Impact of irrigation with mine affected saline sulphate waters on crop performance, soil properties and groundwater quality

by

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DECLARATION

I, Zimoné Danielle Ronquest, hereby certify that this dissertation is my own work, except where duly acknowledged. I also certify that no plagiarism was committed in writing this dissertation.

Signed ____________________

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ABSTRACT

The majority of mine-affected waters contain large quantities of calcium and magnesium sulphate, with some dominated by sodium sulphate or bicarbonate. The availability of large volumes of mine impacted waters and large tracts of unfarmed land owned by mines, creates an opportunity to utilise these waters for irrigation. Not only will this drastically reduce mine water treatment costs, it will create sustainable livelihoods and food production, particularly post-mine closure. The aims of this study were to monitor and model field scale water and salt balances for a small scale mine water irrigation scheme in Mpumalanga, in order to predict the long-term impact and sustainability of gypsiferous mine water irrigation, as well as determining the effect of sulphate salinity on crop response of various temperate annual cereal grain crops. A field trial was established at Mafube Colliery outside Middelburg (Mpumalanga, South Africa) during 2016-2018. White maize was irrigated for one of the two seasons on virgin, unmined land. Regular monitoring was carried out to collect atmospheric, crop and soil data for detailed validation of the soil water balance (SWB) model. For the first season, it has shown that crops (specifically maize) grow well with these mine impacted waters, with minimal environmental impacts in the short term and proved to be more profitable than dryland production. The grain produced is safe for human consumption, which makes this a feasible practice. Pot trials were carried out at the UP Experimental Farm where crops were grown in water culture at five levels of salinity with an EC range of 120 to 2000 mS m^{-1}. A combination of a nutrient solution, gypsum ($CaSO_4.2H_2O$) and Epsom salts ($MgSO_4.7H_2O$) was used to make up each treatment. The effect of salinity on germination, seedling establishment and vegetative growth was investigated. Increasing sulphate salinity negatively affects germination, seedling and vegetative growth of annual temperate crops, especially when dominated by Mg. After exceeding the threshold for salt stress, a linear reduction in relative growth was found for both seedling establishment and vegetative growth, as well as a decline in germination percentage. In general, annual temperate cereal crops are more sensitive to sulphate salinity during the vegetative growth stage compared to the seedling stage at the same sulphate salinity concentrations. Irrigation with mine water is viable, sustainable and feasible, if the appropriate management practices are in place and if some environmental impact is acceptable. Crop and cultivar selection, climatic conditions, irrigation method, soil and water quality are but a few of the parameters that need to be considered when irrigating with saline sulphate waters. Another important aspect to look at it, is nutritional requirements and possible imbalances.

Keywords: Mine water irrigation, irrigation water quality, gypsiferous, salinity, crop growth modelling, SWB, Decision support system, fitness-for-use

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LIST OF ABBREVIATIONS

AMD	Acid Mine Drainage
BD	Bulk Density (kg m^{-3})
CEC	Cation Exchange Capacity ($cmol_c$ kg^{-1})
D	Willmott's (1982) index of agreement
DAP	Days After Planting
DM	Dry matter (kg m^{-2} or kg ha^{-1})
DOY	Day of Year
DSS	Decision Support System
DWR	Dry matter water ratio (Pa)
EC	Electrical Conductivity (mS m^{-1})
EC_e	Saturation paste extract EC (mS m^{-1})
EC_i	EC of irrigation water (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^{-1})
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
MSE	mean absolute error
N	number of observations
PAR	Photosynthetically Active Radiation
PAW	Plant Available Water (mm per m^{-1} of soil depth)
PWP	Permanent Wilting Point (kPa or mm per m^{-1} of soil depth)
r^2	coefficient of determination
RH	Relative Humidity (%)
RMSE	root mean square error
SAWQG	South African Water Quality Guidelines
SLA	Specific leaf area (m^2 kg^{-1})
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})
u	Wind Speed (m s^{-1})
VPD	Vapour Pressure Deficit (kPa)
VWC	Volumetric Water Content (mm per m^{-1} of soil depth)
WRC	Water Research Commission
WUE	Water Use Efficiency (kg ha^{-1} per mm of evapotranspiration)
Y_p	Potential yield (% or fraction)
Y_r	Relative yield (% or fraction)

LIST OF CHEMICAL SYMBOLS

Al	Aluminium
As	Arsenic
B	Boron
Be	Beryllium
Ca	Calcium
$Ca(OH)_2$	Hydrated lime
$CaCO_3$	Limestone
$CaSO_4.2H_2O$	Gypsum
Cd	Cadmium
Cl	Chloride
Cr	Chromium
Cu	Copper
F	Fluoride
Fe	Iron
Hg	Mercury
K	Potassium
Li	Lithium
Mg	Magnesium
$MgSO_4.7H_2O$	Epsom salt
Mn	Manganese
N	Nitrogen
Na	Sodium
Ni	Nickel
P	Phosphorus
Pb	Lead
SO_4	Sulphate
V	Vanadium
Zn	Zinc

INTRODUCTION AND PROBLEM STATEMENT

South Africa is known for its lucrative mining and agricultural industries. Coal mines, more specifically the coal mines in the Mpumalanga area, are known to generate acidic or neutral mine waters that are rich in sulphates. The increased sulphate content often causes a saline water that is saturated with gypsum ($CaSO_4.2H_2O$) and is often referred to as gypsiferous waters. In the case of the Mpumalanga coal fields, the waters are dominated by calcium (Ca) and magnesium (Mg) sulphates. The Mpumalanga coal fields are situated in the Olifants River Catchment, which may pose a salinization risk to receiving water systems. To limit the possibility of salinization and water quality degradation, the salt load to water bodies has to be reduced significantly. Grobbelaar et al. (2004) stated that coal mines in the Mpumalanga area generate up to 360 ML of untreated water per day. That is equal to 131 400 ML per year, and if an average of 1000 mm irrigation (estimate of 400 mm in summer and 600 mm in winter) is applied per year, this could potentially be enough water to irrigate 13 000 ha. The expected discharge rate per colliery is between 12 and 40 ML day^{-1} (Grobbelaar et al. 2004), and with this it could potentially irrigate 400 to 1500 ha every year. However, it needs to be said that this amount is calculated on the basis that one field (average crop rotation) requires 1000 mm of irrigation per year depending on the rainfall for that year. The irrigation should also be scheduled, and will not be required every day, thus the mines will need to have adequate storage to retain water if not required for irrigation. The use of mine water for irrigation, if monitored and managed correctly, may facilitate sustainable mine closure, as it assists with the reclamation of valuable agricultural land and the reuse of water which would otherwise have increased pollution and led to wastage and degradation of natural resources. An increase in population leads to a growing demand for food and other resources. Thus, the application and reuse of mine water will not only address the environmental issues, but also contribute to the growing demand of food and provide much needed employment. Therefore, irrigation potentially offers an environmentally, economically and socially responsible and sustainable mine water management approach (Annandale et al. 2006).

Irrigation with gypsiferous mine waters has been shown to sustainably produce crops and reduce mine water salt loading to catchment water bodies through gypsum precipitation in the soil profile (Du Plessis 1983). Although it has been shown that there is a possibility of salt accumulation in the soil, this might lead to an increase of soluble salts in the soil and especially in the root zone. If this happens it will affect the roots' ability to take up water as the salt accumulation will provide the root zone with a definite salt gradient that decreases with distance from the roots. A common crop response to salt stress is stunted growth. Each crop has a threshold value which it allows a certain level of salts to accumulate to before the high salt content will start affecting the growth and size of the plant. Although this study will be focussing mainly on crop performance, soil properties and groundwater quality, it is important to remember that salinity will also affect nutrient levels in plants. Salinity can result in: (i) decreased nutrient availability, (ii) influencing nutrient uptake and distribution within the plant, (iii) increased nutrient requirement, (iv) stunted or impaired growth, and (v) decreased nutritional value of harvested plant (Maas and Grattan 1999, Läuchli and Grattan 2007)

Crop response to salinity can be simulated using SWB, given that the required parameters are known. The long-term effect of irrigating with saline water can be simulated over 10, 20- and 50-year periods using the South African Water Quality Guideline DSS. This model will give an idea of the fitness for use of such waters for irrigation and the possible long-term risks involved when using it for irrigation. With SWB it is possible to simulate the effect of salinity on a crop's performance, and potentially the effects on soil properties and groundwater quality, however, there are opportunities to improve these simulations. It was emphasized by Van der Laan et al. (2014) to look at the current capacity of the SWB model and investigate possible improvements or adjustments. This can be done by comparing the simulated results to the measured results and looking at the statistical difference and if it can be deemed acceptable or not.

The aims of this study were to monitor and model field scale water and salt balances for a small scale mine water irrigation scheme (19 ha unmined land) in Mpumalanga, in order to predict the long-term impact and sustainability of gypsiferous mine water irrigation and improve the simulation capabilities of the SWB model, as well as determining the effect of sulphate salinity on crop response of various temperate annual cereal grain crops. The objectives included (i) quantifying at field level the short-term impact of irrigating with gypsiferous mine water on maize production and soil and groundwater resources (ii) modelling the short and long term impact of irrigating with gypsiferous mine water on maize production with SWB, and (iii) quantifying germination, seedling establishment and vegetative growth response of 5 cereal grain crops to sulphate salinity. For this study, four hypotheses were considered, (i) Negligible salt accumulation will take place, as the water quality of the irrigation water meets the requirements of the SAWQG fitness for use levels (ideal and acceptable levels), (ii) Gypsiferous mine water irrigated crops will yield more than dryland crops, (iii) Irrigating salt tolerant crops with mine water is sustainable when using untreated saline sulphate mine water, and (iv) crop response to sulphate salinity studies will show that plants are more tolerant to sulphate salinity compared to sodium chloride salinity.

Irrigation with gypsiferous mine waters has been shown to sustainably produce crops and reduce mine water salt loading to catchment water bodies through gypsum precipitation in the soil profile. However, the important knowledge gaps that need to be considered are:

- The long-term sustainability of irrigation with saline mine water;
- The possible improvements or adjustments that can be made to the SWB model;
- The influence on the groundwater system when irrigating with saline mine water;
- The unexplored opportunities to reduce mine water treatment costs if the water is to be used for irrigation.

This dissertation consists of four chapters which include; a literature review, outcomes of a field trial and a pot trial, and lastly a chapter on modelling salinity. The literature review focusses on salinity, the different sources, and the effects of salinity on crop growth and development. In addition, the link between mine water irrigation and salinity is discussed.

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CHAPTER 1: LITERATURE REVIEW

1.1 Introduction

Soil salinity is considered one of the limiting factors when it comes to agricultural production. Salinity is known to affect the growth and development of a plant, and in turn reduces the final crop yield. According to Arasteh (2010), about 900 million hectares are classified as saline soils which accounts for 7% of the global land mass (Martinez-Beltran and Manzur 2005) of which 20% is arable land (Geilfus et al. 2010). Ghassemi et al. (1995) estimates that about 80 million hectares have salinized through human activities, with irrigation contributing up to 60%.

Irrigation with poor quality water can cause salinization, as well as contribute to the rise in water tables, which facilitates the concentration of salts in the root zone (Maas and Grattan 1999, Rengasamy 2010). However, this is not the only cause, as salts naturally occur within soil and water bodies due to the chemical and physical weathering of parent rocks and other organic materials (Maas and Grattan 1999). Weathering of rock materials produce various chloride salts that are dominated by calcium, magnesium and sodium, and often also produce sulphates and carbonates of the same nature (Munns and Tester 2008).

Degree of salinity is defined as the amount of soluble ions in the soil solution and can be measured in terms of the concentration of a specific dissolved salt or ion (Rhoades 1982). These ions include bicarbonates (HCO_3^-), calcium (Ca^{2+}), carbonates (CO_3^{2-}), chlorides (Cl^-), magnesium (Mg^{2+}), potassium (K^+), sodium (Na^+) and sulphates (SO_4^{2-}) (Bernstein 1975, Jamil et al. 2011). Salinity can be reported as a concentration, total dissolved solids (TDS) or electrical conductivity (EC) (Feinerman et al. 1982). When measuring salinity as a concentration, it is expressed in terms of the dominating salt (chloride or sulphate) in mEq L^{-1}, mg L^{-1} or mol m^{-3}. EC is more commonly used to estimate total salt concentration and is measured in deciSiemens per metre (dS m^{-1}) or millimhos per centimetre (mmhos cm^{-1}) which are equal numerically (Hoffman et al. 1990). Another common EC unit used is milliSiemens per meter (mS m^{-1}) which is equal to 0.01 dS m^{-1} (Maas and Grattan 1999). TDS is measured in parts per million (ppm) or mg L^{-1}, and all three (concentration, EC and TDS) can be used interchangeably as there is often a highly linear correlation between the three (Feinerman et al. 1982).

1.2 Crop response to salinity

Salt stress is known to negatively influence the development, growth and yield of a plant. The salinity stress causes an inhibition of both physiological and metabolic processes, resulting in a reduction in growth and thus a decrease in yield (Maas and Hoffman 1977). The most common plant response to salinity is a general stunting in growth and as the salt concentration increases above a certain threshold, both the growth rate and plant size decreases (Maas and

Grattan 1999). However, not all plants are equally sensitive to salinity stress and thus each crop has its own threshold value (see TABLE 1.1), at which the crop will experience a decrease in yield once this threshold is exceeded (Maas and Hoffman 1977). Maas and Hoffman (1977) states that the threshold value is defined as the maximum allowable soil saturation electrical conductivity (EC_e) value before a reduction in yield (compared to non-saline yields) occurs, where after the yield will decrease per unit salinity increase (referred to as the slope value).

TABLE 1.1: Salinity thresholds (in terms of EC_e) and sensitivity rank (Adapted from Maas and Grattan (1999))

EC range (mS m^{-1})	Rank
0 - 150	Sensitive
150 - 300	Moderately sensitive
300 - 600	Moderately tolerant
600 - 1000	Tolerant
>1000	Unsuitable

The reduction in growth is seen to be a nonspecific salt effect that is purely related to the osmotic potential (salt concentration). However, according to Maas and Grattan (1999) a single salt or extreme ion ratios will lead to specific ion effects and toxicities. Usually, saline soils generally consist of various salts and therefore osmotic effects predominate (Bernstein 1975). Another effect of salt stress can be nutritional imbalances due to competing ions which influences nutrient availability, uptake, distribution and requirement (Grattan and Grieve 1994, Maas and Grattan 1999). Plant nutrient uptake and accumulation is reduced under saline conditions due to the competitive processes and selective uptake of ions (Janzen and Chang 1987, Maas and Grattan 1999) especially nitrate (NO_3^-) and phosphate (PO_4^{3-}) (Zekri and Parsons 1989, Sharpley et al. 1992).

Most plants become increasingly tolerant as they mature, thus the earlier the plants are stressed, the greater the reduction in ultimate vegetative growth. However, with cereal grain crops like wheat, barley and oats, the most serious effects are noted during the vegetative and early reproductive stages and thus they are susceptible to yield reducing suppression of tiller formation (Maas and Grattan 1999). Salinity can also affect germination by delaying the initiation process, which is directly related to water uptake capabilities, which is retarded by osmotic stress or ion toxicity experienced by the seed (Munns and Tester 2008, Rahman et al. 2008).

1.3 Effect of salinity on the environment

Soil salinization is considered to be water-soluble salts above a certain acceptable level, accumulated within the different soil layers and negatively affecting crop production and the surrounding environment (Artzy and Hillel 1988). Salinity can affect both the physical and chemical properties of soil (Rowel 1988). Although related, there is a key difference between soil salinity and soil sodicity. Saline soils are classified as soils that contain various soluble salts, have an EC greater than 400 mS m^{-1}, and a pH less than 8.5 (US Salinity Lab 1954, Bernstein 1975, Jamil et al. 2011). Sodic soils can be saline or non-saline (Bernstein 1975) and contain excess exchangeable sodium, which means that 15% or more of the cation exchange sites are dominated by Na^+ (US Salinity Lab 1954). Agassi et al. (1981) states that both soil salinity and soil sodicity affect the structure of the soil. Saline soils are prone to show signs of flocculation due to ions such as Ca^{2+} and Mg^{2+}, whereas sodic soils are prone to show signs of dispersion due to ions like Na^+ (Chibowski 2011). Flocculation takes place when fine particles bind together in aggregated form, whereas dispersion is the exact opposite and often leads to the swelling and shrinking of clays (Warrence et al. 2002, Chibowski 2011, Wallender and Tanji 2011). Flocculation is deemed beneficial for soil aeration and root penetration and growth, whereas dispersion decreases soil permeability which controls the movement of water and air throughout the soil (Podmore 2009, Wallender and Tanji 2011).

Salinization affects both dryland and irrigated areas. In dryland areas, salinization is caused by the extensive clearing of natural vegetation for anthropogenic purposes, which leads to a reduction in evapotranspiration losses and a rise in the groundwater table (Salt Force 1988, Hart et al. 1990). Given that groundwaters are naturally saline (due to weathering of rock materials and influx of seawater), the rise in the groundwater table contributes to land salinization and increases the salinity in surrounding streams and wetlands (Peck et al. 1983, Salinity Committee 1984). In irrigated areas, the same thing takes place, although the groundwater table rise is caused by poor drainage instead of vegetation removal (Hart et al. 1990). The importance of monitoring salinization of rivers, streams and wetlands has been discussed in detail by Hart et al. (1990) and Hart et al. (1991). In freshwater systems, salinity (exceeding 1000 and 10000 mg L^{-1}) has been found to influence not only the autotrophic and saprotrophic communities, but also the detritivore, herbivore and predatory communities, as well as the riparian vegetation (Greenway 1973, Brock 1985, Hart et al. 1990, Hart et al. 1991). The effects of salinity on water systems include; loss of organisms, increase in more salt tolerant (halophytic) organisms, loss of riparian vegetation, decrease in fish and other invertebrate populations as larvae and eggs are negatively affected, and loss of available fresh drinking water for birds and other animals (Hart et al. 1990). As some of the predatory aquatic life feeds mainly on the detritivore community (whom are more susceptible to the effects of salinity), consequently the predatory community may also be affected negatively which will cause a food chain imbalance.

1.4 Salinity management

Crop response to salinity depends on various factors; (i) the quality of the irrigation water, the frequency, duration and method of irrigation, (ii) the crop type, growth stage and tolerance level, (iii) the soil fertility, depth, aeration and drainage rate, (iv) the climate - air temperature, relative humidity, radiation and wind speed (Maas 1990, Jovanovic and Annandale 1998). These factors influence the rate of evaporation and the soil water supply to the crop (Jovanovic and Annandale 1998). Therefore, one of the most important elements to consider when looking at crop production in saline conditions, is the growing environment. Aerial temperature and relative atmospheric humidity significantly influences crop salt tolerance (Hoffman et al. 1990). Hot and dry conditions tend to increase a crops' sensitivity to salinity, whereas crops tend to be more tolerant under cool, humid conditions (Hoffman and Rawlins 1971, Hoffman et al. 1975, Hoffman and Jobes 1978).

Site location and the type of irrigation system is of utmost importance, as this influences the drainage abilities of the soil profile, as well as the tendency to accumulate salts within the soil profile (Grattan 2002, Horneck et al. 2007). Different salinity profiles arise with different irrigation methods (Hoffman et al. 1990). The irrigation method, along with the soil type, directly affects the rate at which leaching will take place (Bernstein 1975). The leaching requirement is defined by US Salinity Lab (1954) as the fraction of total irrigation water applied in order to ensure leaching. An adequate leaching fraction will allow for the removal of excess salts by draining them out of the profile, however, excess leaching is only required once there is an accumulation of salts that exceed the tolerance threshold of the crop (Hoffman et al. 1990).

Surface (furrow or flood), drip or sprinkler irrigation are some of the more commonly used methods of irrigation. Furrow irrigation tends to accumulate salts within the root zone, as leaching mainly occurs below the furrows, whereas sprinkler and surface flood irrigation creates a profile that increases in salinity with depth (Hoffman et al. 1990). However, with infrequent irrigations, salts accumulate increasing salinity, and with high evaporation near the soil surface, even more salt is prone to accumulate. This can be rectified by applying irrigation more frequently and in smaller amounts, as achieved with drip irrigation (Bernstein and Francois 1973). However, Shani et al. (2007) stated that although increasing the quantity of highly saline irrigation waters may compensate for the negative effects of salinity, it will not be able to deliver the yields obtained under low or non-saline conditions. Irrigation frequency will depend on the water demand, the irrigation method and the irrigation water quality (Hoffman et al. 1990). The potential of a given water to be used for crop production is defined by Bernstein (1975) as the best attainable result for that water under optimum conditions of use. When water contains more salts than the crop can tolerate, its potential for crop production is diminished (Bernstein and Francois 1973).

The effect of salinity on crop production can be reduced by planting a more salt tolerant crop or variety (Maas and Grattan 1999). Some varieties are genetically bred to be more tolerant, although the tolerance range is generally similar within a species (Shannon 1984, Shannon and Noble 1990).

1.5 Modelling salinity

Crop response to salinity can be predicted by using a model. Before Maas and Hoffman (1977), the general practice was to use a simple single value index for salinity tolerance, C_{50}, which is the salinity value (in soil) which gives a 50% reduction in yield (Steppuhn et al. 2005). After the introduction of the slope-threshold function by Maas and Hoffman (1977) the updated method of modelling comprised a yield response curve that consisted of two lines; a horizontal line depicting no response to an increase in salinity, and a second line that is concentration dependant (Maas 1993). The slope of the concentration dependant line indicates yield reduction per unit increase in salinity (Maas 1993), for instance 6% decrease per 100 mS m^{-1} increase. The point where the two lines intersect is referred to as the ‘threshold’, which is the maximum tolerable salinity level before any reduction in yield (Maas and Hoffman 1977, Maas 1993). If salinity exceeds the threshold of the given crop, one can estimate the relative yield (Y_r) using equation 1.1 (Maas and Hoffman 1977).

$$\mathrm{Y_r} = 100 - \mathrm{b}\ (\mathrm{EC_e} - \mathrm{a}) \tag{1.1}$$

Where a represents the threshold in dS m^{-1}; b represents the slope value in % per dS m^{-1}; and EC_e is the mean electrical conductivity of saturated soil extracts from the root zone. The EC_e value can be estimated by halving the EC_i (irrigation or test solution EC) (Marschner 1986, Maas 1990) and the assumption can be made that the solutions fill the soil pores to field capacity (Janzen and Chang 1988, Kohut and Dudas 1994, Steppuhn et al. 2005). Steppuhn et al. (2005) discussed six different empirical equations that describe Y_r as a function of average root-zone salinity or ‘C’. These different approaches include everything from a simple linear function to a more complex compound discount function, and all are summarized in TABLE 1.2. Although somewhat different to the more common slope-threshold function, all these functions still rely on an average root zone EC and one or two biophysical parameters that can influence yield.

TABLE 1.2: Summary of the different empirical equations that can be used to estimate Y_r from salinity (Adapted from Steppuhn et al. (2005))

Function	Equation		Source
Simple Linear	$Y_r = a – b\ (C)$		(Palmer 1937, Ayers et al. 1943, Magistad et al. 1943, Wadleigh and Ayers 1945, Batchelder et al. 1963, Holm 1983)
Modified Weibull	$Y_r = \exp[a(C^b)]$		(Weibull 1951, Rawlings and Cure 1985, Taylor et al. 1991, Jalil et al. 1994b, 1994a)
Bi-Exponential	$Y_r = \exp[aC -b(C^2)]$		(van Genuchten 1983, van Genuchten and Hoffman 1984, Steppuhn et al. 1996, Wang et al. 2002)
Modified Gompertz	$Y_r = 1 - \exp[a \exp(bC)]$		(Gompertz 1825)
Three-Piece Linear (threshold-slope)	$Y_r = 1$ $Y_r = 1 – b(C-C_t)$ $Y_r = 0$	$0 < C < C_t$ $C_t < C < C_0$ $C > C_0$	(Maas and Hoffman 1977, van Genuchten 1983)
Modified Discount	$Y_r = 1/[1+(C/C_{50})^{\exp(sC50)}]$		(van Genuchten 1983)

Note: Y_r =relative yield, C = average root zone salinity, C_t = maximum salinity without yield reduction
a = any biophysical characteristic of the response, usually intensity of the relationship
b = any biophysical characteristic of the response, usually shape of the relationship
C_0 = lowest salinity where Y_r = 0, C_{50} = lowest salinity where Y_r = 50

While relative yield is estimated mostly using root zone salinity, it is not accurate to assume that any reduction in yield is related to salinity alone. Yields may vary due to the specific crop species and cultivars, the ambient environment, soil fertility and nutrition, or pest and disease damage (Steppuhn et al. 2005). Crop yield can also be related to various plant components, which can all be affected by salinity in different ways. Plant components that can be used as a commodity include; leaves, stems, flowers, fruits, seeds, roots, tubers, and other plant tissues (Steppuhn et al. 2005). Therefore, in order to predict the effect of salinity on crop response, one has to consider not only the salinity of the soil and irrigation water, but also various other parameters that influence the crop yield and the intensity of the salinity.

According to Ferrer-Alegre and Stockle (1999) there are three aspects to consider when deciding on management practices for salinity control: (i) quantifying the movement of salts and water in the soil, (ii) quantifying crop response to soil water and salinity, and (iii) considering the weather, soil, and crop conditions. Mathematical mechanistic models can help with integration of these factors and will aid in assessing management practices in saline conditions (Majeed et al. 1994, Ferrer-Alegre and Stockle 1999). Hassanli et al. (2016) stated that simulation models can be used to predict the effect of water salinity on crop yield, soil properties, and groundwater. Various models have been developed to simulate the effects of salinity on crop response, and the processes used to derive a simulation differ for each model

(Ragab et al. 2015). The processes and interactions involved in the soil-water-atmosphere-plant system relative to crop growth and development are considered in almost all crop response to salinity models. The general input variables of models such as SWAGMAN (Robbins et al. 1995), SWAMP (Bennie et al. 1998) and SWB (Annandale et al. 1996) include crop or plant parameters, soil and weather data, and irrigation water quality. The specific parameters can be seen in TABLE 1.3. From these parameters, the models interpret values and based on a mechanistic or theoretical approach, obtain information regarding crop growth, salt and water balance, groundwater dynamics and nutrient balance. The general model output values comprise of crop yield, water contents and fluxes, water usage, and salt concentrations (Annandale et al. 1999b, Xevi and Khan 2007, Barnard et al. 2013).

