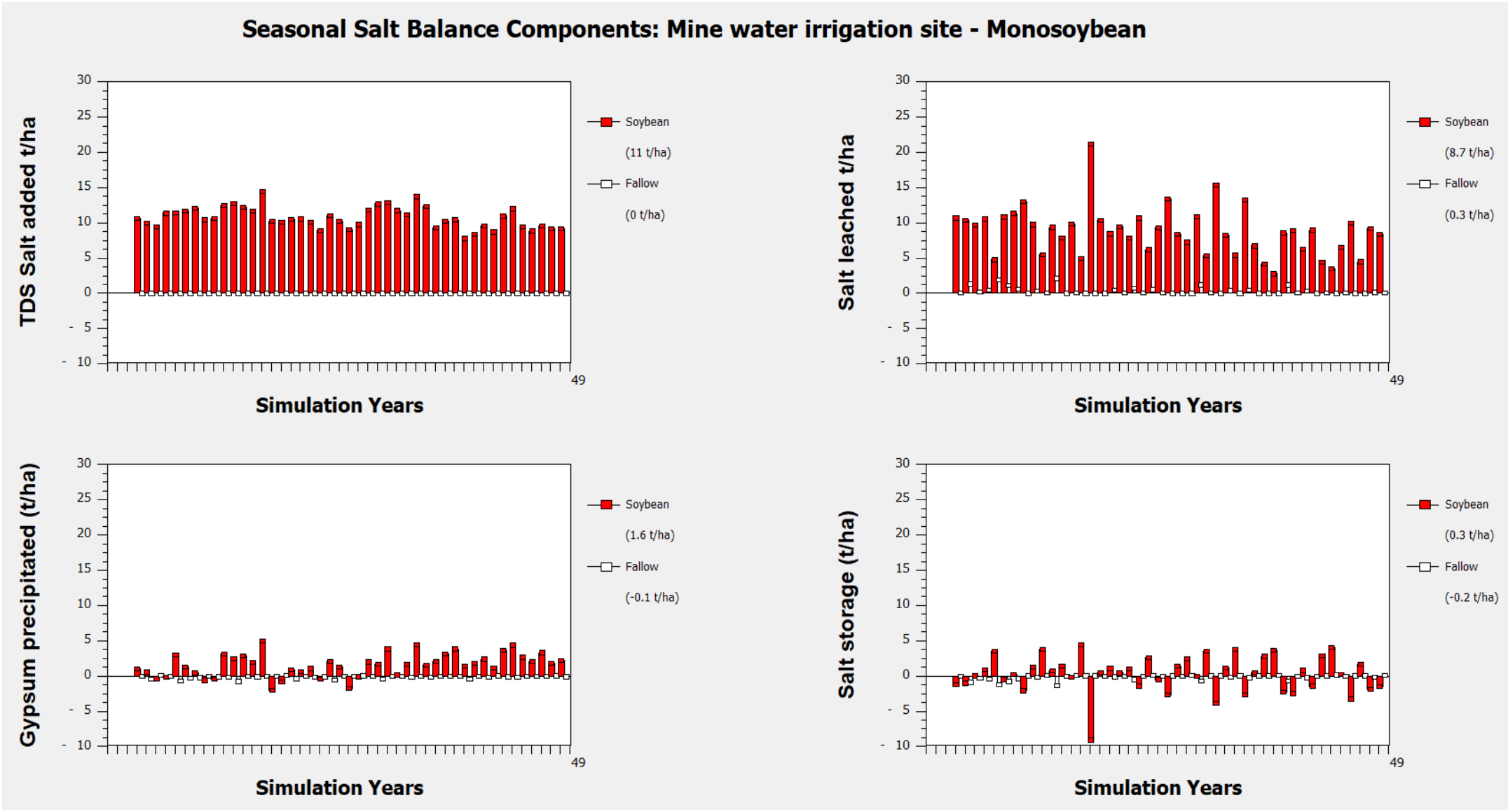


Figure B.4: Monosoybean seasonal salt balance for a 45-year DSS simulation.

APPENDIX C

The analytical procedures and methods required to fulfil and determine the soil trace element thresholds, as described in Chapter 5, section 5.5.4 Action Levels.

1. **Method for aqua regia extraction method of soluble trace elements (ISO 1995)**

Place 3 g of soil sample and 28 mL of aqua regia for the extraction, followed by filtration of the extract through ashless paper filters and dilution with deionised water.

2. **Method for extraction of available trace elements in soil samples using an Ammonium Nitrate (NH_4NO_3) solution (DIN 1997).**

Place 20 g air dry soil in a shaking bottle (100-150 mL), add exactly 50 ml ammonium nitrate solution (1 mol/L) and shake for 2 hours at 20 rpm at room temperature. Then allow the solid particles to settle for 15 min. Decant the supernatant solution and filter (0,45 µm). Dispose the first 5 mL of the filtrate. Collect the remaining solution in a 50 mL bottle for analysis.

Table C.1: Minimum concentrations which have to be quantified accurately with the Ammonium Nitrate extraction method (DIN 19730) for good results in the field of soil protection.

Element		**1 mol/L Ammonium Nitrate Solution**	**Ammonium Nitrate extractable in air dry soil**
		µg/L	**µg/kg**
Ag	Silver	< 0,4	< 1
As	Arsenic	10	25
Be	Beryllium	1	2,5
Bi	Bismuth	< 0,4	< 1
Cd	Cadmium	2	5
Co	Cobalt	20	50
Cr	Chromium	4	10
Cu	Copper	100	250
Hg	Mercury	< 0,4	< 1
Mn	Manganese	2000	5000
Mo	Molybdenum	10	25
Ni	Nickel	100	250
Pb	Lead	< 8	< 20
Sb	Antimony	10	25
Tl	Thallium	4	10
U	Uranium	1	2,5
V	Vanadium	10	25
Zn	Zinc	100	250