TABLE 1.3: Summary of the soil-water-atmosphere-plant system parameters that are considered in modelling crop response (Derived from Annandale et al. (1999b), Ferrer-Alegre and Stockle (1999), Jovanovic et al. (1999), Vanuytrecht et al. (2014))

Soil	**Water**	**Atmosphere**	**Plant**
Soil type and particle distribution	Amount of irrigation and or precipitation	Air temp and relative humidity	Species, planting density, season, plant date
Depth and descriptive profile	Runoff, evaporation, transpiration, percolation	Radiation	Phenology
Bulk density, field capacity, porosity	Quality	Wind speed	Stress functions and thresholds
Soil water content and other hydraulic properties. Infiltration and drainage rate	Irrigation method	Location (longitude and latitude, above sea level)	Yield, Harvest Index and Dry Matter partitioning, rooting depth
Initial conditions	Irrigation frequency	Pollution, ozone, CO_2	Radiation Use Efficiency, Dry matter Water Ratio, Water usage

Other models that can be used for salinity management modelling include AquaCrop (Hsiao et al. 2009, Raes et al. 2009, Steduto et al. 2009), CropSyst (Stockle et al. 1994), LEACHM (Wagenet and Hutson 1989), SALTMED (Ragab 2002), SWAP (Van Dam et al. 1997), and UNSATCHEM (Simunek et al. 1996). Although all of the mentioned models are based on the same concept, the approaches vary slightly. AquaCrop can be used to simulate daily biomass production, as well as final crop yield in relation to water supply and use. The AquaCrop model is based on plant physiology, and soil-water and salt budgets, and uses agronomic management data like irrigation methods and frequencies (Vanuytrecht et al. 2014). CropSyst is a multiyear, multicrop, daily time step model that models the processes of the soil-water-plant-atmosphere system and crop growth. CropSyst is based on agronomic management inputs (irrigation, fertilization, tillage, cultivar selection) and environmental impacts (erosion and leaching) (Ferrer-Alegre and Stockle 1999). The Leaching Estimation and Chemistry Model (LEACHM) is a generalized crop water use estimator, and simulates crop growth and salt-crop interactions, based on soil hydraulic conductivity, water and solute movement and salt chemistry like ion interaction and exchange (Majeed et al. 1994). SALTMED simulates water and solute movement under different agronomic management practices and by using different water qualities it can simulate soil salinity evolution over time. (Ragab et al. 2015). The Soil Water and Groundwater Management (SWAGMAN) model can be used to examine the outcomes of specific crop and irrigation management scenarios on the soil water and salt balance, and is based on crop growth processes, and salt, water and nitrogen balances (Xevi and Khan 2007). The Soil Water Management Program (SWAMP) model is a pragmatic, support model that uses in-situ field observations of water management practices. The soil-water balances can be obtained by using limited climatic, crop and soil input variables (Barnard et al. 2013). The Soil-Water-Atmosphere-Plant (SWAP) model is an ecohydrological model that is based on the physical laws of essential hydrological, chemical and biological processes occurring in the SWAP continuum (Hassanli et al. 2016). The Soil Water Balance (SWB) model is a mechanistic, multi-layer, daily time step, soil-water-balance generic crop growth model that uses crop parameters and weather data to simulate crop growth in different scenarios (Annandale et al. 1999b). The Unsaturated Water and Solute Transport Model with Equilibrium and Kinetic Chemistry (UNSATCHEM) can be used as a one-dimensional unsaturated water flow and solute transport model for predicting major ion and chemical processes in field environments, and includes the processes of plant water uptake, and root and plant growth (Suarez and Šimůnek 1997, Kaledhonkar and Keshari 2006).

1.6 Mine water irrigation

South Africa has a well-developed mining industry, however, the residual impact on the surrounding environment and water bodies are of great concern. Acid mine drainage (AMD) forms when sulphide-bearing minerals, such as pyrite (FeS_2), are exposed to water and or oxygen, and the process is accelerated with the help of the *Thiobacillus ferrooxidans*, a naturally occurring bacteria (Akcil and Koldas 2006, De Almeida et al. 2015, Jamal 2015). Such mine waters are characterized as having a low pH and a high concentration of trace or toxic elements such as aluminum (Al), arsenic (As), iron (Fe), lead (Pb), and manganese (Mn) (Peppas et al. 2000, Johnson and Hallberg 2005, Gaikwad et al. 2010). AMD is seen as one of the most important water and land pollutant agents (Sheoran and Sheoran 2006) and is considered as the water draining from a mine, whether it is abandoned, closed or still operating. AMD is generated in both underground and open cast mines and can originate from tailings and other left over materials after valuable constituents are removed (Akcil and Koldas 2006).

The impact of AMD can be minimized by treating the water by adding hydrated lime ($Ca(OH)_2$) or limestone ($CaCO_3$). When adding lime to AMD, the pH increases, and acidity decreases. This causes trace (heavy) metals to become insoluble and precipitate or settle out along with the hydroxides (OH^-) in the solution. The settled particles produce a high-density sludge (HDS) that can be disposed of, and the treated water can often be discharged into the river system (Aubé and Zinck 2003, Akcil and Koldas 2006). The potable, industrial or agricultural standard or classification of the water (according to legislation and water quality guidelines) depends on the type of mine, the constituents and the salt concentration. Gypsum ($CaSO_4$) is the main by-product of the lime neutralization process, especially when treating sulphate rich waters. The pH after treatment lies between 5 and 9.5 and the EC ranges from 130 to 290 mS m^{-1} (Jovanovic et al. 2001). The treated water still contains a high amount of dissolved salts like Ca, Mg, Na and K in the form of sulphates (Annandale et al. 2009) which can be removed by means of a desalinization plant. However, this process becomes quite costly and thus the idea to reuse the limed water for irrigation becomes more appealing.

The feasibility and sustainability of producing crops under irrigation with gypsiferous mine water has been studied for the past few decades and it is possible with careful management. Annandale et al. (2007) found that irrigating with gypsiferous mine waters under proper management practices, can lead to higher yields compared to dryland production. However, this practice becomes more feasible if a high leaching fraction is allowed, which aids in removing excess salts from the soil profile, thus reducing root zone salinity and inevitable salt stress (Jovanovic et al. 1998). Du Plessis (1983) also studied the effects of sulphate salinity on the soil profile and found that irrigating with a saline sulphate water is far better than a saline chloride water due to the soil profile’s ability to ‘buffer’ the salinity by means of gypsum precipitation, Annandale et al. (2001) and Annandale et al. (2006) also supported this statement.

Mine water irrigation can be sustainable, but in order to be successful, one has to rely on good overall management practices, which include monitoring of the site and the irrigation water quality (Annandale et al. 2009). A good understanding of the chemical composition of the irrigation water, as well as the soil properties and the type of irrigation system is required in order to successfully irrigate with saline water (Hoffman et al. 1990, Annandale et al. 2001). Another thing to keep in mind, is that not all crops are suitable for mine water irrigation and salt tolerant crops may need to be considered.

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CHAPTER 2: UNMINED SITE MAIZE FIELD TRIALS AT MAFUBE COLLIERY

2.1 Introduction

South Africa is well-known for its mining industry, and is one of the ten largest producers of coal in the world (Schmidt 2010). Coal is an important commodity in South Africa, not only for export, but as the main source of electricity generation in the country (Department of Energy 2009). Although this industry is important, both economically and socially, the environmental risks and impacts associated with coal mining are of great concern. Some environmental impacts include, but are not limited to, the loss of natural vegetation and arable land, the use of water resources and the generation of poor quality mine impacted waters. The waters produced have the potential to negatively affect surrounding water bodies, which is of great concern in an already water scarce country like South Africa. Therefore, waters produced from mining activities, as well as water resources surrounding mining areas, need to be carefully monitored and managed (Tanner et al. 1999).

Coal mining is known to produce acid mine drainage (AMD) with high amounts of sulphate and potentially toxic trace elements (Johnson and Hallberg 2005). AMD is generated when sulphide-bearing minerals (such as pyrite which is commonly associated with coal mining) are exposed to oxygen and water. This results in a reduction in pH which allows metals to become more soluble (Mackie and Walsh 2015). Fortunately, these waters can be treated by adding hydrated lime ($Ca(OH)_2$) or limestone ($CaCO_3$) (Akcil and Koldas 2006). The problem is that the treated water is now saline, often dominated by Ca and Mg sulphate, potentially polluting the environment and other natural resources. However, studies on coal mines have shown that there is potential to use such mine waters for crop irrigation (Jovanovic et al. 1998, Annandale et al. 2001, Annandale et al. 2006).

The main premise is that many mine-affected waters contain large quantities of calcium sulphate. When crops are irrigated with such gypsiferous waters, significant quantities of calcium sulphate are precipitated out in soils, primarily as gypsum. As much as 70% of salts contained in mine waters can be removed in this way, and the soils are not negatively affected by the presence of these precipitates (Du Plessis 1983). Because large volumes of such mine impacted waters are available, with large tracts of unfarmed land available on both active and closing mines, with several key crops that are sufficiently tolerant to saline waters, a clear opportunity arises to utilise these waters for irrigation. Not only will this drastically reduce mine water treatment costs, but it will enable sustainable livelihoods and food production, particularly in the post-mine closure situation. The Mafube irrigation with mine water demonstration is the culmination of 20 years' research into the potential for the agricultural use of mine water.

From the regular sampling and monitoring, data was obtained that can be used to parameterize the SWB model in order to ensure that simulations with mine water irrigation are reasonable. Accurate simulations will provide the potential effect of irrigation in the long term (>20 years), as well as the prediction of if and when gypsum will precipitate, and at what depth in the profile it will take place. Such simulations will give an indication of the sustainability of this practice and will be discussed in Chapter 3.

2.2 Materials and Methods

2.2.1 Site description

A field experiment was conducted at an unmined site at Mafube Colliery in Middelburg, Mpumalanga. The trials took place from November 2016 to May 2018. The experimental site is located at latitude 25°48'25"S and longitude 29°45'48"E and is 1670 m above sea level. Soils in the northern section of the field are classified as deep Glencoe, where lateral sub-surface flow is expected to occur as water reaches the deep hard Plinthic B horizon. The signs of wetness in this part of the field are not concerning, as the soils are deep, and all indications are that the water should drain to the wetland to the west of the field. Soils in the southern and eastern areas of the field are deep Hutton soils, which have excellent drainage and are ideal for crop production under pivot irrigation. Soil sampling and classification was done in September 2016, by Dr. Johan van der Waals of Terra Soil.

2.2.2 Planting, soil amendments and harvesting

The planting, soil amendments and harvesting was done by Mr. Peter Kane-Berman, a local commercial farmer who leases the land from the colliery. A white maize variety, PHB 32B07BR (genetically modified with stacked gene for stalk borer and herbicide resistance) was planted on the 9th of November 2016 at a seeding rate of 64 000 ha^{-1} (R1728 ha^{-1}), but irrigation was delayed and was effectively a dryland season. On 3 October 2017, the same cultivar was planted, this time with irrigation, at a seeding rate of 80 000 ha^{-1} (R2707 ha^{-1}). Dryland maize was planted around the pivot, on 5 October at a seeding rate of 50 000 ha^{-1}.

The following section discusses agronomic inputs and the costs incurred to produce white maize during the 2016/17 and 2017/18 summer growing seasons at Mafube. For the 2016/17 season the total fertilizers added before and during planting amounted to 199 kg ha^{-1} nitrogen, 43 kg ha^{-1} phosphorus and 49 kg ha^{-1} potassium, which cost a total of R3916 ha^{-1}. For the 2017/18 season, fertilizers added before, during and after planting amounted to 290 kg ha^{-1} nitrogen, 40 kg ha^{-1} phosphorus, 64 kg ha^{-1} potassium, and 10 kg ha^{-1} sulphur. A nitrogen (Urea) top dressing was applied after crop emergence. The fertilizers for the 2017/18 season cost a total of R5015 ha^{-1}. Herbicides and pesticides applied (TABLE 2.1) via disk incorporation prior to planting and after emergence and amounted to R557 ha^{-1} (2016/17) and R394 ha^{-1} (2017/18).

TABLE 2.1: Herbicides and insecticides applied prior to planting and after emergence at Mafube

	Prior to planting	**After emergence**
2016/17	Eptam Super (EPTC) Guardian S (840 EC) Insectido (50 g L^{-1}) Allbuff Boron (10%)	Terbuzine (600) Acetochlor (900 EC) Campertop (225) Allbuff
2017/18	Galago (480) Guardian S (840 EC) Atrazine 500 (Atraflo) Lamda (5EC) Correcto Liquibor (10%)	Galago (480) Acetochlor (900EC) Terbuzine/Cheetah 600 Lamda (5EC) Correcto

The reasons for use of the herbicides and pesticides are as follows: Eptam Super (EPTC) is a selective soil incorporated emulsifiable concentrate herbicide for the control of annual grasses, nutsedges and certain broadleaf weeds. Guardian S is a pre-plant incorporated herbicide used to control yellow nutsedge in maize. Insectido is a pyrethroid insecticide for the control of various insects, including cutworms and aphids. Allbuff is a pH buffer and adjuvant utilized to increase the efficiency of pH sensitive agricultural chemicals and to improve the wetting and spreading properties of spray mixtures. Both Galago (480) and Atrazine are pre- and post-emergence herbicides for the control of annual broadleaf weeds, grasses and suppression of certain weeds in maize. Lamda (5EC) is an insecticide applied pre-planting to control stem-and stalkborers and their larvae. Correcto is a water quality improving agent with wetting and spreading properties for use with contact and systemic insecticides, fungicides, herbicides and foliar feeds. For practicality, boron, an essential element to all crops, was incorporated into the soil with the herbicide/insecticide mix in the form of Liquibor. Acetochlor and Campertop are selective soil incorporated emulsifiable concentrate herbicides for the control of annual grasses, nutsedges and certain broadleaf weeds in maize. Terbuzine is a suspension concentrate herbicide for selective control of most annual broadleaf weeds and goose grass. Both Spanta S.C. and Performer fungicides were sprayed, post-emergence, in the 2016/17 season to control Northern Leaf Blight, which gave a fungicide cost of R 122 ha^{-1}.

Maize was harvested at a moisture content close to 14% using a combine harvester. The harvests took place during May 2017 and 2018. The full fertilizer regime, herbicide/insecticide dosages, as well as the budget for the two seasons are included in Appendix A1.

2.2.3 Monitoring station setup

For the first season, only two stations were set up, one within the demarcated pivot area and one just outside. Unfortunately, the first season did not receive any irrigation, thus both stations monitored dryland growth which is used as a baseline data series in this study. For the following season, four monitoring stations were established (FIGURE 2.1) as far from the road as possible to reduce the likelihood of theft or vandalism, while remaining within the well to moderately (except for station 3) drained areas of the field. Careful consideration was taken to protect monitoring stations from damage by farm machinery by placing them away from implement tyre and centre pivot tracks. The four stations (FIGURE 2.1) comprise of two within the pivot area and two within the surrounding dryland area. The stations were sited in pairs as follows: stations 1 and 2 (pivot) are in the moderately well-drained (good drainage) area of the field, station 4 (dryland) is in the somewhat less ideal moderate drainage area and stations 3 (dryland) is in the poorly drained area.

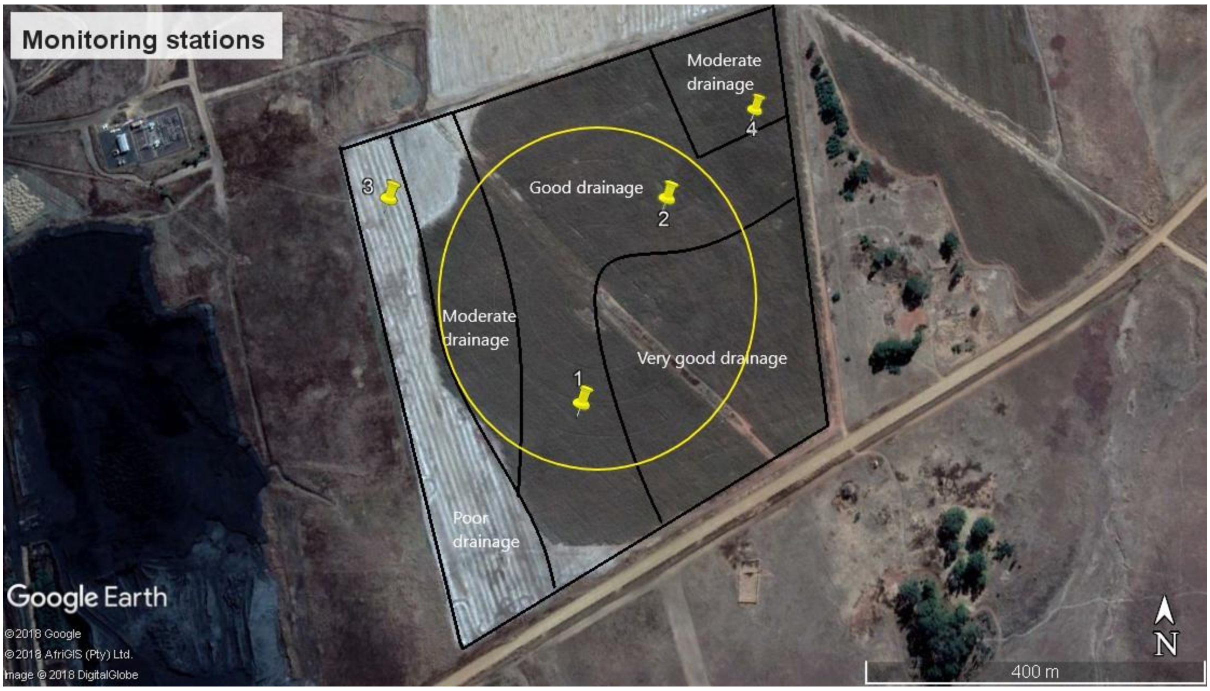

FIGURE 2.1: Locations of monitoring stations on the Mafube unmined site with yellow circle indicating the pivot area

Each monitoring station was equipped with the following:

1. A weather-proof box (FIGURE 2.2) housing a CR300 datalogger and battery. The datalogger stores measurements from CS 655 probes at three depths, and from a TE525 rain gauge every hour and capable of storing up to one month of data. Batteries were replaced (recharged) every two weeks.
2. An automatic TE525 tipping-bucket rain gauge to monitor irrigation and rainfall with a resolution of 0.254 mm per tip.
3. A manual rain gauge for water quality sampling.
4. Three CS 655 probes at depths of 30, 60 and 90 cm to monitor soil water content, dielectric permittivity, bulk electrical conductivity (EC), and soil temperature.

5. Three suction cups (FIGURE 2.3) at depths of 10, 30 and 60 cm to acquire soil water samples for laboratory analysis; namely pH, EC, TDS and major cations (Ca, Mg, Na, K) and anions (SO_4, Cl).

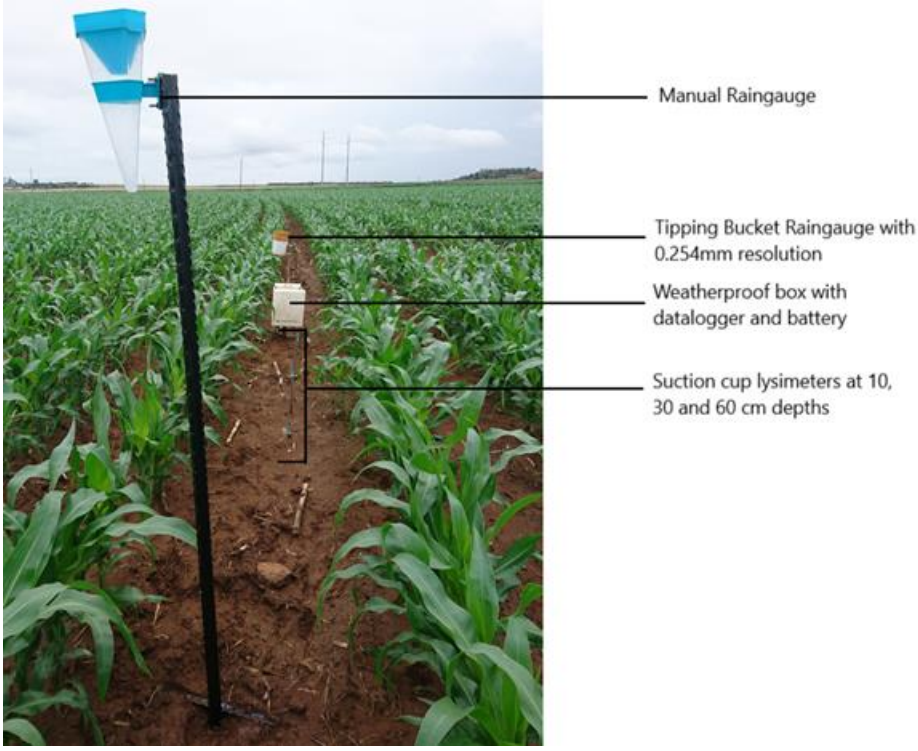

FIGURE 2.2: Monitoring station setup

FIGURE 2.3: Suction cups placed at 10, 30 and 60 cm

Another monitoring station was set up to monitor daily weather variables such as minimum and maximum temperature (°C), minimum and maximum relative humidity (%), average windspeed (km h^{-1}), average solar radiation (W m^{-2}), and precipitation (mm). This station was equipped with a RM Young Wind Sentry Wind Speed and Direction Sensor, a Licor LI200S Pyranometer, a HMP50/HMP60 Temperature and Relative Humidity Sensor, a TE525(WS)

Tipping Rain Gauge, and a CR300 datalogger and battery. The station was situated 360 m east from the centre of the pivot, and was erected to a height of 2 m.

2.2.4 Sampling procedure and lab analyses

Initial fertilizer amendments and herbicide/insecticide applications were done (as discussed previously). The soil water content, bulk EC and temperature was monitored daily (recorded on logger). Crop parameters like plant height and crop development, leaf area index (LAI) and fractional interception (FI) of photosynthetically active radiation (PAR) were measured and sampled every two weeks. Crop height was measured from the ground up to the highest point of the plant using a tape measure, and for LAI, a row of 1 m (8 to 10 plants) was destructively harvested every two weeks and analysed for LAI at the Hatfield Experimental Farm within 3 to 5 hours after collection using a LI3000 leaf area meter. Photosynthetically Active Radiation (PAR) is measured at the bottom of the canopy and above the canopy. A couple of measurements are made to ensure a representative average can be calculated. These values (PAR_{top} and PAR_{bottom}) are then used along with the measured LAI to determine a radiation extinction coefficient. With this coefficient, the fraction of PAR (FI_{PAR}) that is intercepted by the canopy can be modelled from LAI and is an important parameter for the partitioning of available evaporative energy into that available for transpiration and that available for direct evaporation from the soil . This also gives insight into whether or not radiation is a limiting factor in crop growth. FI_{PAR} was measured using a ceptometer that measures incoming and transmitted PAR.

Along with crop data, there were analyses done on the irrigation water and groundwater quality (FIGURE 2.4). Irrigation water is supplied and monitored by Mafube Colliery. Two boreholes (one deep and one shallow) are located in the poorly drained western side of the field and another two (one deep and one shallow) are located in the well-drained eastern side of the field. The shallow boreholes (2 and 4 referred to as Shallow Upstream and Shallow Downstream, respectively) are about 10 m deep and the deep boreholes (1 and 3 referred to as Deep Upstream and Deep Downstream, respectively) are around 30 m deep. The borehole water samples were taken every quarter by field technicians and hydrogeologists from the Mpumamanzi Group and analysed by Waterlab (Pty) Ltd in Pretoria. Samples were taken using a bailer and stored in sterilized polyethylene containers, which were labelled and preserved in a cooler box until analysis could be carried out (Akwensioge et al. 2019). These analyses, along with irrigation water qualities are compiled and used in the data analysis and for modelling purposes. Three piezometers (FIGURE 2.5) were installed at depths of around 3 m. The holes were augured and slotted PVC pipes with capped ends were installed. To prevent the slots from clogging or allowing any debris to enter the pipe, the annular space between the augured hole and piezometer tube was filled with coarse swimming pool filter sand. It also stabilised and reduced movement of the PVC pipe. The pipes can be accessed by a screw top cap, and with the help of a water level detector and a bailer, the water level can be detected, and water samples can be taken for laboratory analyses. These piezometers were placed in an upstream (P1), and downstream (P2) location within the wet westerly side of the field. P3 was installed in the well-drained eastern side of the field and never yielded any water samples as the piezometer was always found to be dry.

FIGURE 2.4: Map showing the boreholes (BH1 - BH4), discard dump boreholes (DMBH8 - DMBH11) and piezometer (P1 - P3) locations, as well as the monitoring dam (Beestepan Dam) surrounding the Mafube unmined site

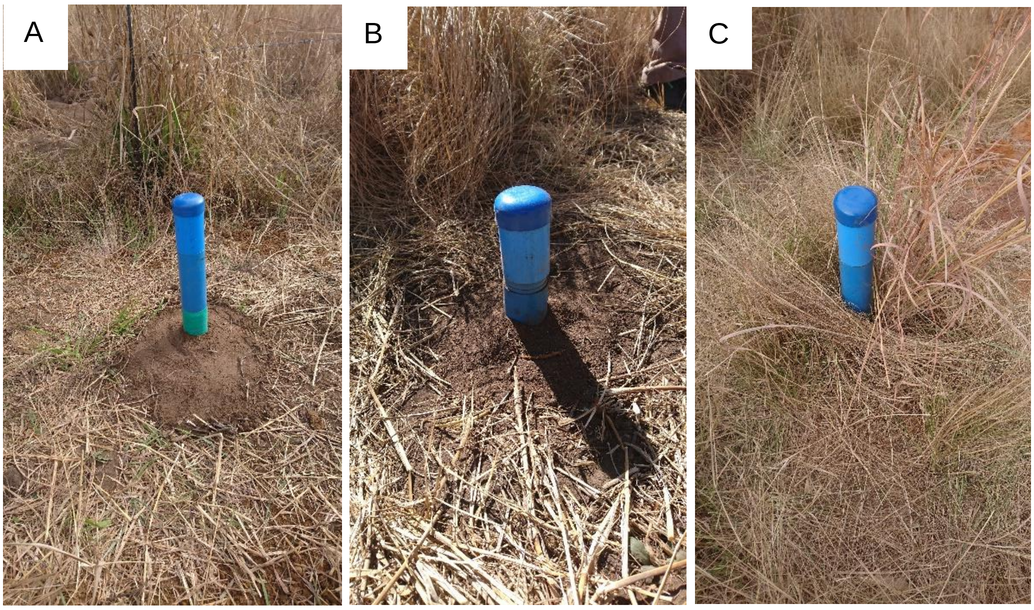

FIGURE 2.5: Installed piezometers a) downstream b) upstream and c) top upstream

Soil samples were taken before and after each irrigation season. A sampling grid was setup, which includes 14 locations (FIGURE 2.6) that are more or less evenly distributed throughout the pivot area. The samples are taken at depths of 0.3, 0.6 and 0.9 m, if possible. Soil analysis included measurements for $pH_{(KCl)}$, $EC_{1:2.5}$, total extractable and soluble Ca, Mg, Na, K, PO_4^{3-}, SO_4^{2-} and Cl^-. A Mehlich-3 extraction was used to determine the total extractable portion, and a saturated paste was used to determine the total soluble portion. Cl was determined using an AgCl electrode. Sampling coordinates are given in Appendix A2.

FIGURE 2.6: Map of soil sampling locations (S01 – S14) on Mafube unmined site

For food safety analysis, the elemental composition of the edible portion of the plant needs to be determined. For this, an acid digestion of the milled plant (in this case, the grain) was done to obtain these values in order to compare it to the South African Food Safety guidelines.

2.3 Results and discussion

2.3.1 Crop parameters

Along with plant height, total above ground dry mass, and leaf area index, the phenological stage was observed every second week. Knowing the phenological growth stage (FIGURE 2.7) of the crop helps keep track of overall crop growth and development. In the Soil Water Balance model (SWB), the growth stage is calculated based on the growing degree days (GDDs) using thermal time. This is discussed in Chapter 3.

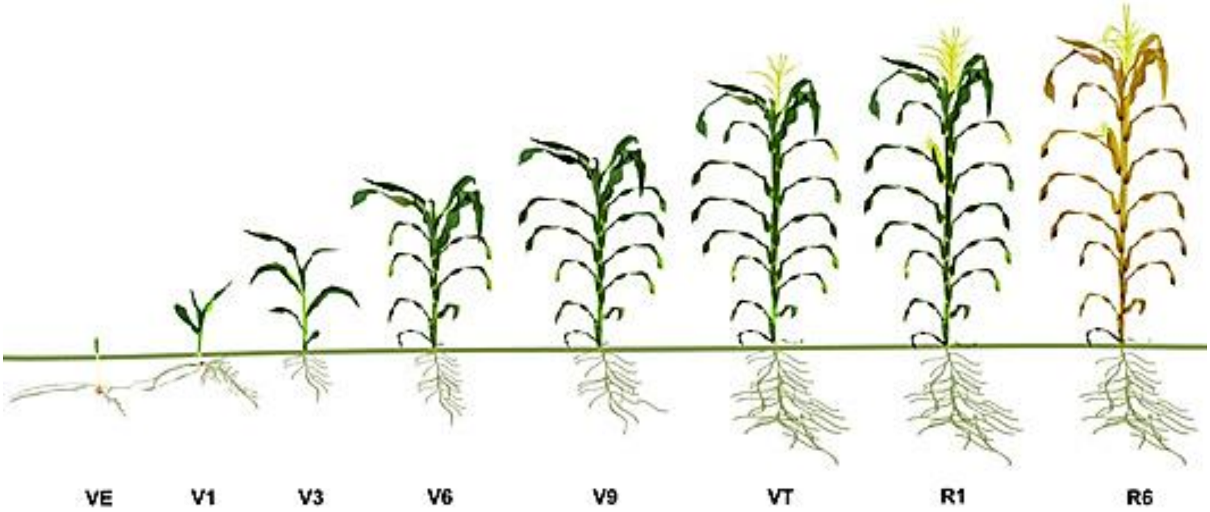

FIGURE 2.7: Visual representation of the phenological growth stages for a maize crop (Pioneer)
Note: VE = Emergence, V1-VT = Vegetative phase, R1-R6 = Reproductive phase

2016/17 Summer season (dryland)

During the summer season of 2016/17, the Highveld experienced a mid-season drought. The drought occurred during a critical development stage, placing the crop under severe water stress during anthesis and early grain-filling, which resulted in heavy yield losses. It is at this time that grain partitioning is most affected. The SWB growth model predicted that if irrigation interventions took place during this period, the crop would have seen a 40 to 50% yield increase (see section 3.3.4). This illustrates the potentially large gains to be made by utilising gypsiferous mine water as an irrigation source in the Mpumalanga Highveld region, which typically produces dryland maize and is subject to climatic variability and drought. In TABLE 2.2 the phenological stages of observed maize growth and development for the 2016/17 season are presented. This will act as a key to the other figures and graphs discussed in this section. In total, the field received 579 mm of rainfall and no irrigation throughout the 2016/17 season. The cumulative rainfall and irrigation amounts can be seen in FIGURE 2.8. As this was the first season monitored, only two monitoring stations were setup – one inside the demarcated pivot area to monitor irrigated growth and one outside the pivot to monitor dryland growth. However, as the field received no irrigation, both stations were seen as dryland monitoring and thus the data from the two stations have been combined and are represented as one set of data.

TABLE 2.2: Key to maize phenological stages, combined with the date stage as observed during the 2016/17 season

Date	DOY*	DAP**	GDD***	Observed phenological Stage
09 November 2016	313	-	0	Planting
19 November 2016	323	10	91	VE (emergence)
29 November 2016	333	20	178	V3
15 December 2016	349	36	346	V7
20 December 2016	354	41	404	V12
05 January 2017	5	57	568	V16
18 January 2017	18	70	680	R1 (silking)
17 February 2017	48	100	999	R3 (milk)
03 March 2017	62	114	1122	R4 (dough)
30 March 2017	89	141	1350	R6 (physiological maturity)

**DOY – Day of Year   **DAP – Days After Planting ***GDD – Growing Degree Days*

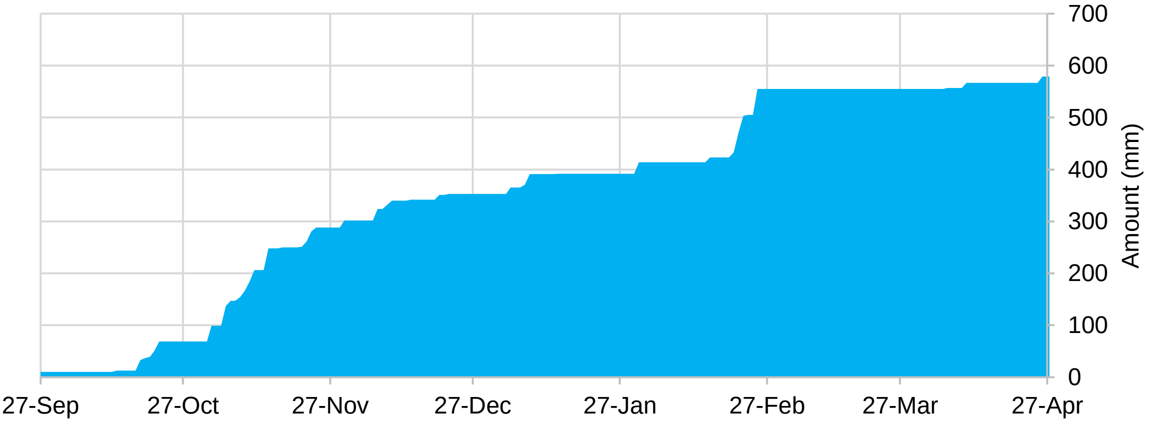

FIGURE 2.8: Cumulative rainfall recorded at the Mafube unmined site from 27 September 2016 to 27 April 2017

The following figures illustrate the growth and development of the maize crop grown over the 2016/17 summer season at the unmined Mafube site. This data has been used to parameterise the SWB model and will be discussed further in Chapter 3.

Plant height was monitored throughout the growing season and followed the typical maize growth pattern, as shown in FIGURE 2.9. The typical sigmoidal curve shows a gradual increase from emergence to V3, thereafter the increase in crop height is rapid from V3 to V16, followed by a plateau during grain-filling, R1 to R6, as this is a determinate crop and after reproduction there is no increase in crop height.

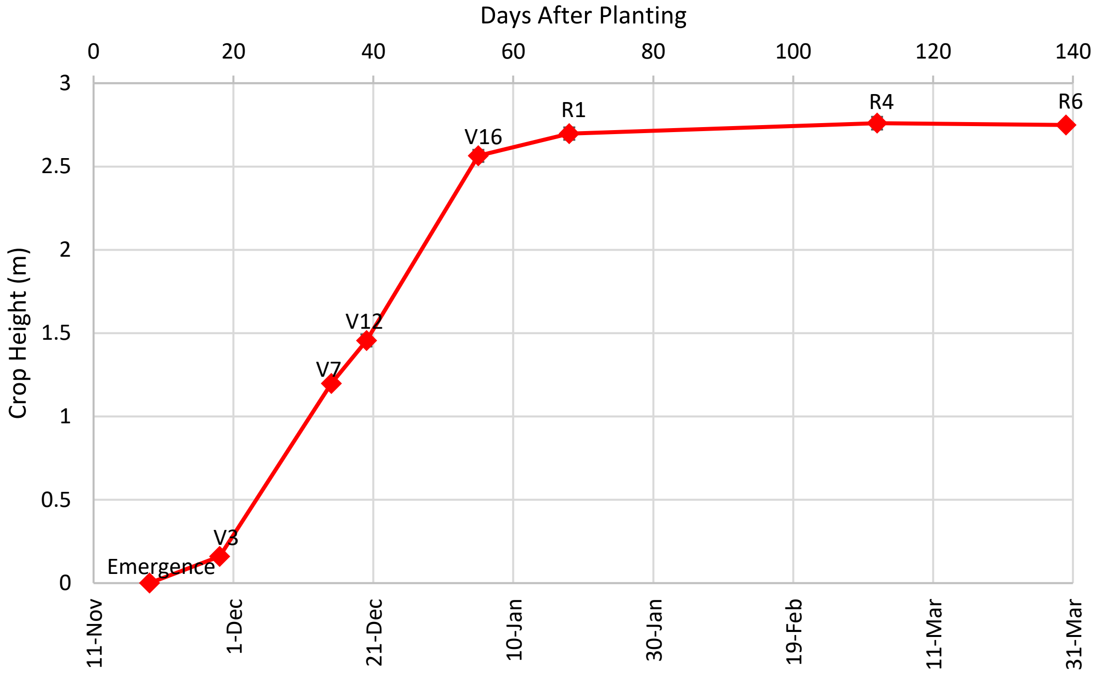

FIGURE 2.9: Crop height of dryland white maize grown at the Mafube unmined site in the 2016/17 summer season

FIGURE 2.10 illustrates the leaf area index of the maize crop over the 2016/17 summer growing season. 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 m^{-2}. The curve is typical of a maize crop planted later in the season, showing rapid canopy development within the first 50 days after emergence until a peak of 3.6 m^2 m^{-2} at the V16-R1 (tasselling) stage. Thereafter, canopy development plateaus from tasselling to dough (R4) stages, followed by a gentle decline from dough to physiological maturity (R6) with a LAI of 2.2 m^2 m^{-2}. LAI would then continue to decline after physiological maturity, as the crop is dried on-field and chlorophyll is degraded. Leaves began showing signs of water stress from the R1 growth stage, which correlates with the mid-season drought and LAI plateau. Since LAI is mostly determined by soil water content prior to planting and early-season rainfall, the mid-season drought likely had limited impact on canopy development.

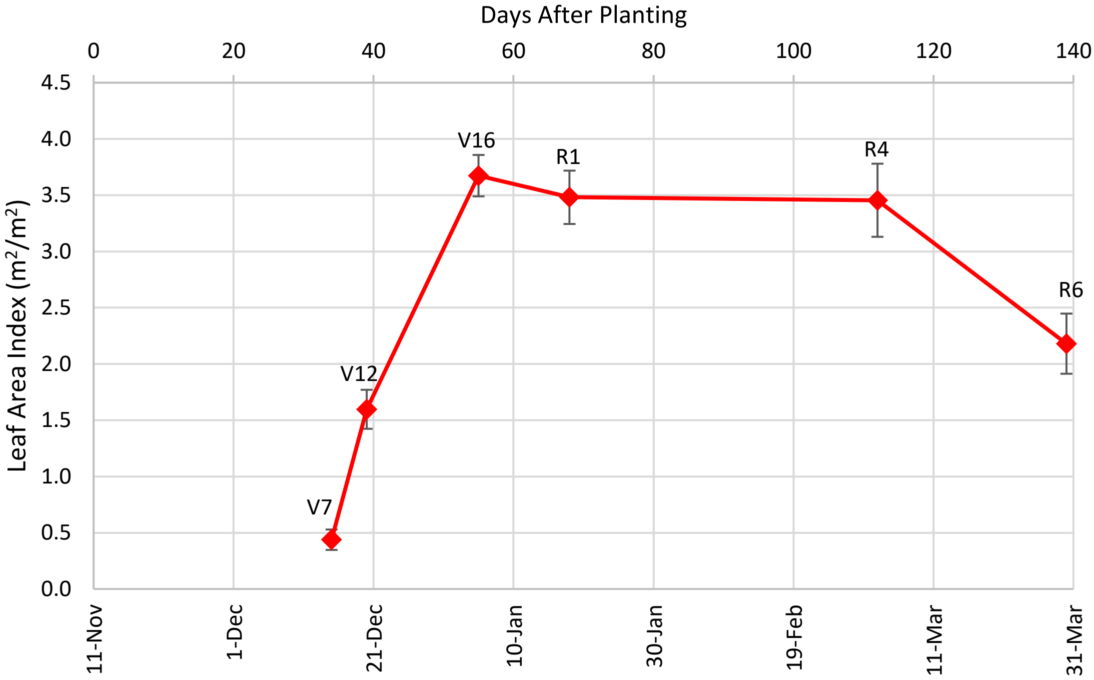

FIGURE 2.10: Leaf area index (m^2 m^{-2}) of dryland white maize grown at the Mafube unmined site in the 2016/17 summer season

Total above-ground biomass provides better insight into the effect of the mid-season drought on maize growth, since approximately 50% of the above-ground dry biomass at harvest is partitioned into grain. TABLE 2.3 illustrates above-ground dry mass of the crop over the 2016/17 summer growing season. The effects of water stress during the grain-filling stages are illustrated in FIGURE 2.11. The defective maize cob samples were taken at physiological maturity to demonstrate the effects of the mid-season drought and poor pollination on production. Yield-losses could have been mitigated if irrigation was applied to the crop.

FIGURE 2.11: Poorly pollinated dryland maize cobs at physiological maturity, collected from Mafube unmined site on 30 March 2017

Under ideal growing conditions, without water stress, the rate of dry mater accumulation seen from V7 to V16 in should remain constant until physiological maturity (R6). However, this was not the case, as there was a distinct decrease in rate of biomass accumulation during the crucial grain-filling stages, R1 (silking) to R5 (dent stage). This time period is critical to maintaining good yields, as all assimilates are partitioned to grain from silking to maturity. The mid-season drought was the cause of both reduced biomass accumulation and ultimate yield-loss. The final above-ground dry mass was determined at 11.5 t ha^{-1} at physiological maturity. The farmer reported maize yield was 5.4 t ha^{-1}, which gives a harvest index of 47% of the total above-ground dry mass. Harvest Index is calculated as the ratio of harvested grain to total above ground dry matter, and can be used as a measure of reproductive efficiency (Unkovich et al. 2010). TABLE 2.3 gives a full summary of the total above-ground dry mass (TDM), harvestable dry mass (HDM), harvest indices (HI) and yields for a best case and worst-case scenario. There was a difference in cob size in the different drainage areas of the field and thus the yield was calculated on a best (20 cm cob length) and worst (15 cm cob length) case scenario.

TABLE 2.3: Summary of range of TDM, HDM, HI and yields observed in the 2016/17 season

	HDM	**TDM**	**HI**	**Yield**
	t ha^{-1}		**%**	**t ha^{-1}**
Worst case	5.0	11.5	43.5	4
Best case	9.7	11.5	84.4	8

Note: HDM includes cob and grain mass, TDM includes stalks, leaves, cob and grain mass, Yield is based on grain mass alone

In summary, the data collected from the white maize crop grown on the Mafube unmined site during the 2016/17 summer season illustrates the potential negative impacts of a mid-season drought on dryland maize yields. While crop height and LAI were only slightly impacted by the drought, total above-ground dry matter and yield were severely impacted. These negative effects could have been minimised if the site were to receive optimal irrigation. Acknowledgements to Ms. Candice McGladdery who did most of the sampling and analysis for this season.

2017/18 Summer season (irrigated)

The following figures illustrate the growth and development of the maize crop grown over the 2017/18 summer season at the unmined Mafube site. The cumulative rainfall and irrigation amounts can be seen in FIGURE 2.12. In total, the field received 304 mm of irrigation and 634 mm of rainfall throughout the season. As this was the first season with irrigation, four monitoring stations were setup – two inside the demarcated pivot area to monitor irrigated growth and two outside the pivot are to monitor dryland growth. The data from the two irrigated stations were not combined, as the stations were located in different drainage environments.

In TABLE 2.4 and TABLE 2.5 the phenological stages of observed maize growth and development for the 2017/18 season are presented.

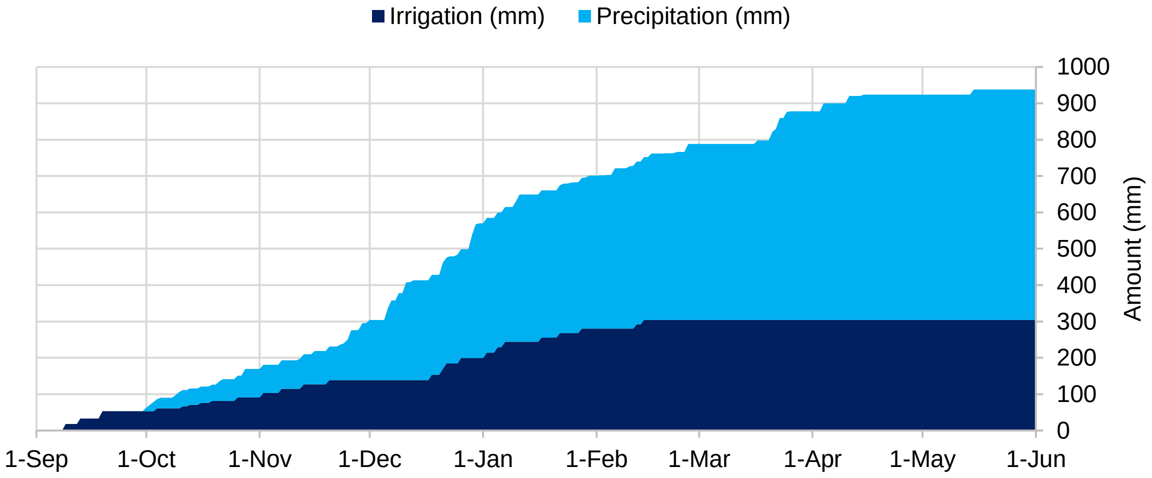

FIGURE 2.12: Cumulative rainfall and irrigation values throughout the 2017/18 summer season at the Mafube unmined site

TABLE 2.4: Key to maize phenological stages for stations 1 to 3, combined with the date stage was observed during the 2017/18 season

Date	DOY*	DAP**	GDD***	Observed Physiological Stage
3 October 2017	276	-	0	Planting
12 October 2017	285	9	60	VE
23 October 2017	296	20	145	V2
6 November 2017	310	34	255	V4
20 November 2017	324	48	370	V5
7 December 2017	341	65	517	V8
20 December 2017	354	78	643	V16
2 January 2018	2	91	781	R1
12 January 2018	12	101	881	R2
1 February 2018	32	121	1079	R3
14 February 2018	45	134	1220	R4
2 March 2018	61	150	1385	R5
16 March 2018	75	164	1535	R6

**DOY – Day of Year **DAP – Days After Planting ***GDD – Growing Degree Days*

TABLE 2.5: Key to maize phenological stages for station 4 (late planted dryland), combined with the date stage was observed during the 2017/18 season

Date	DOY*	DAP**	GDD***	Observed Physiological Stage
23 October 2017	296	-	0	Planting
1 November 2017	305	9	70	VE
20 November 2017	324	28	214	V3
7 December 2017	341	45	360	V5
20 December 2017	354	58	486	V12
2 January 2018	2	71	624	V16
12 January 2018	12	81	724	R1
1 February 2018	32	101	922	R2
14 February 2018	45	114	1063	R3
2 March 2018	61	130	1228	R4
16 March 2018	75	144	1378	R5
6 April 2018	96	163	1558	R6

**DOY – Day of Year **DAP – Days After Planting ***GDD – Growing Degree Days*

Plant height was monitored throughout the growing season and followed the typical maize growth pattern. The typical sigmoidal curve (FIGURE 2.13) shows a gradual increase from emergence to V2, thereafter increase in crop height is rapid from V2 to V16, followed by a plateau (determinate crop) during grain-filling, R1 to R5. The maximum plant height was found to be around 3.2 m (irrigated) and 2.7 m (dryland).

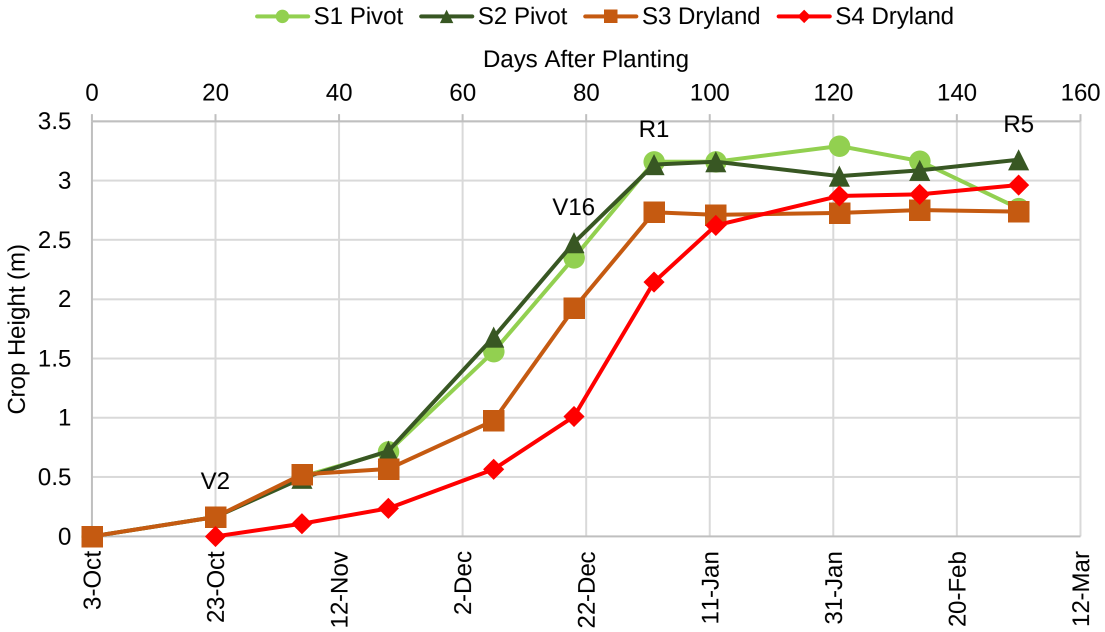

FIGURE 2.13: Crop height (m) measured for pivot and dryland areas for white maize grown at Mafube unmined site in 2017/18 summer season

FIGURE 2.14 illustrates the leaf area index of the maize crop over the 2017/18 summer growing season. The LAI curve is typical of a maize crop, showing rapid canopy development within the first 50 days after emergence until a peak of 4.2 to 4.5 m^2 m^{-2} at the V16-R1 (tasselling) stage. Thereafter, canopy development plateaus from tasselling to dough (R4) stages, followed by a decline from dough to physiological maturity (R6) with a LAI of 1.2 to 2.2

m^2 m^{-2}. LAI continued to decline after physiological maturity as leaves senesced and the crop dried in-field.

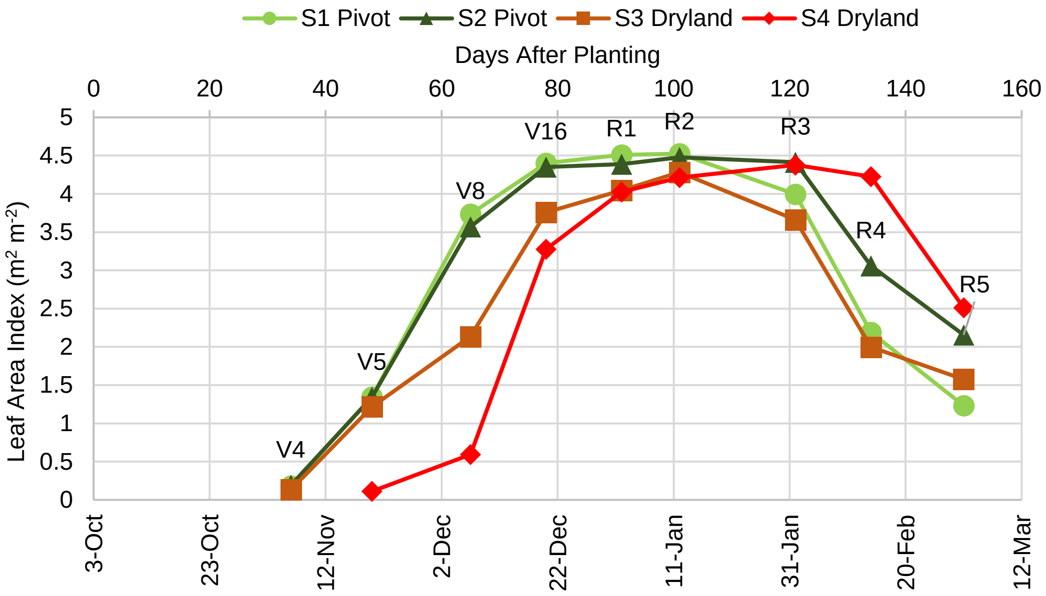

FIGURE 2.14: Leaf area index (m^2 m^{-2}) measured for the four monitoring stations during 2017/18 season

The fractional interception of a crop follows an asymptotic curve, the reason for the fluctuations found in FIGURE 2.15 can be attributed to the fact that the ceptometer (which is used to measure PAR) is sensitive to incoming solar radiation and thus an overcast day will give a different reading to a bright sunny day.

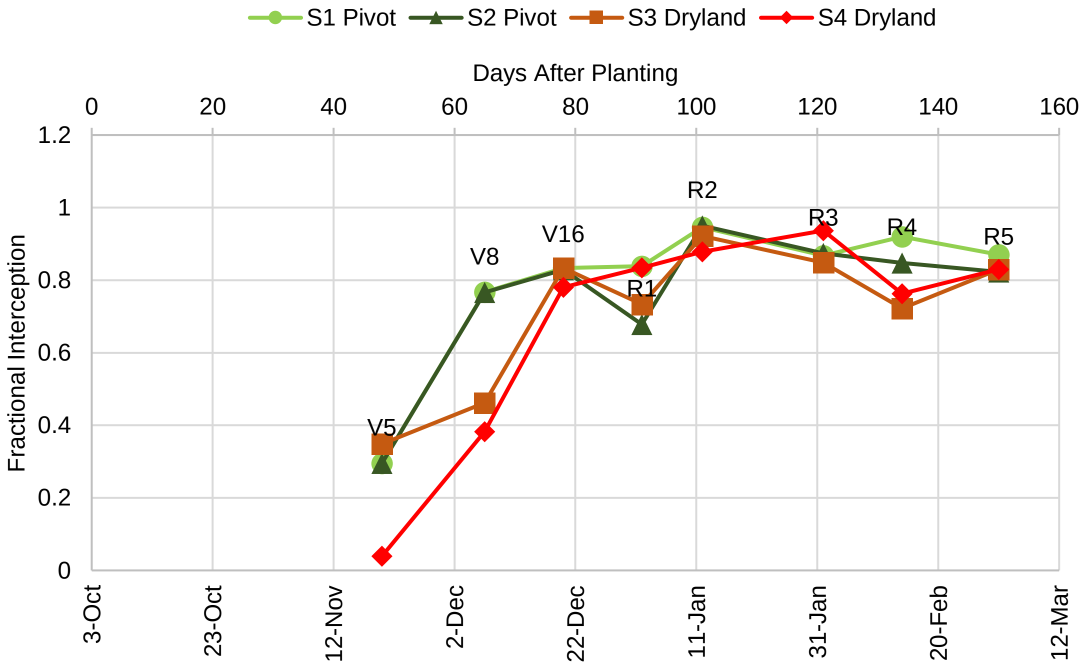

FIGURE 2.15: Fractional interception measured for pivot and dryland areas for white maize grown at Mafube unmined site in 2017/18 summer season

Total above-ground biomass (together with grain yield) provides some insight into the effect of mine water irrigation on crop production, since approximately 45 % of the above-ground dry biomass at harvest is partitioned into the maize grain under non-stress conditions, and if harvest index (HI) is much lower than this, it is indicative of stress (Unkovich et al. 2010). Under ideal growing conditions, without water stress, the rate of dry matter accumulation found from V7 to V16 should increase exponentially until physiological maturity where there will be a decline in the dry matter produced 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 farmer reported a yield of 13.8 t ha^{-1} (irrigated) and 5.4 t ha^{-1} (dryland), whereas the research team measured a yield of between 13.1 and 13.8 t ha^{-1} (irrigated) and 3.5 and 5.4 t ha^{-1} (dryland).

TABLE 2.6 gives a full summary of the total above-ground dry mass (TDM), harvestable dry mass (HDM), harvest indices (HI) and yields for all four monitoring sites. When looking at the harvest index of the irrigated crop, it is clear the crop did not undergo much stress during the season, as the HI > 45%, whereas the dryland HI is well below this and shows that the crop was stressed. This emphasizes the value of irrigation, even with relatively poor quality mine impacted waters. However, it must be said that successful irrigation can only take place if the site allows for adequate drainage. Otherwise, there might be some waterlogging and surface flooding issues as seen in FIGURE 2.16 and without adequate leaching, the salts can accumulate within the soil profile.

TABLE 2.6: Summary of TDM, HDM, HI and yields observed at the four monitoring stations during the 2017/18 season

	HDM	**TDM**	**HI**	**Yield**
	t ha^{-1}		**%**	**t ha^{-1}**
S1 Pivot	16.6	28.5	48.4	13.8
S2 Pivot	16.0	30.7	42.7	13.1
S3 Dryland	7.9	18.9	28.6	5.4
S4 Dryland	6.7	17.2	20.3	3.5

Note: HDM includes cob and grain mass, TDM includes stalks, leaves, cob and grain mass, Yield is based on grain mass alone

FIGURE 2.16: Temporary surface flooding just outside the south side of the pivot area after heavy rains in December 2017

2.3.2 Soil quality

Volumetric water content was measured using CS655 probes installed at 0.3, 0.6 and 0.9 m, and the data was stored on dataloggers. FIGURE 2.17 illustrates the volumetric water content of the four monitoring site profiles, along with the daily irrigation and precipitation values. Profile water content (PWC) is estimated for a 90 cm deep profile, by giving equal weighting to measurements at 30, 60 and 90 cm. Peaks in PWC occurred more or less 24 hours after each substantial rainfall or irrigation event, and when there was no substantial increase or spike in rainfall and irrigation, PWC decreased slightly. Even with the slight peaks after rainfall/irrigation events, PWC for the irrigated part of the field remained fairly constant throughout the season with an average of 200 mm for the station located in the poorly drained western side of the field, and 175 mm for the station located in the well-drained eastern side of the field. In FIGURE 2.17n, it is clear that the S3 dryland site has a higher profile water content (average of 375 mm) when compared to the other dryland station (S4) and the two pivot stations (S1 and S2). This is due to differences in drainage intervals, as the S3 dryland station is situated in the poorly drained area of the field. The exact opposite is found at the S4 dryland site, where drainage is moderate to good, and PWC actually decreases with time. S4 dryland site measurements only started mid-December, after the monitoring station was set up.

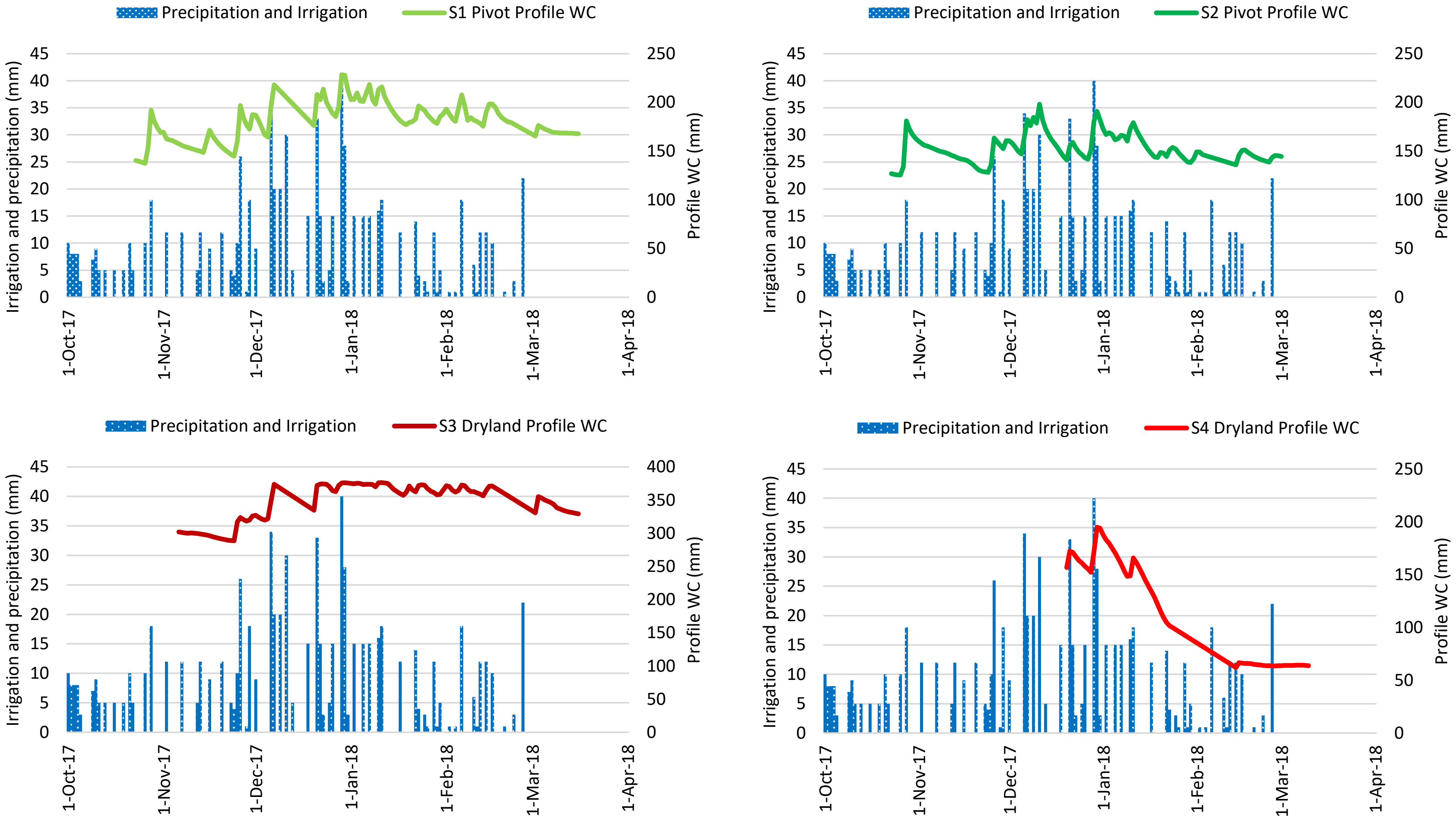

FIGURE 2.17: Profile water content (mm) and irrigation and precipitation (mm)

As expected, there has been a slight increase in salinity (FIGURE 2.18) after the commencement of irrigation with mine water. However, EC_e in the first 30 cm of the soil profile is still below the 170 mS m^{-1} threshold for maize (Maas and Hoffman 1977) and therefore no significant yield reduction due to salinity is expected at this stage. In FIGURE 2.19, soil solution EC, as measured from suction cup samples, is shown for both dryland and irrigated sites. The pivot EC_e values are almost double that of the dryland, and average around 170 (at 10 cm) and 230 (at 60 cm) mS m^{-1}. More data as measured from suction cup samples can be seen in Appendix A2. Soil samples taken after the season ended showed similar trends. The values were obtained by averaging sampling (FIGURE 2.6) locations 1 to 7 as the poorly drained western side of the field and locations 8 to 14 as the well-drained eastern side of the field. The pH increased slightly after irrigation commenced. The pH in the poorly drained west of the field increased from 5 to 5.2 and the pH in the well-drained east of the field increased from 4.7 to 5. All water-soluble Ca, Mg, Na and SO_4 increased after irrigation commenced, however total extractable ions decreased (except for SO_4 see TABLE 2.7). Total soluble P, Mn, Cu and Zn were found to be less than 1 mg kg^{-1} in the soil before and after irrigation took place. Soluble Fe and Al in the profile were found to be quite high, with Fe of up to 12 mg kg^{-1} before irrigation and 14 mg kg^{-1} after irrigation, and Al up to 34 mg kg^{-1} before irrigation and 38 mg kg^{-1} after irrigation. Soluble Ca increased from 25 mg kg^{-1} to 65 mg kg^{-1} after irrigation, soluble Mg increased from 7 mg kg^{-1} to 21 mg kg^{-1}, soluble Na increased from 1 mg kg^{-1} to 7 mg kg^{-1} and soluble K decreased from 5 mg kg^{-1} to 3 mg kg^{-1}. Soluble SO_4 increased from 60 mg kg^{-1} to 226 mg kg^{-1} after irrigation. Although these increases can be attributed to the mine water irrigation that took place, the fertilizer added before planting, as well as crop nutrient uptake should also be taken into account (TABLE 2.8). A summary of the constituent levels in the soil can be seen in Appendix A2.

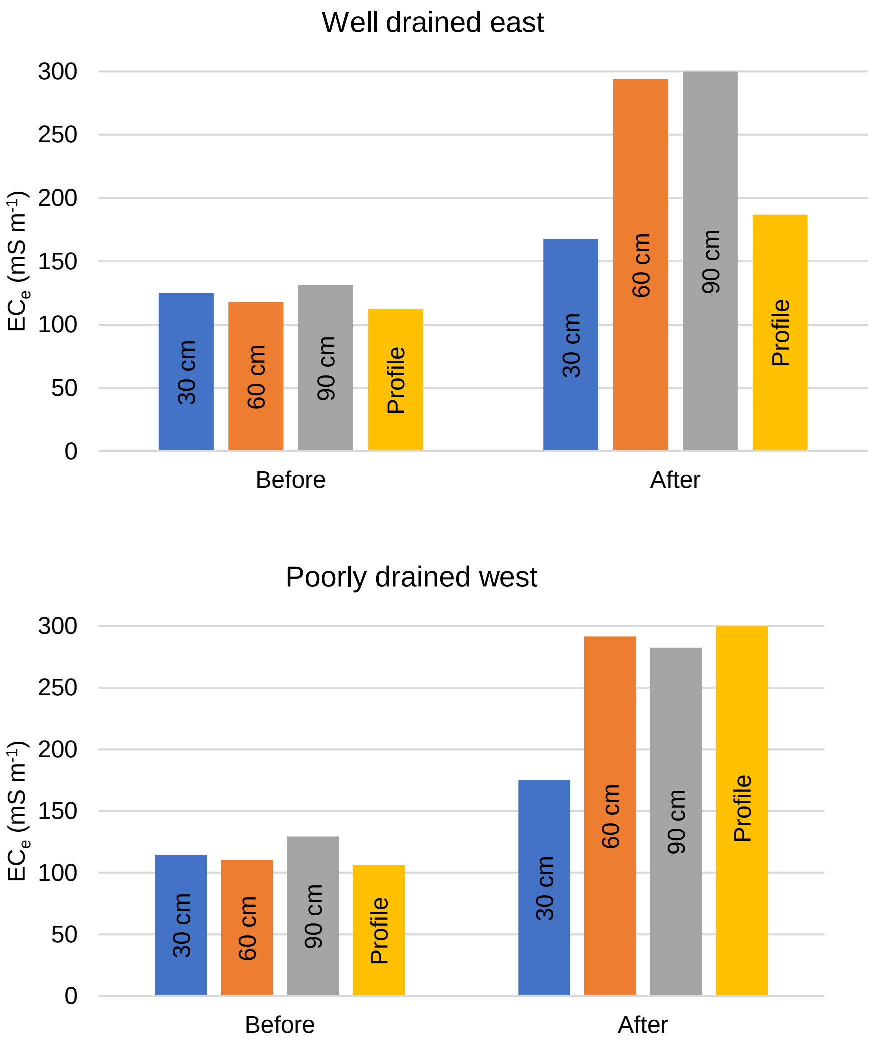

FIGURE 2.18: Soil solution EC_e (mS m^{-1}) as measured before and after irrigation

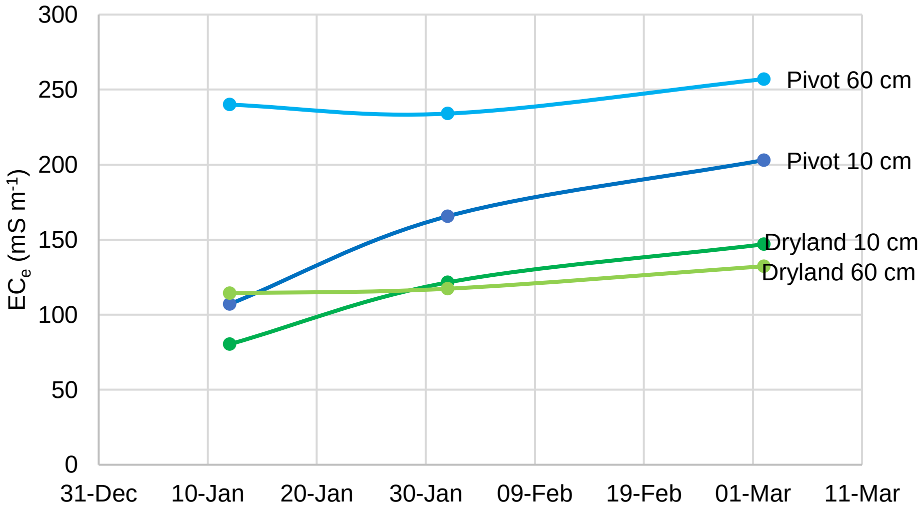

FIGURE 2.19: Soil solution EC (mS m^{-1}) as measured in samples retrieved from suction cups in dryland and pivot area

TABLE 2.7: Total mean extractable SO_4 (mg kg^{-1}) measured in soil before and after irrigation

	Depth (cm)	Before irrigation	After irrigation
Poorly drained west	30	77	202
	60	119	239
	90	204	283
Well drained east	30	86	178
	60	116	210
	90	220	271

TABLE 2.8: Salt balance of salts added (kg ha^{-1}) through irrigation and fertilizers

	Added with irrigation	Added with fertilizer	In soil before irrigation*	Sum in soil plus added**	In soil after irrigation	Lost
Ca	598	-	2407	3005	2226	779
Mg	439	-	547	986	583	403
Na	210	-	86	296	87	209
K	90	64	273	427	152	275
P	-	40	70	110	40	70
Cl	71	-	44	115	23	92
SO_4	3233	30	616	3879	1036	2842

**Based on mean total extractable ions*
***Irrigation + Fertilizer + In soil before irrigation*

2.3.3 Water quality

Irrigation water quality

The irrigation water is sourced from the Mafube voids, more specifically Void 3. The water is analysed by the mine every two weeks. TABLE 2.9 shows the average irrigation water quality as the water quality remained fairly constant. Full water quality results can be seen in Appendix A3.

TABLE 2.9: Average water quality of Void 3 used for irrigation at Mafube unmined site

Parameter	Level	Parameter	Level
EC (mS m^{-1})	209	Cl (mg L^{-1})	22
pH	8	SO_4 (mg L^{-1})	1122
TDS (mg L^{-1})	1872	Fe (mg L^{-1})	5
K (mg L^{-1})	36	Mn (mg L^{-1})	3
Mg (mg L^{-1})	133	Al (mg L^{-1})	0.034
Ca (mg L^{-1})	215	Pb (mg L^{-1})	0.009
Na (mg L^{-1})	83	Zn (mg L^{-1})	0.016

When irrigating with mine waters, it is important to know what constituents are present, as well as their concentrations and total loading over a season. It was found that a total of 3233 kg ha^{-1} SO_4, 598 kg ha^{-1} Ca, 439 kg ha^{-1} Mg, 210 kg ha^{-1} Na, 71 kg ha^{-1} Cl and 90 kg ha^{-1} K was applied after the 2017/18 summer season in about 300 mm of irrigation. Knowing these loading values is of importance to the farmer, as it can influence the overall fertilizer regime of the crop and may even help to save costs by preventing unnecessary fertilization. The large amount of K (90 kg ha-1) applied through the irrigation needs to be considered by the farmer, as he usually applies around 60 kg ha-1 of K in the beginning of the season. In FIGURE 2.20 and FIGURE 2.21, the cumulative salt loading throughout the 2017/18 summer season can be observed.

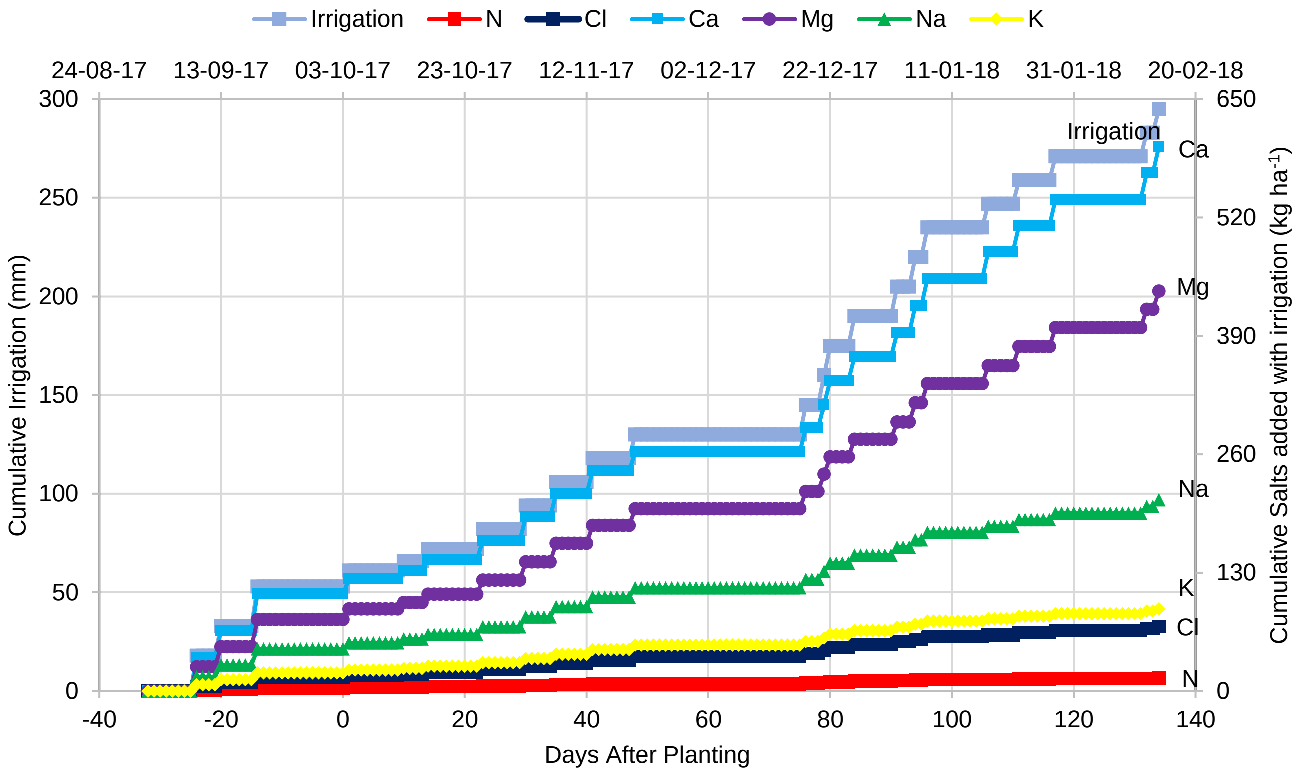

FIGURE 2.20: Cumulative salt loading (kg ha-1) as calculated using the actual concentrations for the 2017/18 summer season at the Mafube unmined site

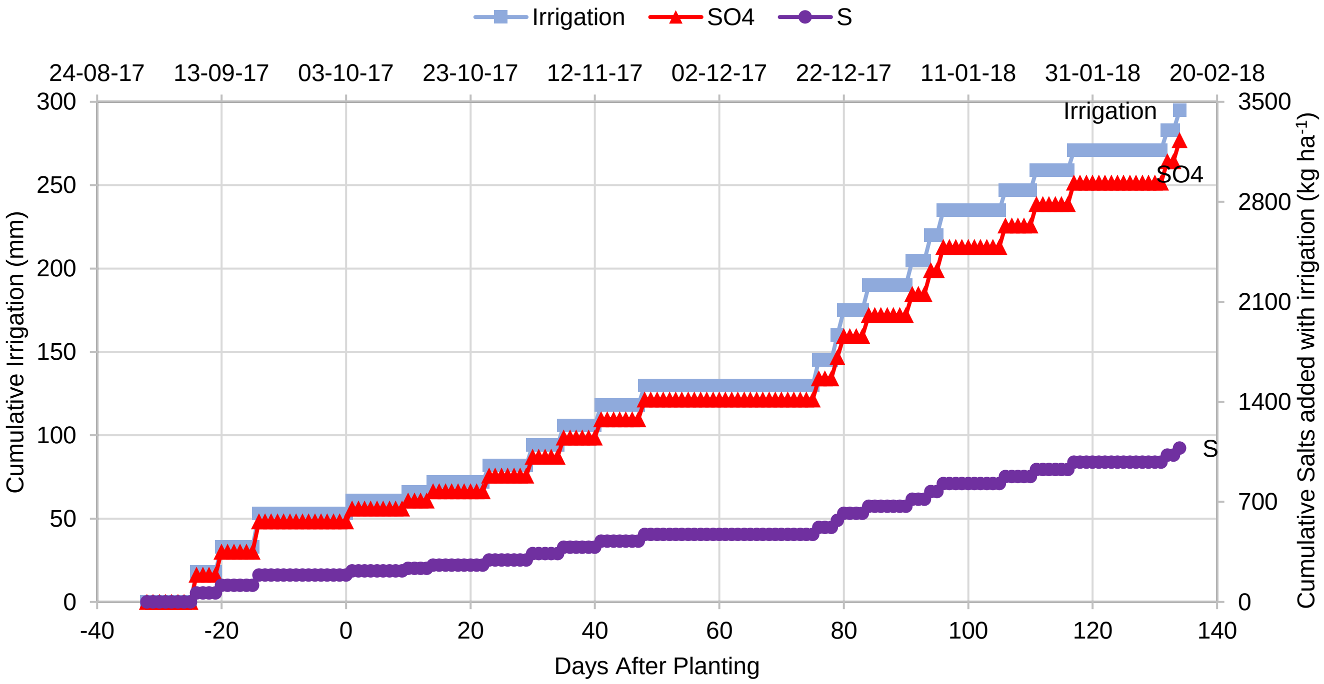

FIGURE 2.21: Cumulative sulphate and sulphur loading (kg ha-1) as calculated using the actual concentrations for the 2017/18 summer season at the Mafube unmined site

Boreholes

Considering the data from the past year (2018), it was evident that the upstream boreholes (1 and 2) in the well-drained side of the field showed much lower levels of Ca, Mg, K, Na and SO_4 when compared to the downstream boreholes (3 and 4) in the poorly drained side of the field. The sulphate concentrations and the ECs are also higher for the downstream boreholes when compared to the two upstream boreholes (see FIGURE 2.22 and FIGURE 2.23). The average values for each on site borehole can be seen in TABLE 2.10. However, it is clear that the measured EC and SO_4 of the downstream boreholes were quite high even before any irrigation had taken place (irrigation commenced in September 2017), thus indicating that these solute signatures are determined by an external salt source. The chemical signatures of these downstream boreholes also indicate that these waters are NaCl dominated and not Ca/Mg sulphate dominated, as is the case for the irrigation water. The most likely explanation for these observed elevated salt levels prior to irrigation is that they can be attributed to runoff from the discard dump that is located right next to these boreholes. Mafube Colliery has recently (August 2018) installed four additional boreholes around the discard dump (DMBH 8-11 in FIGURE 2.4), which enables groundwater monitoring closer to the discard dumps to be monitored, thereby eliminating uncertainty around the impact of irrigation on groundwater resources. These boreholes are referred to as the discard dump (or off site) boreholes and are installed at depths of 30 to 45 m. When looking at the analysis (TABLE 2.11) it is clear that the chemical signature of the waters in these boreholes (especially DMBH 10 and 11) are also more Cl than SO_4 dominated. This not only indicates that there is an external source of Cl waters, but that the irrigation water so far has had minimal effect on the groundwater as there is no sign of SO_4 accumulating.

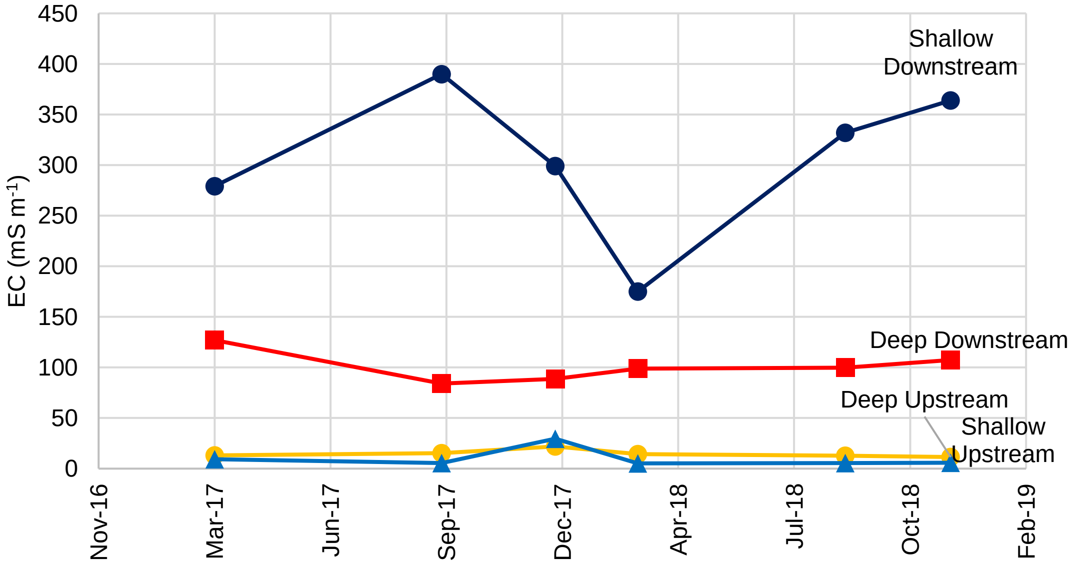

FIGURE 2.22: Electrical conductivity (mS m^{-1}) measured for the four boreholes at Mafube unmined site in the 2017/18 summer season

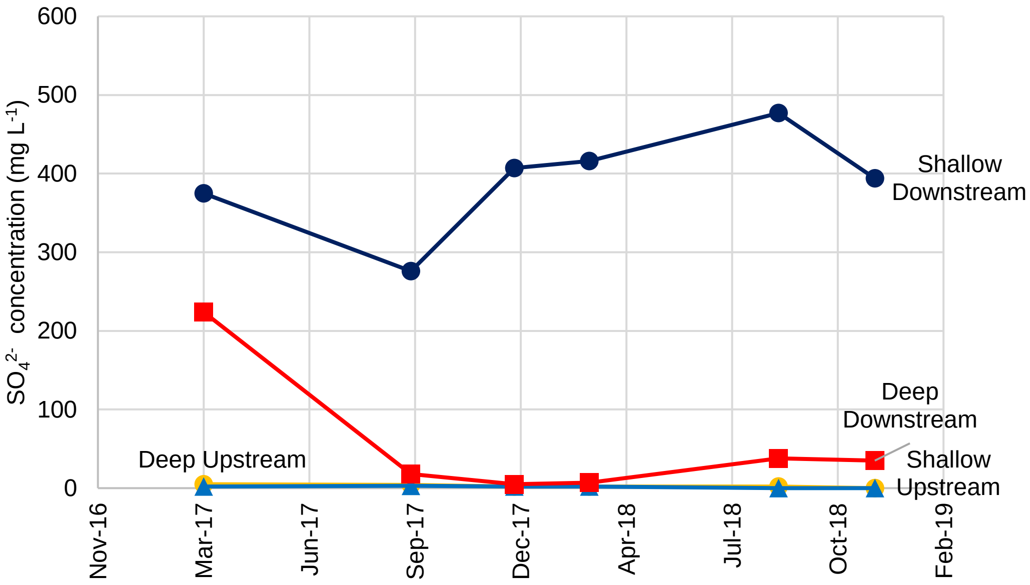

FIGURE 2.23: Sulphate concentration (mg L^{-1}) measured for the four boreholes at Mafube unmined site in the 2017/18 summer season

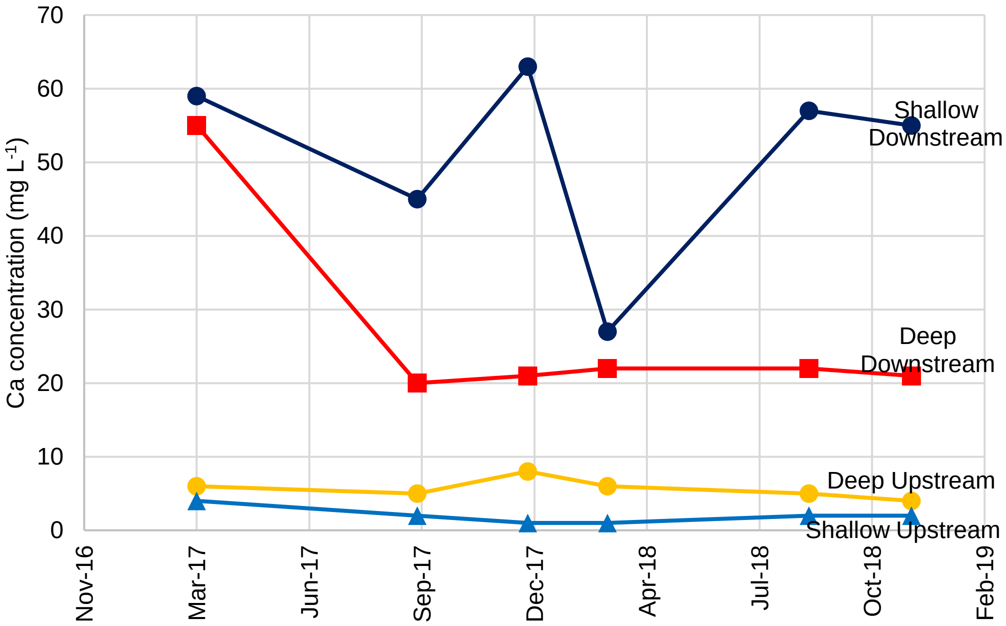

FIGURE 2.24: Calcium concentration (mg L^{-1}) measured for the four boreholes at Mafube unmined site in the 2017/18 summer season

TABLE 2.10: Summary of average constituent concentrations observed at the four on-site boreholes for the 2017/18 season

Parameter	Shallow Upstream	Shallow Downstream	Deep Upstream	Deep Downstream
Depth (m)	11	10	28	23
TDS (mg L^{-1})	66	1846	111	662
pH	6.0	6.5	6.5	6.6
EC (mS m^{-1})	10	307	15	101
SO_4 (mg L^{-1})	2	369	3	64
Ca (mg L^{-1})	2	49	6	30
Mg (mg L^{-1})	1	50	5	17
Na (mg L^{-1})	5	458	8	129
K (mg L^{-1})	3	7	6	6
Cl (mg L^{-1})	5	663	12	230
Total P (mg L^{-1})	1	0.3	0.90	0.40
Total N (mg L^{-1})	9	80	10	4
Al (mg L^{-1})	0.10	0.10	0.10	0.30
Fe (mg L^{-1})	0.04	0.28	0.23	0.50
Mn (mg L^{-1})	0.15	0.96	1.43	0.08
Zn (mg L^{-1})	0.03	0.12	0.04	0.03

TABLE 2.11: Summary of average constituent concentrations observed at the four off-site (discard dump) boreholes for the last quarter of 2018

Parameter	DMBH-8	DMBH-9	DMBH-10	DMBH-11
Depth (m)	30	35	45	35
TDS (mg L^{-1})	512	273	57	256
pH	7.7	7.1	6.4	7.8
EC (mS m^{-1})	75	40	7	38
SO_4 (mg L^{-1})	160	6	<2	4
Ca (mg L^{-1})	49	27	4	36
Mg (mg L^{-1})	23	10	2	10
Na (mg L^{-1})	73	41	5	30
K (mg L^{-1})	6	7	3	3
Cl (mg L^{-1})	32	21	12	20
Total P (mg L^{-1})	0.2	0.2	0.3	0.2
Total N (mg L^{-1})	<0.2	<0.2	6	0.4
Al (mg L^{-1})	<0.1	<0.1	<0.1	<0.1
Fe (mg L^{-1})	0.028	<0.025	0.026	<0.025
Mn (mg L^{-1})	<0.025	0.071	0.147	0.121
Zn (mg L^{-1})	<0.025	<0.025	<0.025	<0.025

Piezometers

Three piezometers were installed on the 14th of September 2017. The locations of these piezometers, along with the boreholes, can be seen in FIGURE 2.4 and allowed access to groundwater samples in order to analyze the potential impact of mine water irrigation on subsurface water flow and salt accumulation. The piezometers provide an idea of the lateral water movement, and also gives an indication of the shallow or perched groundwater quality. In FIGURE 2.25 and FIGURE 2.26 it can be observed that the upstream piezometer water level remains fairly constant until the start of December 2017, where the water level spiked due to the increased rainfall (200 mm in December 2017, whereas October and November combined had 150 mm) and subsequent ponding. Thereafter, the water level steadily decreases into February. FIGURE 2.27 shows the EC as measured throughout the 2017/18 summer season. The upstream piezometer EC appears to be fairly stable, whereas the downstream piezometer had a decrease in EC at the middle of December. The decrease in the downstream EC can be related to the increased precipitation and thus increased runoff which in turn diluted the salt concentration in the downstream piezometer. FIGURE 2.28 shows the SO_4^{2-} concentration measured throughout the 2017/18 summer season, and it is clear that the same trend as seen with the downstream boreholes is present here with the downstream piezometer sulphate and chloride levels. This trend might be attributed to the runoff from the mines discard dumps located just east of these piezometers. In TABLE 2.12 the average elemental concentrations of both the upstream and downstream piezometers can be observed. The same trend, where the downstream values are higher than the upstream values, can be seen especially when looking at things like Na, Cl and SO_4.

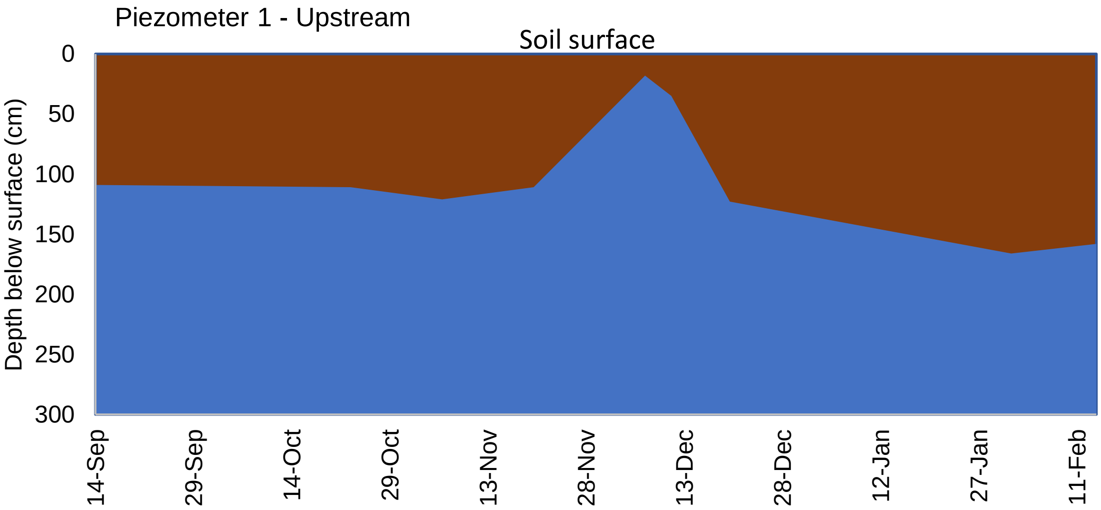

FIGURE 2.25: Water level (cm) measured for the upstream piezometer at Mafube unmined site in the 2017/18 season

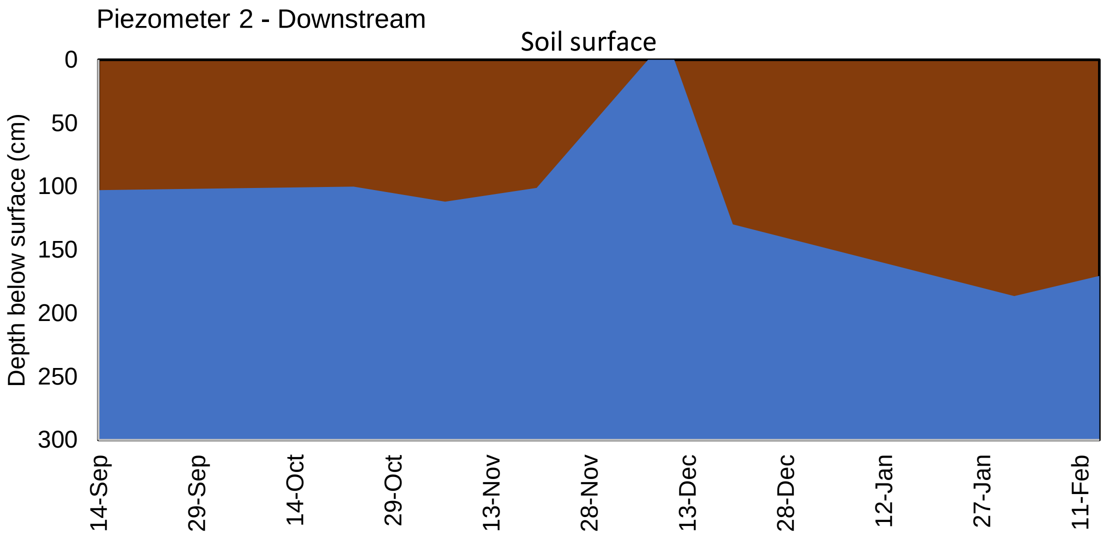

FIGURE 2.26: Water level (cm) measured for the downstream piezometer at Mafube unmined site in the 2017/18 season

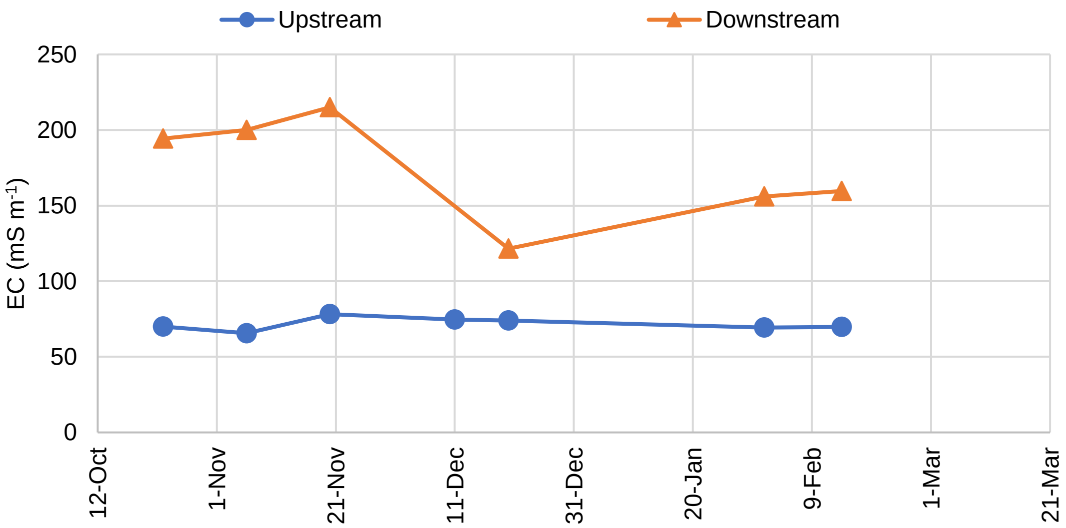

FIGURE 2.27: Electrical conductivity (mS m^{-1}) measured for both piezometers at Mafube unmined site in the 2017/18 season

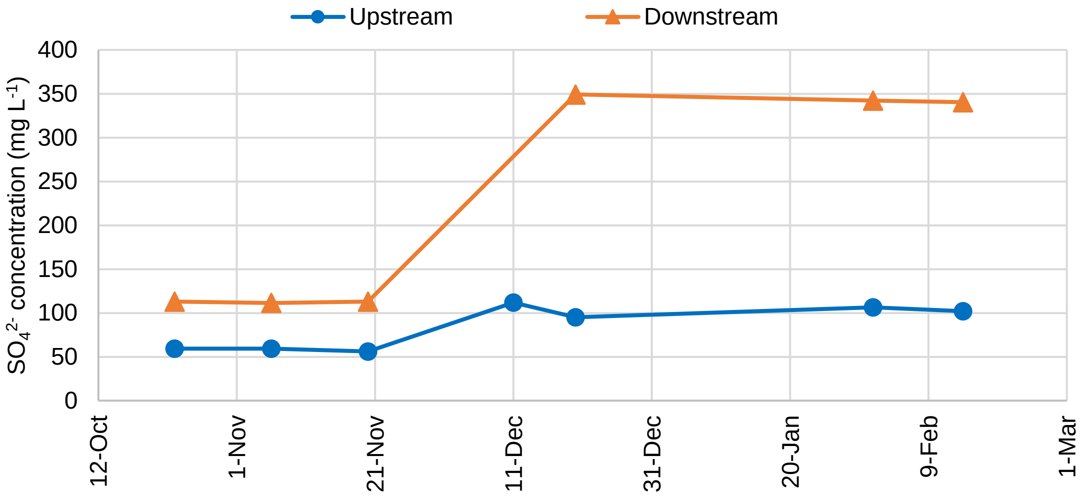

FIGURE 2.28: Sulphate concentration (mg L^{-1}) measured for both piezometers at Mafube unmined sitein the 2017/18 season

TABLE 2.12: Summary of average constituent concentrations observed at the two piezometers for the 2017/18 season

Parameter	Upstream (P1)	Downstream (P2)
EC (mS m^{-1})	63	174
K (mg L^{-1})	8	10
Mg (mg L^{-1})	23	20
Ca (mg L^{-1})	18	19
Na (mg L^{-1})	45	328
Cl (mg L^{-1})	229	435
SO_4 (mg L^{-1})	86	228

Monitoring dam

Beestepan Dam was identified as a monitoring point where one could potentially see the impact of irrigation on the surface or groundwater bodies that are situated downstream from the field. Sulphate was chosen as the identifiable ‘flagging’ constituent and if a 20% increase in original (before irrigation) concentration, attributable to irrigation is observed, all irrigation should be stopped immediately, this would mean that the sulphate limit would be 642 mg L^{-1}. This, however, is a slightly flawed method as the monitoring point is also downstream from one of the mines discard dumps and any increase in sulphate (or any other element) cannot be related to irrigation alone. The discard dumps as the source of potential ‘pollution’, might be due to the overtopping of the pollution control structures which control water flow around the discard dump. FIGURE 2.4 shows the existing boreholes (BH 1-4), the four new boreholes (DMBH 8-11) as well as Beestepan Dam.

Fortunately, the monitoring so far demonstrates that the threshold for action has not been reached. TABLE 2.13 shows the average water quality before and after irrigation started, highlighting the elements of concern. The full water quality results can be seen in Appendix A2.

TABLE 2.13: Average water quality of Beestepan Dam used for monitoring irrigation impacts

	Before irrigation	**After irrigation**
EC (mS m^{-1})	115	75
SO_4^{2-} (mg L^{-1})	535	309
Na (mg L^{-1})	51	33
Total P (mg L^{-1})	0.7	0.4
Total N (mg L^{-1})	1.4	1.1

2.3.4 Food Safety

When looking at food safety, one can refer to the international, as well as the local guidelines on food safety thresholds for grains (TABLE 2.14). The South African food safety guidelines are based on the European guidelines. Although mine waters contain a range of metals including iron (Fe), aluminium (Al), and manganese (Mn), the main elements of concern were identified as arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb) and mercury (Hg).

TABLE 2.14: International guidelines and thresholds on grain food safety for human consumption (Adapted from Codex Alimentarius Commission (2011, 2013), South African Department of Health (2016))

		Country	
	China	**EU and South Africa**	**Ireland**
As (ppm)	0.5	-	-
Cd (ppm)	0.1	0.1	0.1
Cr (ppm)	1	-	-
Pb (ppm)	0.2	0.2	0.1
Hg (ppm)	0.02	-	-

As the 2016/17 season received no irrigation, it was not of concern and thus it was not analysed for food safety. In TABLE 2.15, the full elemental composition of the grain for both the irrigated and dryland maize of the 2017/18 season can be seen. Nickel (Ni), vanadium (V), aluminium (Al), cadmium (Cd), beryllium (Be), mercury (Hg) and lithium (Li) were all found to be negligibly small (<0.001 mg kg^{-1}). From the analysis, it is clear that the grain is in fact safe for human consumption and the elements of concern (highlighted green in the table) do not reach the stated thresholds. Plant material was not tested for fodder safety, however, if it were to be used for animal feed it will need to be tested and deemed safe for animal consumption first.

TABLE 2.15: Elemental composition of dried maize grain for both the irrigated and dryland grain (2017/18 season)

Irrigated		Dryland	
	Macronutrients (ppm or mg kg^{-1})		
K	17.4	**K**	18.3
Mg	9.8	**Mg**	8.9
P	31.2	**P**	32.3
S	9.9	**S**	9.5
Ca	0.3	**Ca**	0.4
	Micronutrients (ppm or mg kg^{-1})		
Cu	0.008	**Cu**	0.008
Fe	0.142	**Fe**	0.112
Se	0.011	**Se**	0.009
Zn	0.157	**Zn**	0.143
Co	0.001	**Co**	0.001
B	0.017	**B**	0.015
Mo	0.002	**Mo**	0.003
Na	0.024	**Na**	0.022
Mn	0.045	**Mn**	0.044
	Trace elements (ppm or mg kg^{-1})		
Sr	0.007	**Sr**	0.001
Cr	0.002	**Cr**	0.002
Ba	0.056	**Ba**	0.03
As	0.003	**As**	0.004
Pb	0.006	**Pb**	0.005
Cd	<0.001	**Cd**	<0.001
Hg	<0.001	**Hg**	<0.001

2.4 Conclusions

South Africa is a semi-arid country and water scarcity is an omnipresent issue that needs to be addressed. The mining industry further exacerbates South Africa's water availability and quality issues, which causes increased challenges in the utilization and management practices of this resource. Due to climatic constraints in South Africa, agricultural practices are often dependent on irrigation. Irrigation with this mine impacted water creates an opportunity to successfully produce crops during the dry season as well as obtain relatively high yields.

These trials are part of on-going research to demonstrate the sustainability of irrigating with mine water. For the first season, it was shown that crops (specifically maize) grow well with this mine impacted water, with minimal environmental impacts in the short term and proves to be more profitable than dryland production. The grain produced is safe for human consumption, which makes this a feasible practice. However, it is very important to monitor production under these circumstances and to stop irrigation if any unacceptable impacts are encountered. Irrigation with mine water is viable, sustainable and feasible, if the appropriate management practices are in place. One way to estimate the long term viability is by using models to simulate long term effects in yield and the irrigation fitness for use, as described in Chapter 3.

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CHAPTER 3: CROP, SALT AND WATER BALANCE MODELLING OF MAIZE

3.1 Introduction

The SWB-Sci model (Benadé et al. 1995, Annandale et al. 1996, Annandale et al. 1999a) that was developed over many years with WRC and mine industry funding, and can be used to predict gypsum precipitation in soil for several mine impacted waters under various cropping system and water management scenarios. The model then gives an indication of the amount of water that can be used with irrigation, and the opportunity to sequester salt as gypsum in the profile, that will reduce salt loading to water courses. In the case of dry land production, like in the 2016/17 summer season, the model can also be used to predict the expected yield in the event that mine water irrigation had taken place.

The South African Irrigation Water Quality Guidelines comprise one of the most widely-used tools in water quality management. It aids in the determination of water quality requirements for irrigation water use as well as quantitative fitness-for-use assessments. An important goal of this guideline is to maintain the productivity of irrigated agricultural land and associated water resources. A revision of the guideline was necessary to reflect the most appropriate and latest research and practices in this field. Recently, a computer program-based decision support system (DSS) (Du Plessis et al. 2017) was developed to assess the fitness for use of different quality waters for irrigation.

3.2 Soil Water Balance model

The SWB model simulates crop growth, whilst being a real-time, easy to use, irrigation scheduling tool. SWB uses weather, crop and soil data to give a detailed description of the soil-plant-atmosphere continuum. The crop database includes several growth parameters that are crop specific, and values that are not given can be estimated.

3.2.1 Crop parameter determination

The SWB model uses transpiration (corrected for vapour pressure deficit) to calculate dry matter accumulation (Tanner and Sinclair 1983). It also calculates radiation-limited growth (Monteith 1977) and dry matter partitioning. The partitioning depends on crop phenology that is calculated with thermal time (growing degree days) and is modified by water stress. Dry matter is partitioned to stems, roots, leaves and grain (Annandale et al. 1999a). Crop parameters required in SWB are described in TABLE 3.1.

TABLE 3.1: Crop parameters required for SWB modelling

Crop parameter	Unit
Radiation extinction coefficient (K_c for solar radiation)	-
Dry matter to water ratio (DWR)	Pa
Radiation use efficiency (E_c)	kg MJ^{-1}
Base temperature	°C
Optimum light limiting temperature	°C
Cut-off temperature	°C
Emergence day degrees	d °C
Flowering day degrees	d °C
Maturity day degrees	d °C
Transition period day degrees	d °C
Leaf senescence day degrees	d °C
Maximum crop height (H_{max})	m
Maximum root depth (RD_{max})	m
Minimum leaf water potential	kPa
Specific leaf area (SLA)	m^2 kg^{-1}
Leaf-stem partition (p)	m^2 kg^{-1}
Root growth rate	m^2 $kg^{-0.5}$
TDM at emergence	kg m^{-2}
Maximum transpiration	mm d^{-1}
Stem-grain translocation	-
Canopy storage	mm
Root fraction	-
Stress index	-

3.2.2 Weather variables

Weather data is used in SWB as the driving variables for evaporation and crop growth. SWB only requires solar radiation, wind speed, temperature and humidity, however, if only the minimum and maximum temperatures are known, SWB can estimate the other parameters although it is more accurate to have measured values. Using the provided data, SWB uses the Penman-Monteith crop reference evaporation (Smith et al. 1996) to calculate the daily evapotranspiration (ET_o) (Annandale et al. 1999a). The variables required are listed in TABLE 3.2.

TABLE 3.2: Daily weather parameters required for SWB modelling

Weather variable	Unit
Minimum Temperature	°C
Maximum Temperature	°C
Minimum Humidity	%
Maximum Humidity	%
Average Wind Speed	m s^{-1}
Average Solar Radiation	W m^{-2}
Precipitation	mm

3.2.3 Soil parameters

Actual physical and chemical properties of the soil can be used as input in SWB, otherwise a default soil will be used. This data is used to calculate soil-water movement. By estimating radiation interception by the canopy from crop leaf area, potential evaporation and transpiration is predicted. A root density weighted average soil water potential is estimated, which characterizes the water supply capacity of the soil-root system. This multi-layer soil component gives a realistic simulation of infiltration and water uptake processes, which uses a cascading soil water balance once runoff and crop interception have been accounted for (Annandale et al. 1999a). Other than soil texture other variables that are required for the soil database are listed in TABLE 3.3 and if these are not specified, the model assumes that there are no initial salts in the soil profile.

TABLE 3.3: Soil parameters required for SWB modelling

Soil variable	Unit
Ca	mg kg^{-1}
Mg	mg kg^{-1}
K	mg kg^{-1}
Na	mg kg^{-1}
Cl	mg kg^{-1}
SO_4	mg kg^{-1}
pH	-
Exchangeable Ca	mg kg^{-1}
Exchangeable Mg	mg kg^{-1}
Exchangeable K	mg kg^{-1}
Exchangeable Na	mg kg^{-1}
Gypsum	g m^{-2}
Lime	g m^{-2}
Texture	-
Silt content	%
Clay content	%
Field capacity (FC)	kPa or m m^{-1} when estimated from texture
Permanent wilting point (PWP)	kPa or m m^{-1} when estimated from texture
Root depth limit	m
Drain rate	mm d^{-1}

3.3 Modelling mine water irrigation and crop growth

The objective of this study was to collect field data in order to determine crop-specific parameters, which can be used to calibrate and validate the SWB model for this scenario (mine water irrigation). The calibrated model can then be used to simulate potential yields, as well as simulate the potential salt movement (precipitation or leaching) in the soil profile over time. The experimental setup and field measurement methods are described in Chapter 2. Data from the 2017/18 season (maize) was used to parameterise the SWB model.

3.3.1 Crop parameters

Crop parameters like transition period day degrees (d °C), day degrees for leaf senescence (d °C), maximum root depth (m), canopy storage (mm), stem to grain translocation, minimum leaf water potential (kPa), leaf to stem partioning parameter (m^2 kg^{-1}), TDM at emergence (kg m^{-2}), root fraction, root growth rate and stress index for maize were obtained from the SWB database (Annandale et al. 1999a). Base temperature (°C), optimum light limiting temperature (°C) and cut off temperature (°C) were acquired from Du Toit et al. (1999) .

Emergence day degrees (d °C), flowering day degrees (d °C), day degrees to maturity (d °C), extinction coefficient, specific leaf area (m^2 kg^{-1}), dry matter water ratio (Pa), and radiation use efficiency (kg MJ^{-1}) were calculated based on measurements obtained in the field. All values used as input can be seen in TABLE 3.4.

Thermal time is used to simulate crop development (Annandale et al. 1999a). Growing degree days (GDD) are calculated after the crop is planted and accumulates daily (GDD_i) (Monteith 1977). This is compared to crop phenology stages as measured in the field to get the GDD of emergence, flowering and maturity stages.

$$\mathrm{GDD} = \mathrm{GDD} + \mathrm{GDD_i} \tag{3.1}$$

$$\mathrm{GDD_i} = \mathrm{T_{ave}} - \mathrm{T_b} \tag{3.2}$$

Where GDD_i is the daily increment of growing degree days, T_{ave} is the average daily temperature (°C), and T_b is a crop specific (10°C for maize) base temperature (°C).

Specific leaf area (SLA in m^2 kg^{-1}), is calculated by dividing the leaf area index (LAI in m^2 m^{-2}) by total leaf dry matter (LDM in kg m^{-2}) as stated by Jovanovic et al. (1999).

$$\mathrm{SLA} = \frac{\mathrm{LAI}}{\mathrm{LDM}} \tag{3.3}$$

The canopy extinction coefficient for solar radiation (K_s) (Monteith 1977) is converted from the canopy extinction coefficient for PAR (K_{PAR}) which is calculated using the measured fractional interception of PAR (FI_{PAR}) and measured leaf area index (LAI) (Campbell and Van Evert 1994).

$$\mathrm{FI_{PAR}} = 1 - \mathrm{e}^{-\mathrm{K_{PAR}} \times \mathrm{LAI}} \tag{3.4}$$

$$\mathrm{K_s} = \mathrm{K_{bd}} \sqrt{\mathrm{a_s}} \tag{3.5}$$

$$\mathrm{K_{bd}} = \frac{\mathrm{K_{PAR}}}{\sqrt{\mathrm{a_p}}} \tag{3.6}$$

$$\mathrm{a_s} = \sqrt{\mathrm{a_p} \times \mathrm{a_n}} \tag{3.7}$$

Where K_{bd} is the canopy radiation extinction coefficient for ‘black’ leaves with diffuse radiation, a_s is leaf absorptance of solar radiation, a_p is leaf absorptance of PAR, a_n is leaf absorptance of near infrared radiation. The value of a_p is assumed to be 0.8 and a_n is assumed to be 0.2 (Goudriaan 1977).

Radiation use efficiency (E_c in kg MJ^{-1}) is used to calculate dry matter production under conditions where radiation limits growth (Monteith 1977).

$$\mathrm{DM} = \mathrm{E_c} \times \mathrm{FI_s} \times \mathrm{RS} \tag{3.8}$$

Where DM (kg m^{-2}) is dry matter as measured at harvest, FI_{PAR} is fractional interception of PAR, and RS (W m^{-2}) is solar radiation. Radiation use efficiency can also be estimated using the slope of the graph when plotting cumulative dry matter and cumulative FI_s*RS (FIGURE 3.1).

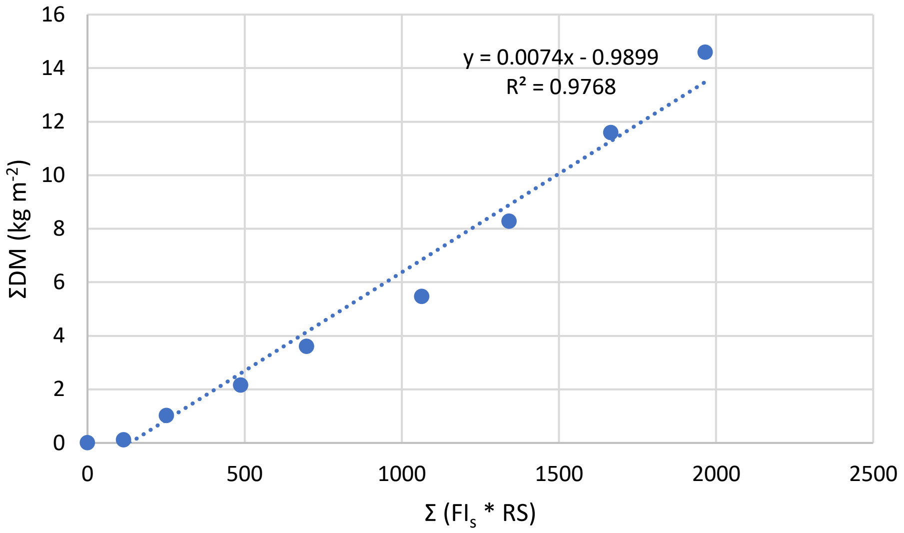

FIGURE 3.1: Radiation use efficiency as the slope of the relation between cumulative dry matter production and cumulative interception of solar radiation

Seasonal crop evapotranspiration (ET in mm or kg m^{-2}) (Jovanovic et al. 1999) is used along with seasonal average vapour pressure deficit (VPD in Pa) (Jovanovic et al. 1999) to estimate the dry matter water ratio (DWR in Pa) (Tanner and Sinclair 1983).

$$\mathrm{ET} = \mathrm{P} + \mathrm{I} - \mathrm{R} - \mathrm{D} - \Delta\mathrm{Q} \tag{3.9}$$

$$\mathrm{VPD} = \frac{\left(e_{s_{\mathrm{Tmax}}} + e_{s_{\mathrm{Tmin}}}\right)}{2} - e_a \tag{3.10}$$

$$e_s = 0.611\exp\left[\frac{17.27\,\mathrm{T}}{(\mathrm{T}+273.3)}\right] \tag{3.11}$$

$$e_a = \frac{\left[e_{s_{\mathrm{Tmax}}} \times \frac{\mathrm{RH_{max}}}{100} + e_{s_{\mathrm{Tmin}}} \times \frac{\mathrm{RH_{min}}}{100}\right]}{2} \tag{3.12}$$

$$\mathrm{DWR} = \frac{\mathrm{DM} \times \mathrm{VPD}}{\mathrm{ET}} \tag{3.13}$$

Where P is precipitation, I is irrigation, R is runoff, D is drainage, and ΔQ is the change in soil water storage, all in mm (Jovanovic et al. 1999). e_s is the saturated vapour pressure (Pa) at maximum (T_{max}) and minimum (T_{min}) air temperatures (°C) (Tetens (1930) as cited by Jovanovic et al. (1999)) and e_a is the actual vapour pressure (Pa) as a function of relative minimum (RH_{min}) and maximum (RH_{max}) humidity (Bosen (1958) as cited by Jovanovic et al. (1999)). DM (kg m^{-2}) is dry matter as measured at harvest.

TABLE 3.4: Crop input parameters used for simulations

Crop parameter	Value
Radiation extinction coefficient for solar radiation*	0.487
DWR (Pa)*	6.0
Radiation use efficiency (kg MJ^{-1})*	0.007
Base temperature (°C)**	10
Optimum temperature under light limiting conditions (°C)**	25
Cut-off temperature (°C)**	30
Emergence day degrees (d °C)*	60
Flowering day degrees (d °C)*	730
Maturity day degrees (d °C)*	1600
Transition period day degrees (d °C)***	10
Leaf senescence day degrees (d °C)***	950
Maximum crop height (m)*	3.2
Maximum root depth (m)***	1.5
Stem-grain translocation***	0.05
Canopy storage (mm)***	1
Minimum leaf water potential (kPa)***	-2000
Maximum transpiration (mm day^{-1})***	9
Specific leaf area (m^2 kg^{-1})*	12
Leaf-stem partition (m^2 kg^{-1})***	0.8
TDM at emergence (kg m^{-2})***	0.0019
Root fraction***	0.01
Root growth rate (m^2 $kg^{-0.5}$)***	8
Stress index***	0.95

*Note: * - calculated from field measurements*
*** - obtained from Du Toit et al. (1999)*
**** - obtained from SWB database (Annandale et al. 1999a)*

3.3.2 Soil parameters

Soil chemical and physical properties were determined by analysing soil samples taken before planting. The soil parameters used as input variables for SWB can be seen in TABLE 3.5.

TABLE 3.5: Soil input parameters used for simulations

Soil variable	Value
Ca (ppm)	519
Mg (ppm)	111
K (ppm)	126
Na (ppm)	8
pH	5.75
Field capacity (m m^{-1})	0.269
Bulk density (g cm^{-3})	1.6
Permanent wilting point (m m^{-1})	0.148
Clay %	25
Silt %	10
Texture	Sandy loam

3.3.3 Weather variables

Weather variables were obtained by using a combination (TABLE 3.6) of two automatic weather stations, one at Mafube Colliery and one on-site UP station. Long term weather data used for scenario simulations and long-term modelling was provided by the ARC using the Middelburg Eden Farms (Middelburg, Mpumalanga) station.

TABLE 3.6: Weather station locations and data provided

	Mafube Colliery	**UP fixed station**
Location	25°47’36.00” S 29°44’15.00” E Alt: 1663 m	25°48’22.38” S 29°45’59.58” E Alt: 1674 m
Minimum Temperature (°C)	Yes	Yes
Maximum Temperature (°C)	Yes	Yes
Minimum Humidity (%)	Yes	Yes
Maximum Humidity (%)	Yes	Yes
Average Wind Speed (km h^{-1})	Yes	Yes
Average Solar Radiation (W m^{-2})	No	Yes
Precipitation (mm)	Yes	-

3.3.4 Results

Data from the 2017/18 season was used to parameterize the SWB model, the 2016/17 dryland season was then predicted with the new parameters to confirm accuracy. The parameterization of top (TDM) and harvestable (HDM) dry matter with salt simulation is deemed acceptable as r^2 and D > 0.8 and MAE < 20% (as recommended by De Jager (1994)) and can be seen in FIGURE 3.2. Measured LAI might be underestimated due to the time delay before measuring, which could cause leaves to wilt, break or go missing. The 2016/17 dryland season data was used to double check the parameterisation, and the result can be seen in FIGURE 3.3 and can be described as a relatively good fit as r^2 and D > 0.8 and MAE < 20% (as recommended by De Jager (1994)). Other simulated crop parameters can be seen in Appendix B1.

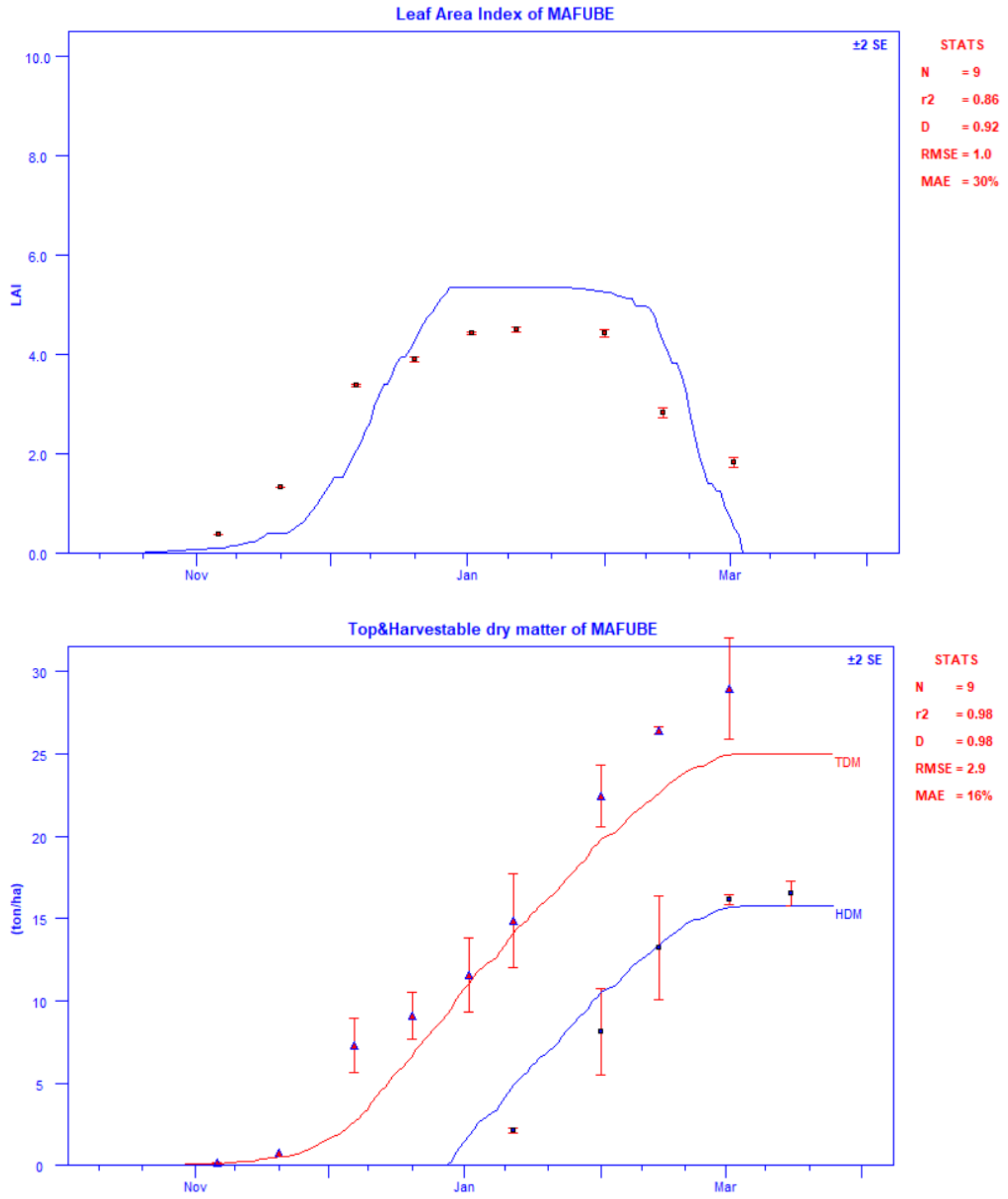

FIGURE 3.2: Measured (symbols) and simulated (lines) leaf area index (top), and top and harvestable dry matter (bottom) simulating the effect of saline water irrigation

Note: N – number of observations, r^2 -coefficient of determination, D – Willmott's (1982) index of agreement, RMSE – root mean square error, MAE – mean absolute error

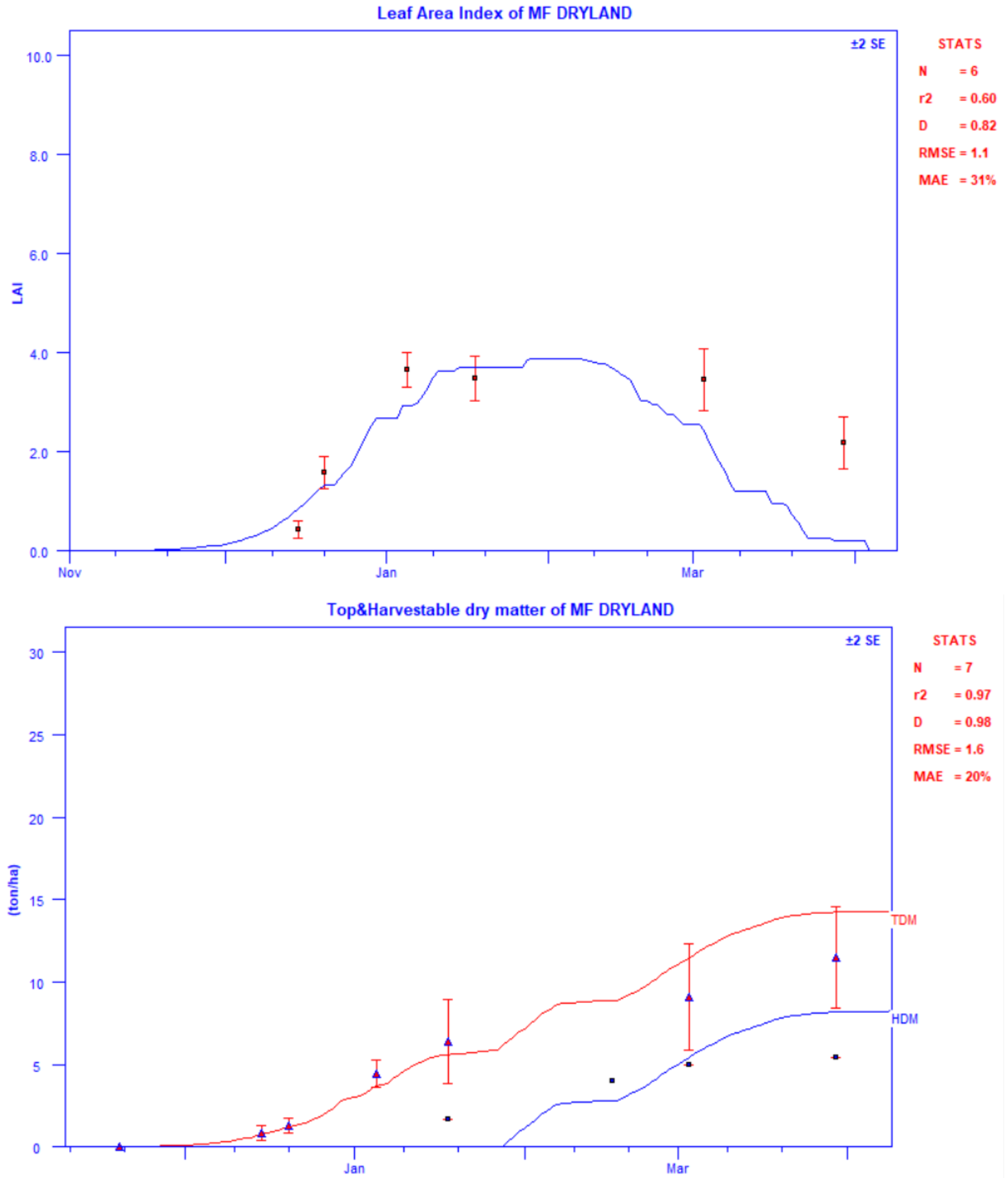

FIGURE 3.3: Measured (symbols) and simulated (lines) leaf area index (top), and top and harvestable dry matter (bottom) simulating a dryland season

Note: N – number of observations, r^2 -coefficient of determination, D – Willmott's (1982) index of agreement, RMSE – root mean square error, MAE – mean absolute error

3.3.5 Scenario simulations

Long term simulations of about 50 years show that the yields of both maize and wheat remain fairly constant throughout 50 years of irrigation (FIGURE 3.4). Maize yield averages around 20 t ha^{-1}, with a minimum of 15 and a maximum of 24 t ha^{-1}. Wheat yield averages around 10 t ha^{-1}, with a minimum of 8 and a maximum of 13 t ha^{-1}. However, there is a slight variation, which can be attributed to seasonal variation which includes seasonal weather pattern changes. This simulation shows that irrigating with this specific water (saline mine water) is not predicted to cause a decrease in yield over the long-term.

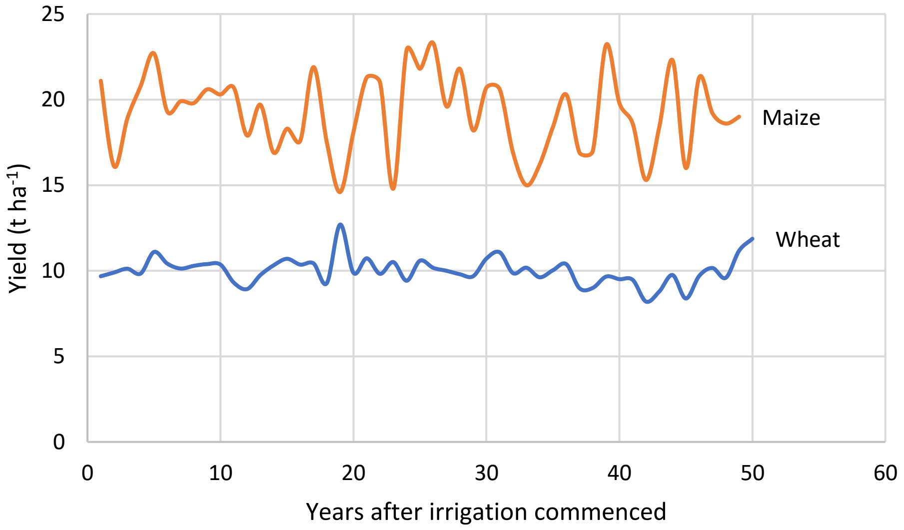

FIGURE 3.4: SWB simulation of yields (t ha^{-1}) for a maize/wheat rotation over a 50-year period

When using different water qualities (TABLE 3.), the salt balance and expected yields change. For example, simulating the wheat yield over 50 years (FIGURE 3.5) with a fairly good quality water (Mafube Voids) and a poorer quality water (Arnot), it is clear that the poorer quality water has lower yields compared to the good quality water, as well as showing significant decreases in yield at about 20 year intervals, coinciding with very dry seasons. In FIGURE 3.6 the EC_e (soil profile salinity) is depicted for each of the water qualities in TABLE 3., along with the thresholds for maize, soybean and wheat. In this simulation it shows that only fresh water and water from the raw water dam may be suitable for irrigation of maize, whereas all four water qualities may be suitable for irrigation of soybean and wheat. FIGURE 3.7 shows gypsum precipitation and % salts removed for each water quality. Although water from Arnot exhibits the most gypsum precipitation over a 50-year period, it shows that a lower percentage of salts is removed, indicating a lower efficiency in salt removal through gypsum precpitation.

TABLE 3.7: Different water qualities in the vicinity of Mafube Colliery

	Good quality fresh water	Mafube Voids	Raw Water Dam	Arnot
pH	7.5	7.7	7.8	7.7
EC (mS m^{-1})	60	208	229	558
Ca (mg L^{-1})	50	241	268	526
Mg (mg L^{-1})	29	151	176	585
Na (mg L^{-1})	30	103	56	108
K (mg L^{-1})	0.2	35	30	72
Cl (mg L^{-1})	85	28	23	21
SO_4 (mg L^{-1})	120	1065	1414	3580

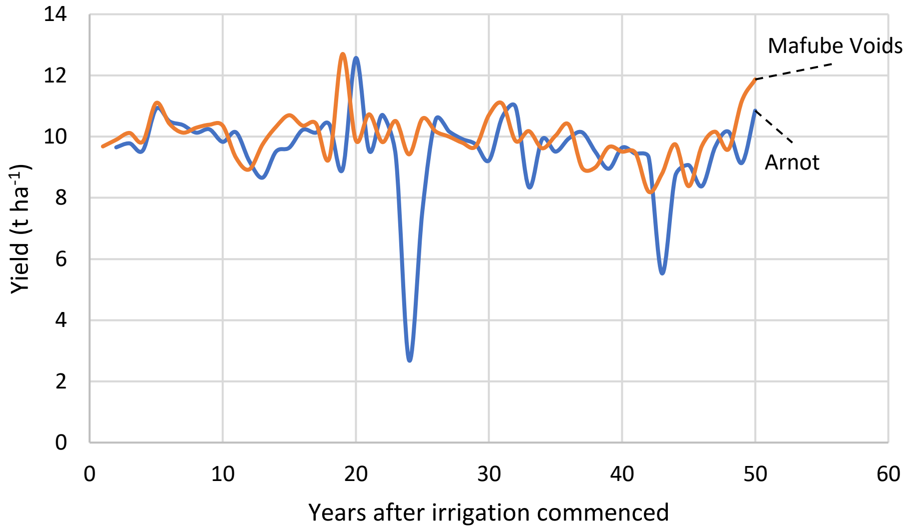

FIGURE 3.5: Simulated wheat yield (t ha^{-1}) over 50-year period for two different water qualities using SWB

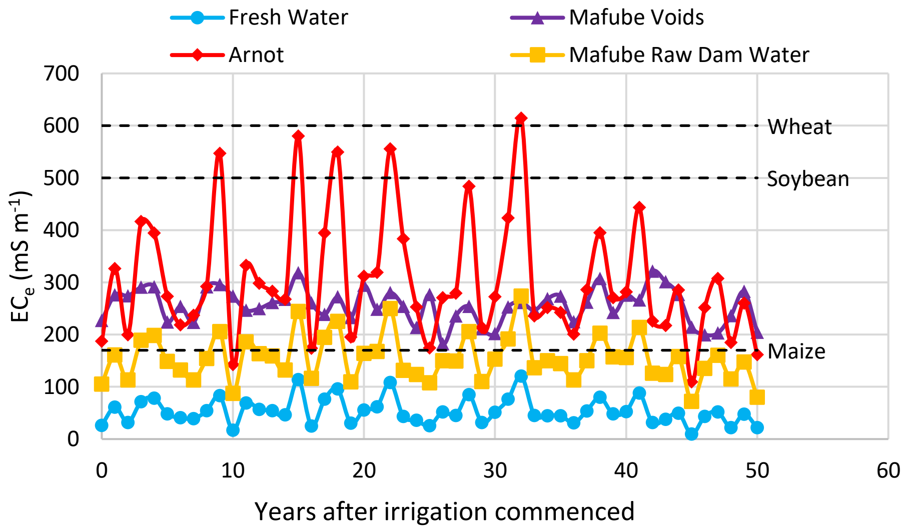

FIGURE 3.6: Soil profile salinity (EC_e in mS m^{-1}) predicted for 50 years of irrigation with four different water qualities using SWB. Salinity thresholds (Maas and Hoffman 1977) for maize, wheat and soybean are also indicated

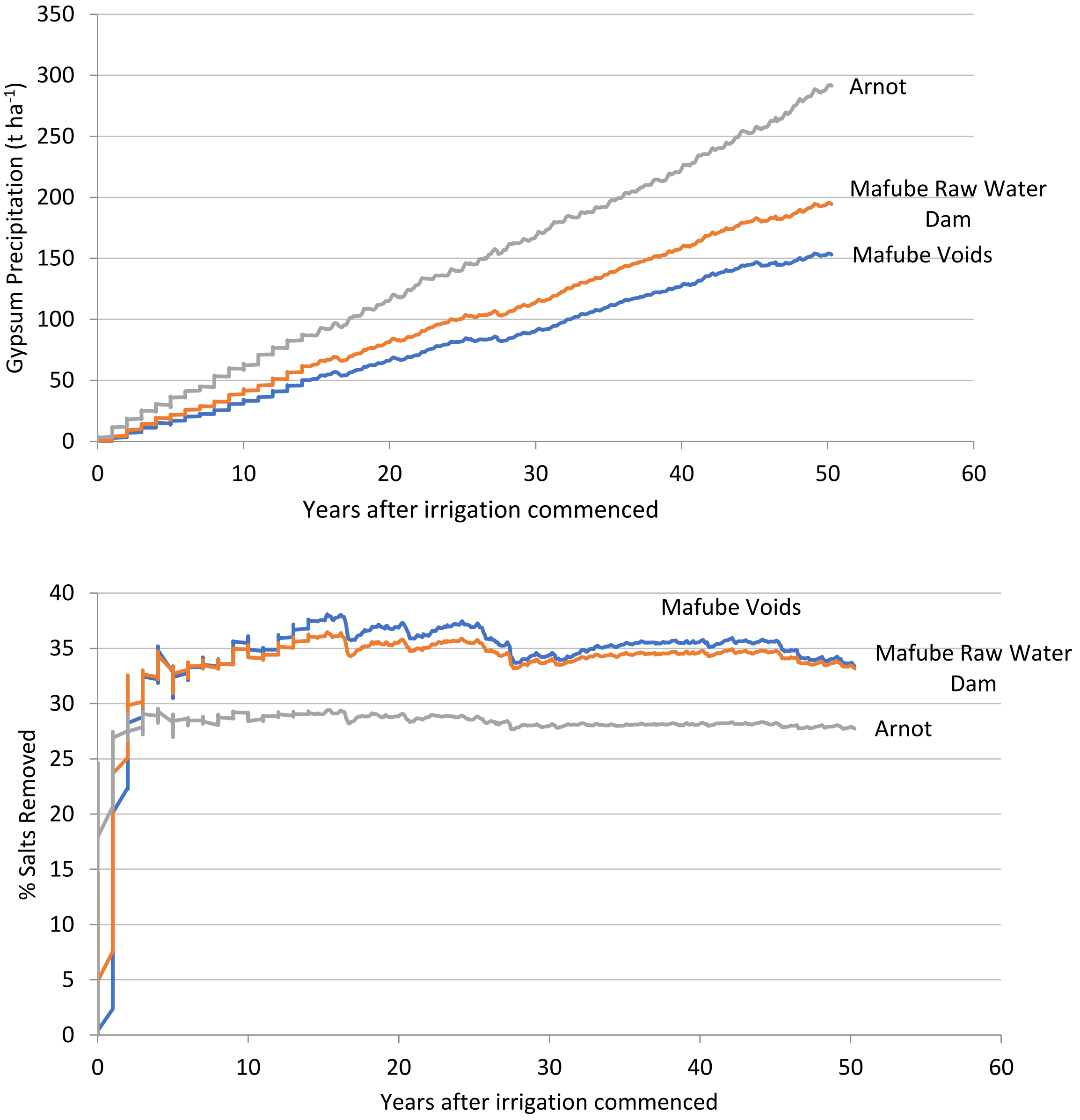

FIGURE 3.7: Gypsum precipitation (t ha^{-1}) and % salt removed as predicted by SWB over a 50-year period for three different water qualities

3.4 South African Water Quality Guidelines – DSS

A fitness for use assessment of a given water composition is obtained by running a 45-year simulation in the SAWQG (South African Water Quality Guidelines) model which uses a simplified version of SWB to make its predictions. A Tier 1 simulation is usually done first and considered a conservative and generic salt sensitive crop simulation that will highlight potential problems, and Tier 2 is a more site-specific (soil, weather, crop, irrigation system and management) simulation where the factors are used to determine if there are circumstances under which the water will be rendered usable. All results can be seen in Appendix B2.

The mine water used, is untreated and pumped from one of the opencast voids (Void 3) and is mostly near neutral to slightly alkaline (pH 7.1), with a relatively low EC of around 200 to 300 mS m^{-1}. This range is acceptable according to the South African Water Quality Guidelines for irrigation (Du Plessis et al. 2017). The major cations include Ca at 235 mg L^{-1}, Mg at 160 mg L^{-1} and Na at 70 mg L^{-1}. Major anions include HCO_3 at 335 mg L^{-1}, Cl at 10 mg L^{-1}, and SO_4 at 1130 mg L^{-1}. The water also contains 3.5 mg L^{-1} N and 35 mg L^{-1} K. The trace elements that could be measured included Al at 510 ug L^{-1}, Mn at 390 ug L^{-1}, Fe at 110 ug L^{-1}, Zn at 40 ug L^{-1}, B at 225 ug L^{-1}, Co at 3.2 ug L^{-1}, V at 7.5 ug L^{-1} and F at 0.7 ug L^{-1}. As these waters contain high concentrations of Ca and SO_4^{2-}, precipitation of gypsum ($CaSO_4$) in the soil profile is highly likely. When gypsum precipitates in the soil, not only are these salts retained in the soil, it is also being kept out of the solution and thus reduces the salt load to surrounding water bodies.

The Tier 1 fitness-for-use assessment highlighted potential problems with regards to trace element accumulation. It shows that Mn (51 years) has the potential to accumulate to the threshold value in the topsoil in less than 100 years, if 1000 mm irrigation is applied per year. Tier 1 also indicates that a negligible reduction in yield due to salinity may be expected. The irrigation water is not corrosive, yet slightly scaling, but too an acceptable degree. There is a slight potential impact on leaf scorching due to Na. The contribution of NPK to the crop is deemed unacceptable for both N and K. When using the same water quality but running the more site-specific Tier 2 simulation with just maize, the accumulation of Mn is highlighted once again, with Mn taking 130 years to accumulate if an average of 400 mm irrigation is applied yearly. Once again, the contribution of NPK to the crop is deemed unacceptable for K. When using a maize and wheat crop rotation, these values change once again show Mn to accumulate in 43 years as the annual irrigation is estimated to be around 1200 mm. However, this states that this accumulation will take place with 1000 mm of irrigation per year. With a crop rotation, the likeliness of irrigating more than 1000 mm increases as, in this case, maize will use an average of 470 mm of irrigation per season and wheat will use 700 mm per season. The same can be said if soybean is used instead of maize, as the irrigation amounts per annum still exceeds 1000 mm. These simulations also indicated a potential problem with regards to K fertilization and applying more than what is required (or can be removed by the crop). Therefore, it emphasizes the importance of knowing the constituent loading, especially in terms of fertilization. It is important that the irrigator takes into account what is being added with the mine water irrigation, in order to adjust fertilisation programmes accordingly as this can potentially save fertilization cost. In addition, regular soil samples can help to identify any nutrient imbalances that may develop.

With a generic crop rotation, an average of 1000 mm of irrigation will be applied per year. Over a 50 year period, this would add 860 t ha^{-1} salt, of which 520 t ha^{-1} is leached, and 310 t ha^{-1} is predicted to precipitate as gypsum, about 40% of the salt added (FIGURE 3.8) . It would appear that Ca limits gypsum precipitation, as there is twice the amount of SO_4 than that required for precipitation with Ca, however, with an adjusted fertilization programme, precipitation can be increased and in turn the salt load to water bodies reduced. The EC_e (soil saturated paste EC) fluctuates between 100 and 300 ms m^{-1}, averaging just below 200 mS m^{-1} (FIGURE 3.9). This indicates that there is enough gypsum precipitation and leaching of excess salts to prevent the soil profile from becoming too saline. If the water quality deteriorates, maize may not be the best choice for summer production and may need to be replaced by a more salt tolerant crop like soybean.

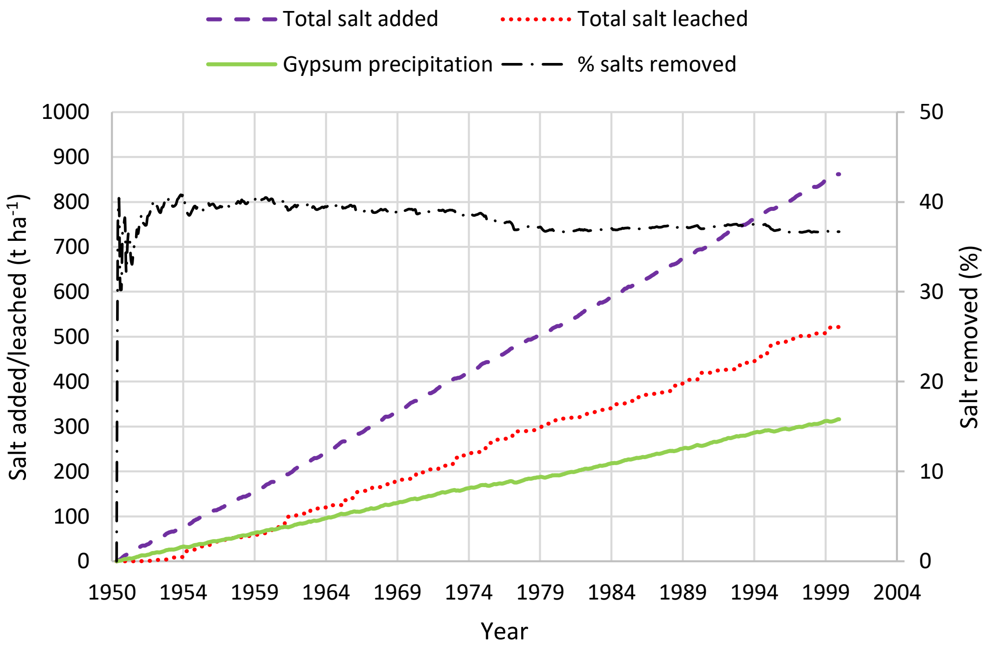

FIGURE 3.8: Total salt added (t ha^{-1}), total salt leached (t ha^{-1}), gypsum precipitation (t ha^{-1}) and % salt removed as predicted by the DSS over a 45 year period using historic weather data

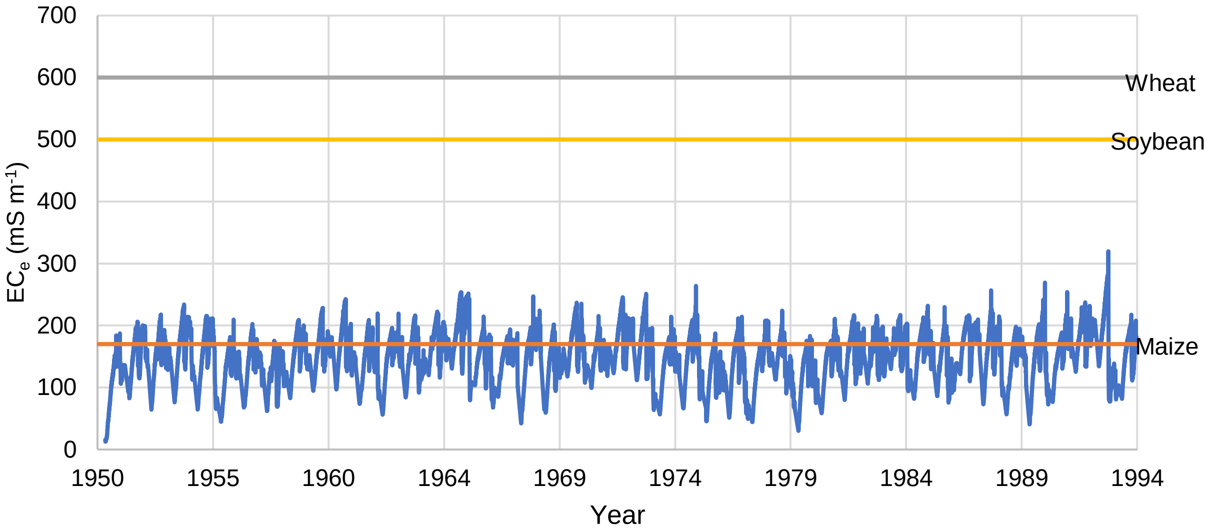

FIGURE 3.9: Soil profile salinity (EC_e in mS m^{-1}) predicted by the DSS for 45 years of irrigation of a maize-wheat rotation with saline sulphate mine water (Void 3) using historic weather data. Salinity thresholds (Maas and Hoffman 1977) for maize, wheat and soybean are also indicated

3.5 Conclusions

The results from this study show that not all of these mine waters are suitable for irrigation. However, when using models such as SWB and SAWQG-DSS, one can assess site-specific factors that influence the suitability of mine waters for irrigation. Careful monitoring of water quality, soil nutrient levels and food and forage safety are necessary to ensure feasibility. Irrigation with mine water over a long term can be viable, sustainable and feasible, if the appropriate management practices are in place. Another important aspect to look at, is crop response to sulphate salinity as majority of coal mine waters are sulphate dominated saline waters. This will be further discussed in Chapter 4.

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CHAPTER 4: SULPHATE SALINITY GROWTH RESPONSE OF TEMPERATE ANNUAL CROPS IN DIFFERENT GROWTH STAGES

4.1 Introduction

The majority of mine-affected waters contain large quantities of calcium and magnesium sulphate, with some dominated by sodium sulphate. The availability of large volumes of mine impacted waters and large tracts of unfarmed land owned by mines, creates an opportunity to utilise these waters for irrigation. Not only will this drastically reduce mine water treatment costs, it will create sustainable livelihoods and food production, particularly post-mine closure. The suitability of these waters for irrigation is dependent on the water quality, which is related to salinity, sodicity and toxicity (Hoffman et al. 1990). Research has shown that irrigation with saline waters does not substantially reduce crop yields unless the salinity threshold is exceeded (Jovanovic et al. 1998, Mentz 2001, Annandale et al. 2006). Salinity stress is not only related to the amount of salts in the solution, but also the conditions under which the crop is grown. Hoffman et al. (1990) stated that irrigating with salt-affected waters can yield high crop productivity, if appropriate management practices and favourable environmental conditions are in place. Climatic conditions such as temperature, relative humidity and air pollution play a significant role in crop response to salinity (Maas 1993). Plants are known to tolerate higher salinities in cool, humid conditions than in hot and dry conditions (Maas and Grattan 1999).

Traditionally crop tolerance to salinity is determined by using increasingly saline mixtures of Ca and Na chlorides. The aim of this investigation was to assess how selected cool season crops will respond to sulphate dominated saline solutions during three main growth stages, namely germination, seedling and early vegetative growth and to confirm the salt tolerance and response parameters for selected cool season crops in the three main growth stages to enable reliable water and salt balance modelling to support decisions around responsible mine water use. The salt *tolerance parameter* is referred to as the “threshold” value, and the *growth response parameter* once salinity exceeds the threshold, is referred to as the “slope” of the yield reduction response (FIGURE 4.1). The threshold refers to the maximum salinity level that will not reduce growth (compared to non-saline, control conditions), and the slope refers to the percentage reduction in relative growth per unit increase of electrical conductivity of a saturation paste extract (EC_e) beyond the threshold (Maas and Grattan 1999).

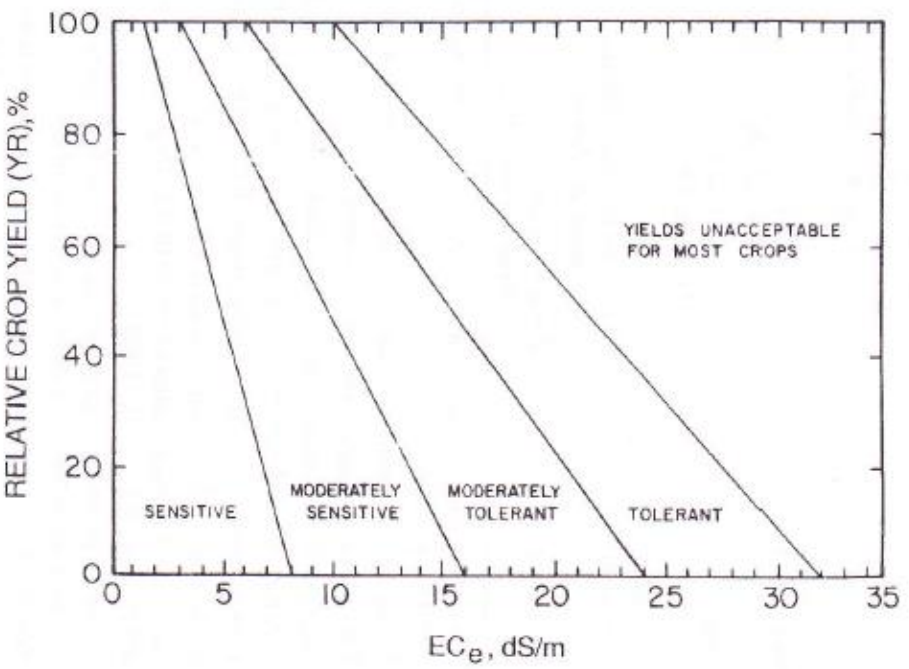

FIGURE 4.1: Slope-threshold graph displaying the relative yield percentage as it decreases with increasing salinity (Maas and Grattan 1999)
Note 1 dS m^{-1} = 100 mS m^{-1}

4.2 Materials and methods

Five crops were evaluated. These included temperate annual pastures and cereal small grain crops, namely barley, oats, stooling rye, annual ryegrass and wheat (TABLE 4.1). The published salinity threshold (TABLE 4.1) of each of these crops were taken into consideration when determining salinity treatments, in order to span the expected threshold EC and develop a reliable relationship between relative yield and salinity. The published EC_e thresholds of these crops range from 300 to 1200 mS m^{-1}, depending on whether yield is based on grain or shoot dry mass (if used as forage). Thresholds based on grain yield tend to be higher, as most plants become increasingly tolerant as they mature, with plants more susceptible to the effects of salinity before reaching the reproductive stage (Maas 1993). The published thresholds are based on the EC_e value, the EC of a saturated soil extract. In order to make a saturated soil paste, deionized water is added to soil until it “glistens”, indicating that all of the soil pores are saturated with water. Thereafter, soil solution is extracted, and the EC is measured, the so-called EC_e with the subscript e for ‘extract’. Another standard method for measuring soil EC is by making a 1:5 soil to water suspension and converting the EC measured on this solution into an estimated EC of a saturation paste extract (EC_e) by multiplying with a factor that takes soil texture into account (Hughes et al. 1994, Khorsandi and Yazdi 2011). The EC_e is equal to approximately half of the soil solution EC (Marschner 1986, Maas 1993) on the assumption that soil water content at field capacity is about half that at saturation. The assumption made in selecting salinity levels for this trial (that used water culture) was that soil solutions of the experiments in which the published thresholds were reported (which used sand cultures), would typically be diluted by adding an equal amount of water to what was already in the soil, to achieve the saturated water content. Therefore, it is important to ensure that salinities in this trial would span at least double the published EC_e threshold values and were concentrated enough to ensure a few data points beyond the threshold in order to ascertain slope values. The selected EC range was therefore from 130 to 4000 mS m^{-1} (TABLE 4.3).

TABLE 4.1: Summary of the five crops used for this trial, including the variety, published EC threshold and salinity tolerance rating

Common name	**Scientific name**	**Variety**	**EC_e threshold (mS m^{-1})** (Maas and Grattan 1999)	**Slope (% yield decrease per dS m^{-1} increase)** (Maas and Grattan 1999)	**Rating** (Maas and Grattan 1999)
Annual Ryegrass	*Lolium multiflorum*	Forage Max, Kikuyu Companion mix	560 - 760	7.6	Tolerant
Barley	*Hordeum vulgare*	Overture	600 – 800	5.0	Tolerant
Oats	*Avena sativa*	Majoris	330 – 450	-	Moderately Tolerant
Stooling Rye	*Secale cereale*	Agriblue	760 – 1140	10.8	Tolerant
Wheat	*Triticum spp.*	PAN3471	450 – 600	7.1	Tolerant

The method used for this trial was adapted from Barnard et al. (1998). They used water culture and catered for the evaluation of the effect of salinity on different growth stages of a crop. These growth stages were germination, seedling establishment and vegetative growth. Most cereal crops show a severe decrease in relative yield during the vegetative growth and early reproductive stages (flag leaf and ear emergence) and are not particularly sensitive during the flowering stage. It has also been stated in literature that with an increase in salt concentration there is a reduction in germination.

In the Barnard et al. (1998) study, simulated mine waters were used to achieve different levels of sulphate salinity. The salinity levels selected ranged from 100 to 840 mS m^{-1}. Although they reported a 10% decrease in relative yield, these selected salinities were probably too low, and would not have exceeded the published EC_e threshold values as these values need to be halved to compare it to published threshold values (TABLE 4.1). The use of these low salinity values weakens the usefulness of their findings, as most of the reported results were found to be non-significant between treatments and the slope-threshold graphs showed an erratic pattern (some values were found to exceed 100% relative growth) and did not follow the expected trend (FIGURE 4.1). Their reported threshold values at a ten percent decrease in yield were found to be between 260 and 350 mS m^{-1} for annual ryegrass, 310 and 350 mS m^{-1} for barley, 260 and 330 mS m^{-1} for oats, 260 and 340 mS m^{-1} for stooling rye, and 330 and 340 mS m^{-1} for wheat. These values are all quite similar and do not correlate with the published thresholds for these crops, especially considering that their values need to be halved to make the comparison with EC_e, resulting in these values still being lower and even more unrealistic.

For this trial, instead of using a simulated mine water, a combination of a nutrient solution, gypsum ($CaSO_4.2H_2O$) and Epsom salt ($MgSO_4.7H_2O$) was used to make up the salt solutions for each target EC (TABLE 4.3). Using Mg and Ca dominated sulphate waters can be linked to mine waters used for irrigation, as these waters (specifically coal mine waters) contain more SO_4 than Cl. Normally, slope-threshold experiments are based on Na or CaCl as the source of salinity. This becomes problematic, as both sodium (Na^+) and chloride (Cl^-) can lead to toxicity effects in plants. These effects include a retardation of growth, decrease in photosynthetic capacity and interference in the uptake of other nutrients (Tavakkoli et al. 2010). Du Plessis (1983) stated irrigating with a calcium sulphate water will result in a lower soil salinity than with chloride water as the precipitation of gypsum in the soil will effectively lower the soil salinity. It is important to know that high magnesium (Mg) levels can also affect plant growth, and this needs to be taken into account when interpreting the results of this trial. One way that high Mg levels can affect plant growth, is by interfering with the uptake of other nutrients such as calcium (Ca) and potassium (K) (Kobayashi et al. 2005).

All treatments received a nutrient solution (TABLE 4.2) that is based on a half strength Hoagland (1920) solution. The amount of calcium, magnesium and sulphate present in the growth solutions (either a part of the half Hoagland nutrient solution or added as calcium or magnesium sulphate to achieve the target EC for the different treatments) and the average EC measured during experiments, are presented in TABLE 4.3. The first treatment, the lowest EC level, consisted of only the nutrient solution mixture and serves as the control in this trial, at which maximum yields were expected. The second treatment consisted of the nutrient solution, as well as the addition of $CaSO_4$. The remaining three treatments consisted of the nutrient solution, $CaSO_4$ and different levels of $MgSO_4$ to achieve the desired EC levels. Nutrient solution was used to ensure that there were no nutritional deficiencies and the concentrations were selected carefully as to not exceed the expected threshold values.

The salt concentrations that were required, were calculated by using a hydrochemistry software tool, Aqion (www.aqion.de). This aided in the determination of the solution EC (based on the ionic strength) and the probability of mineral precipitation (based on saturation indices). When using only $CaSO_4$, it is highly probable that precipitation will occur as the concentration increases. According to calculations done in Aqion, gypsum ($CaSO_4.2H_2O$) is only soluble until it reaches concentrations of around 2300 mg L^{-1}, thereafter it starts becoming insoluble (with a saturation index of more than 1) and is more likely to precipitate. This is also the reason that $CaSO_4$ dominated waters are preferred for irrigation. The maximum EC that can be achieved by using only $CaSO_4.2H_2O$ is around 200 mS.m^{-1}. However, a combination of the nutrient solution and the proposed amount of $CaSO_4.2H_2O$ added, should give an EC between 300 and 400 mS m^{-1}, as the nutrient solution used in this trial has an estimated EC of 100 to 150 mS m^{-1}. The amount of calcium, magnesium and sulphate present in the growth solutions (either a part of the half Hoagland nutrient solution or added as calcium or magnesium sulphate to achieve the target EC for the different treatments) and the average EC measured during experiments, are presented in TABLE 4.3.

TABLE 4.2: Composition of a nutrient solution based on a half strength Hoagland (1920) solution

Element	**Solution concentration (mg L^{-1})**	**Element**	**Solution concentration (ug L^{-1})**
Ca	66.4	Fe	752.4
N	87.6	Mn	179.4
P	25.2	Zn	89.4
K	124.8	Cu	13.2
Mg	18	B	223.8
S	38.4	Mo	22.2

TABLE 4.3: Summary of the treatments applied. Measured EC and the applied salt concentrations to make the solutions are shown

	Treatment				
	1	**2**	**3**	**4**	**5**
		Germination			
Half Hoagland	Added	Added	Added	Added	Added
Ca (mg L^{-1})	98	460	380	360	340
Mg (mg L^{-1})	26	35	1100	5010	10500
SO_4 (mg L^{-1})	150	1360	5150	16980	40720
Average EC (mS m^{-1})*	**140**	**260**	**640**	**1560**	**2950**
		Seedling establishment			
Half Hoagland	Added	Added	Added	Added	Added
Ca (mg L^{-1})	90	210	190	150	140
Mg (mg L^{-1})	29	34	930	3500	7070
SO_4 (mg L^{-1})	160	490	3970	12750	25150
Average EC (mS m^{-1})*	**120**	**220**	**580**	**1430**	**2500**
		Vegetative growth			
Half Hoagland	Added	Added	Added	Added	Added
Ca (mg L^{-1})	81	121	108	116	106
Mg (mg L^{-1})	27	26	650	3090	7150
SO_4 (mg L^{-1})	150	240	3050	11500	26860
Average EC (mS m^{-1})*	**130**	**150**	**480**	**1200**	**2400**

*Note: * Measured and averaged for the growth period of the specific stage*

4.2.1 Experimental design and setup

<u>Part one: Germination</u>

The effect of sulphate salinity on germination was determined using the paper roll method. Rolls were prepared by cutting three same sized brown paper sheets per treatment, with two white absorbent paper sheets placed on each brown paper sheet. A total of 50 seeds per crop were placed on each absorbent paper sheet (FIGURE 4.2A) and were sprayed with the respective treatments (FIGURE 4.2B) before they were rolled uniformly and placed in a growth chamber. The growth chamber was kept at a constant temperature of ~25°C to make sure all treatments experience the same temperature (FIGURE 4.3).

Paper rolls were left undisturbed for the first four days. The number of seeds germinated was then counted to check if germination had taken place and were placed back in the growth chamber for a further eight days. After twelve days, the final germination percentage was determined. This was done by counting the number of seeds that had successfully germinated and dividing this by the total number of seeds in the roll. A seed is counted as successfully germinated when the radicle (root) has emerged, and the radicle length exceeds 2 cm.

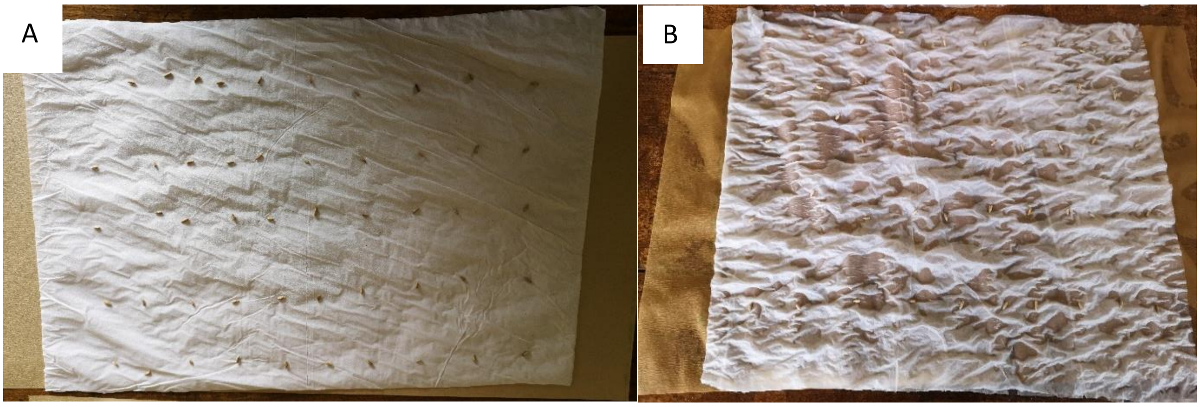

FIGURE 4.2: a) Stooling rye seeds placed on a prepared paper roll, b) Wet paper roll after treatment solution was applied

FIGURE 4.3: a) Folded bag with replicates together in one bag, b) Upright bags in a growth chamber with a temperature sensor

Part two: Seedling establishment

Seeds were planted in seedling trays that contained a vermiculite medium (FIGURE 4.4A) and kept moist with tap water until emergence. The seedling trays were placed in a glasshouse with a constant temperature of ~22°C and covered with a thin, clear plastic sheet, to ensure high humidity (FIGURE 4.4B). Seedling trays were opened to allow for aeration and watered (with tap water) if necessary. Four days after planting, as seedlings started to emerge, the clear plastic was removed. At this stage, no treatment was applied because the main aim was to grow seedlings that would be used for both the seedling and vegetative growth stage. After seven days, nearly all seeds were fully emerged, and seedlings were watered (with tap water) twice a day until day 14 when all seedlings were transplanted (FIGURE 4.5A) into hydroponic containers (FIGURE 4.5B).

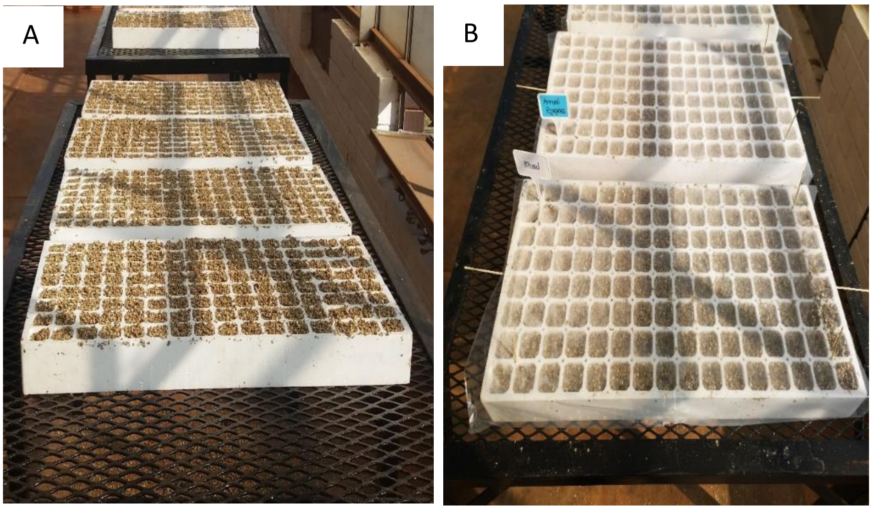

FIGURE 4.4: a) Seedling trays filled with vermiculite, b) Seedling trays after planting covered with a clear thin plastic sheet

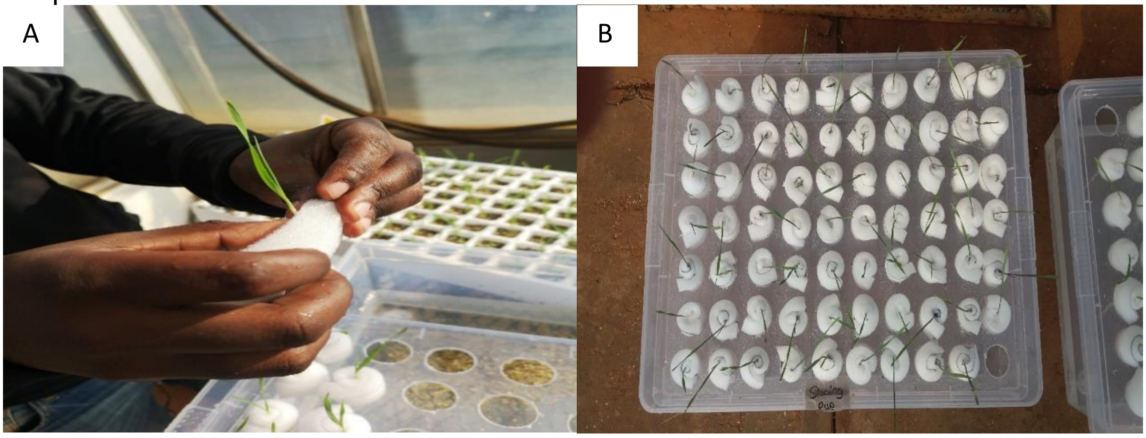

FIGURE 4.5: a) Seedlings secured using a foam strip before being transplanted into b) Plastic hydroponic containers

The seedlings were secured in these containers so that only the lower portion of the roots system was in contact with the solution (FIGURE 4.6A). The containers were placed on a rotating table so that all seedlings were exposed to the same radiant environment to minimize variation (FIGURE 4.6B). The solutions were aerated for 3 minutes every 30 minutes by means of a timer activated air pump. Aeration of solutions is essential, as it supplies the roots with oxygen which is required for respiration and healthy growth. Each treatment was replicated three times (three containers per treatment) and each container had five different crops (barley, oats, annual ryegrass, wheat and stooling rye) with 10 -15 plants of each crop per container.

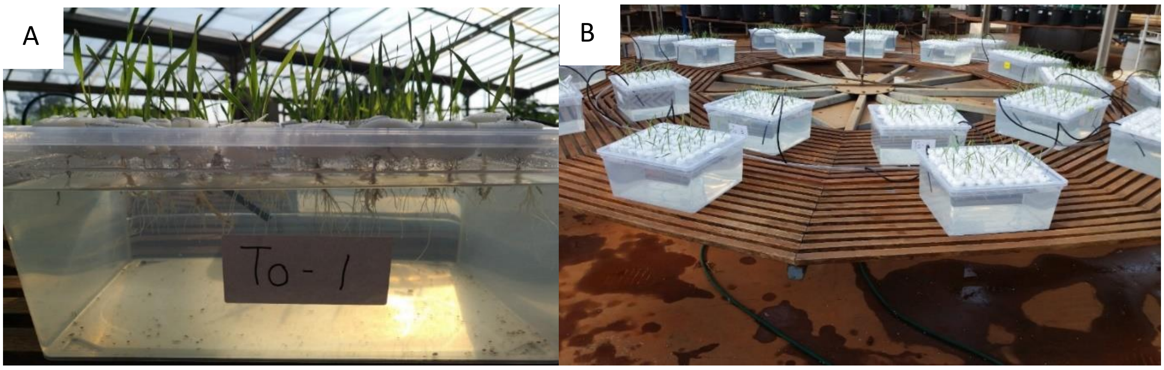

FIGURE 4.6: a) Portion of root system in contact with solution, b) Containers arranged on rotating table with aeration pipes connected

The EC was measured daily using an EC meter, and treatment solutions were changed once a week. Concurrently, seedlings were grown for the vegetative growth stage trials, and these were also transplanted into the plastic hydroponics containers but only received nutrient solution. The seedling growth stage lasted for about three weeks from transplanting until they were harvested. At harvest, the shoots and roots were dried to determine respective dry masses, as well as root to shoot ratios. Relative growth (%) was calculated by dividing the shoot dry mass of a treatment by the shoot dry mass of the control. Shoot dry mass was calculated by combining the mass of the 10 plants per rep.

<u>Part three: Vegetative growth</u>

Seeds were germinated in vermiculite and transplanted into plastic containers and received only nutrient solution (replaced weekly) for the first three weeks (FIGURE 4.7). This was done in the same glasshouse that was used for the seedling establishment and growth trial.

FIGURE 4.7: Oat seedlings that received only nutrient solution before being transplanted a second time

After three weeks, the plants were once again transplanted, this time into larger 10-litre hydroponic pots (FIGURE 4.8A). These were lined with plastic bags and fitted with a plastic cover with holes in it to make space for the plants. Pots were arranged randomly on a rotating table following a randomized complete block design (RCBD) (FIGURE 4.8B). Each treatment was replicated three times with three plants per pot. Treatments were aerated for three minutes every 30 minutes by means of a timer activated air pump with the aim of providing oxygen to the roots. A daily EC measurement (represents peak EC for the daily cycle) was made to keep track of any fluctuations and thereafter the water level was topped up with tap water to a predetermined level. Solutions were replaced weekly.

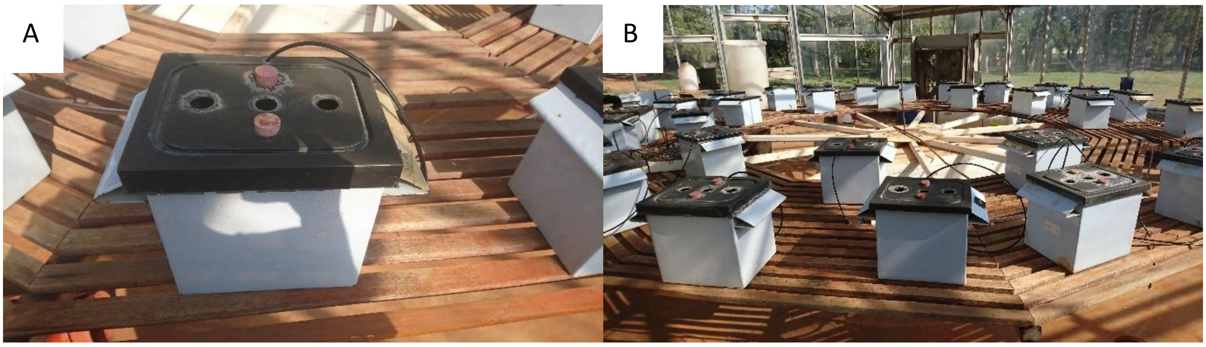

FIGURE 4.8: a) Hydroponic pot setup, b) Rotating table with aeration pipes connected to main air compressor

After four to six weeks of treatment (70 to 85 days after planting), the top and root growth was harvested. After determining dry mass, the root to shoot ratios were calculated and samples were milled and acid digested to determine elemental composition by atomic absorption spectrophotometric techniques. The elements considered for analysis included phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), and sulphur (S) as sulphate (SO_4). These elements were analysed to verify that the effects noted were due to salinity and not any nutritional imbalances. Relative growth (%) was calculated by combining the shoot mass of 3 plants.

4.2.2 Statistical analyses

The statistical analyses for all experiments were done using the computer package Statistical Analysis Software (SAS) using the General Linear Model (GLM) procedure which fitted linear models to the data to determine statistical differences. Asterisks indicate significant (*) and highly significant (**) differences from the control as indicated in the respective tables. Microsoft Excel was used for all calculations and creating visual representations (graphs) of the data.

4.3 Results and discussion

4.3.1 Germination

Although most crops are more tolerant during germination and only become more susceptible during the early developmental stages (Maas and Grattan 1999), the germination percentage was affected by different concentrations of sulphate salts (TABLE 4.4). There was no significant difference in germination percentage between the initial and final germination measurements for all treatments, and therefore this is not shown in TABLE 4.4. Of all the crops, wheat was the most tolerant to salinity stress during germination, as it had the highest germination percentage (64%) at an EC of 2950 mS m^{-1}. Stooling rye was the second most tolerant, although only 11% of the seeds germinated at this salinity level, with no barley, oat or annual ryegrass seeds germinating. The decrease in seed germination as salt concentration increased could be due to an increase in osmotic stress (Bernstein 1975), which prevents seeds from absorbing enough water to drive germination. These findings are in agreement with the results of Shahri et al. (2012) and Shahri et al. (2015), who observed that increasing salt concentration leads to a decrease in germination percentage. These results also support the findings of Francois et al. (1989) who reported that an EC of more than 700 mS m^{-1} (in this case the third lowest salinity level) will affect germination significantly. The results, furthermore, seem to confirm that seeds at germination are more tolerant to salinity than at maturity. When the results of TABLE 4.4 and TABLE 4.7 are compared it is clear that the crops are at least as tolerant to salinity during germination as at maturity.

TABLE 4.4: Salinity response of the germination stage for all crops and treatments

Crop	Treatment EC (mS m^{-1})	Germination %		Root length (cm)		Shoot length (cm)	
Annual Ryegrass	140	91		10		12	
	260	92		11		10	*
	640	91		11		10	*
	1560	64	**	9	*	9	**
	2950	0	**	0	**	0	**
Barley	140	82		15		21	
	260	83		16		20	
	640	95	*	15		19	
	1560	79		4	**	15	**
	2950	0	**	2	**	2	**
Oats	140	87		13		15	
	260	78	*	15		16	
	640	72	**	13		13	*
	1560	30	**	6	**	11	**
	2950	0	**	0	**	0	**
Stooling Rye	140	99		14		16	
	260	93		15		15	
	640	97		15	*	14	*
	1560	81	**	11	**	15	
	2950	11	**	2	**	4	**
Wheat	140	98		16		14	
	260	99		19	*	14	
	640	97		16		14	
	1560	99		7	**	11	**
	2950	64	**	0	**	3	**

*Note: * - significant difference (LSD>5%) compared to control of that species*
*** - highly significant difference (LSD>1%) compared to control of that species*

According to Jamil and Rha (2004), root and shoot tolerance to salinity is the most important trait to consider when considering growth in saline environments. A reduction in the absorption of water negatively affects cell expansion and lowers turgor, resulting in a reduction of the radicle (root) and plumule (shoot) length (Atak et al. 2006). Salinities exceeding 1560 mS m^{-1} show that there was a significant difference for both radicle and plumule lengths. When comparing radicle length (per crop species) between treatments, there was no significant difference between salinity levels below 640 mS m^{-1}, but above 1560 mS m^{-1} the differences were significant. Overall, barley had the longest average shoot length and wheat had the longest average root length. As the salt concentration increased, the roots and shoots did not just become shorter, they also changed colour. Roots became more opaque (compared to controls) and shoots yellowed (FIGURE 4.9) as salinity increased. The reduction in radicle and plumule length as salt concentration is increased could also be due to an increase in osmotic stress which reduced water absorption.

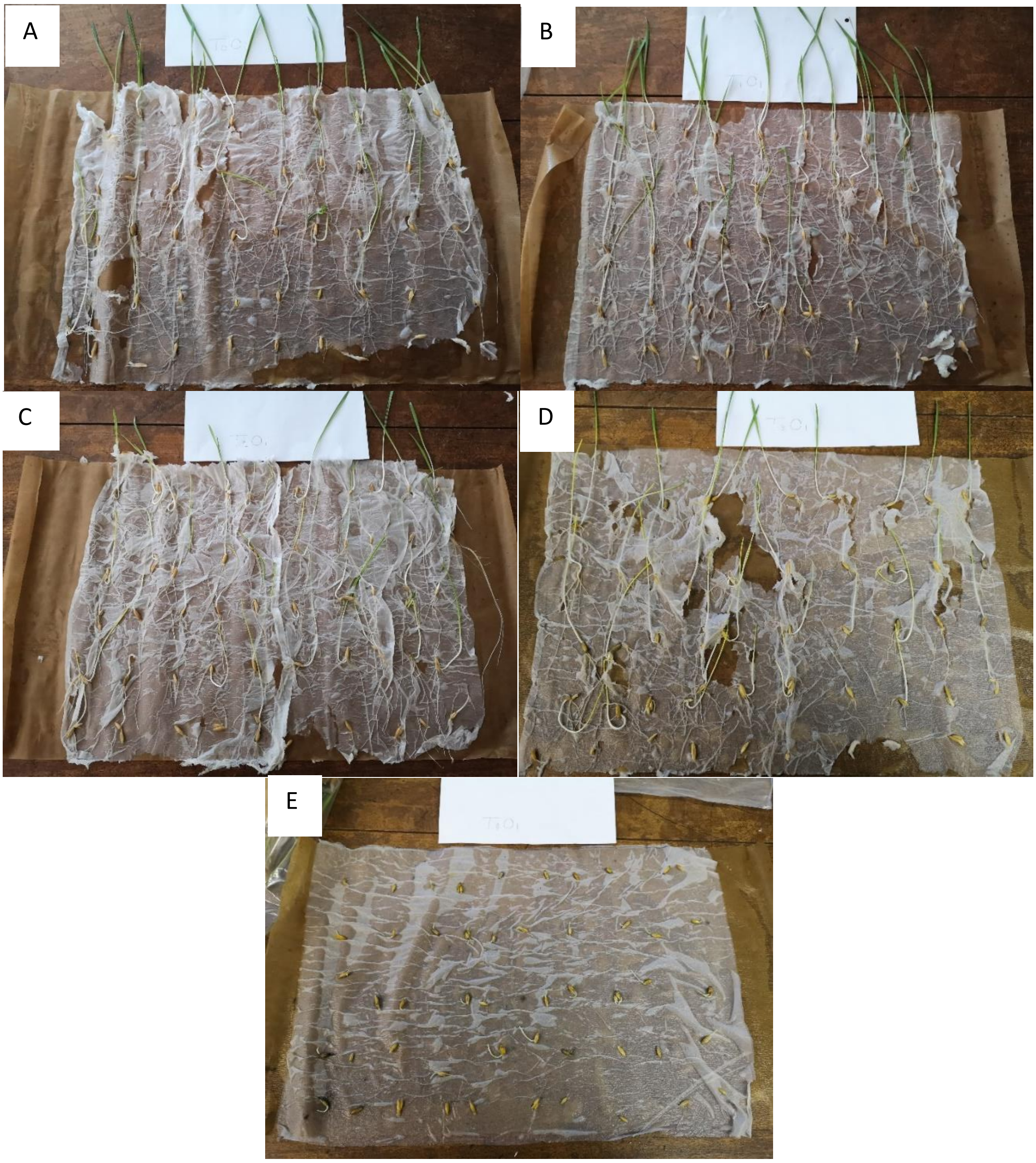

FIGURE 4.9: Oat germination after 11 days for each of the salinity treatments; a) 140 (control), b) 260, c) 640, d) 1560, and e) 2950 mS m^{-1}

4.3.2 Seedling establishment

FIGURE 4.10 shows the average EC as measured over the growing season for seedling establishment. The figure shows that at lower sulphate concentration (EC_{140}, EC_{260} and EC_{640}), there was less variation in EC between the highest EC and the lowest EC level of that treatment. This is due to a concentration effect. After the solutions are replaced, the water content is at a maximum and the soluble salt concentration is at its lowest level. Plants have an adaptive mechanism which allows them to exclude excess salts when taking up water. As water is lost though evaporation and crop transpiration, most of the salts are excluded by the plant, leaving behind more salts in a reduced volume of water (Maas and Hoffman 1977), thereby concentrating the solution. Salt-stressed plants use a smaller percentage of water than non-saline plants (Maas and Grattan 1999) and at higher sulphate concentrations, there was a greater variation between the highest and the lowest EC measured, mainly due to evaporation and not due to the plant taking up water. The EC was measured before the daily top up, thus it is expected that these EC measurements are to be at a daily peak and therefore weekly measurements (after replacing the solutions) represents the lowest EC readings.

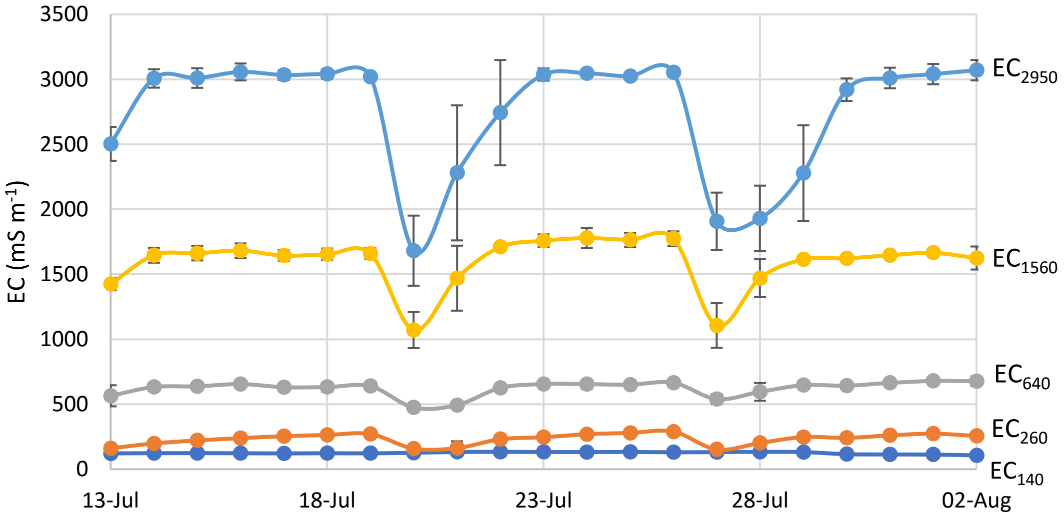

FIGURE 4.10: Average EC (mS m^{-1}) measured over the seedling establishment phase

Root to shoot ratios were significantly different for salinities exceeding 1430 mS m^{-1} compared to the control (FIGURE 4.11 and TABLE 4.5) and increased with an increase in salinity. Sharp et al. (2004) reported that under high salinity levels, different plants have shown a larger root dry mass than shoot dry mass, which is a mechanism used to improve the source/sink ratio for nutrients and water under saline conditions (Zekri and Parsons 1989). The effects of osmotic stress appear to be more severe on the shoots than on root growth, and this could be due to osmotic stress adjustment of roots in response to salinity. This is done to maintain adequate water uptake and to allow the plant the ability to take in enough nutrients.

TABLE 4.5 shows that there was no significant difference in plant height for salinities below 580 mS m^{-1}. On average, salinities below 220 mS m^{-1} recorded the highest average plant height. Salinities exceeding 1430 mS m^{-1} yielded plants that were at least 3 to 4 times smaller than the control. These findings show that increasing salt concentration can significantly reduce the height and mass of all the studied crops which is one of the most common effects of salinity (Maas and Grattan 1999). The results also show that salinity has an effect on the growth of all crops, as the shoot mass decreases significantly as the salt concentration increases. The reduction in growth could be related to osmotic stress which reduces uptake of water and nutrients, and negatively affects cell expansion which leads to a reduction in growth.

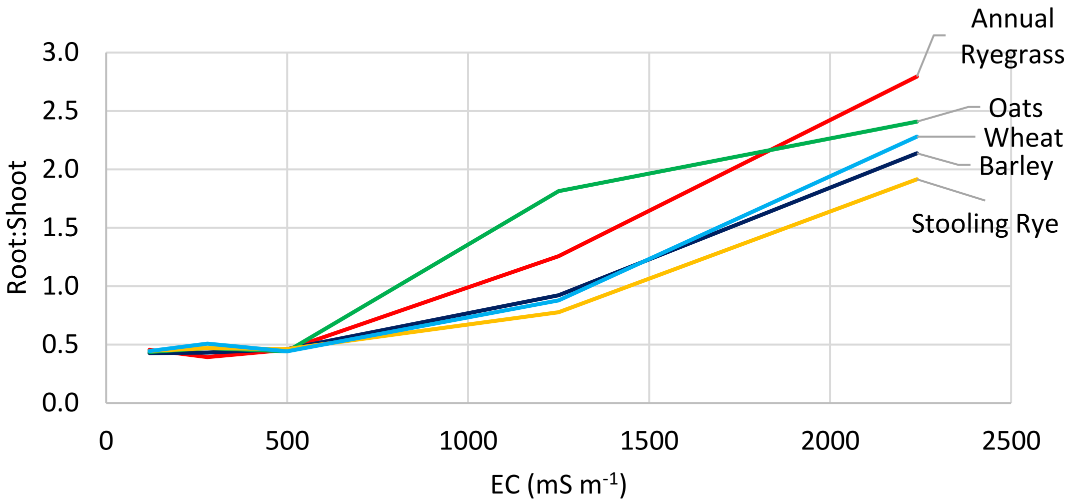

FIGURE 4.11: Root to shoot ratios as measured for seedling growth

TABLE 4.5: Growth parameters for the seedling establishment stage of annual temperate crops grown in sulphate rich waters

Crop	Treatment EC (mS m^{-1})	Plant height (cm)	Dry mass of roots (g)	Dry mass of shoots (g)	Relative top growth %	Root:Shoot
Annual Ryegrass	**120**	27	0.03	0.06	100	0.46
	220	28	0.03	0.07	115	0.39
	580	26	0.02	0.05	94	0.46
	1430	10 **	0.02 *	0.02 *	28 **	1.26 **
	2500	7 **	0.01 **	0.00 **	6 **	2.79 **
Barley	**120**	33	0.12	0.28	100	0.43
	220	36	0.14	0.34	129	0.43
	580	30	0.11	0.24	91	0.46
	1430	10 **	0.05 **	0.06 **	22 **	0.92 *
	2500	9 **	0.05 **	0.02 **	9 **	2.14 **
Oats	**120**	39	0.12	0.27	100	0.44
	220	37	0.12	0.26	97	0.47
	580	32 **	0.08 *	0.18 **	69 *	0.44
	1430	8 **	0.08 *	0.04 **	17 **	1.81 **
	2500	7 **	0.05 **	0.02 **	8 **	2.41 **
Stooling Rye	**120**	31	0.09	0.20	100	0.45
	220	31	0.10	0.21	101	0.47
	580	28 *	0.08	0.17	84 *	0.46
	1430	13 **	0.06 *	0.08 **	38 **	0.78
	2500	9 **	0.04 **	0.02 **	11 **	1.91 **
Wheat	**120**	33	0.10	0.23	100	0.44
	220	35	0.11	0.21	94	0.51
	580	31	0.09	0.22	98	0.44
	1430	11 **	0.06 **	0.07 **	31 **	0.88 **
	2500	7 **	0.05 **	0.02 **	11 **	2.28 **

*Note: * - significant difference (LSD>5%) compared to control of that species*
*** - highly significant difference (LSD>1%) compared to control of that species*

The difference in plant growth can be seen in FIGURE 4.12. Here it is clear that there is quite a significant difference as salinity increases. In FIGURE 4.12E, it can be seen that the plants showed signs of necrosis and showed a lower root density. As salinity increased, roots also turned yellow to dark brown, as opposed to the almost white colour of the control treatments. Plants started showing signs of necrosis after only one week of high salinity (EC > 640 mS m^{-1}) treatment.

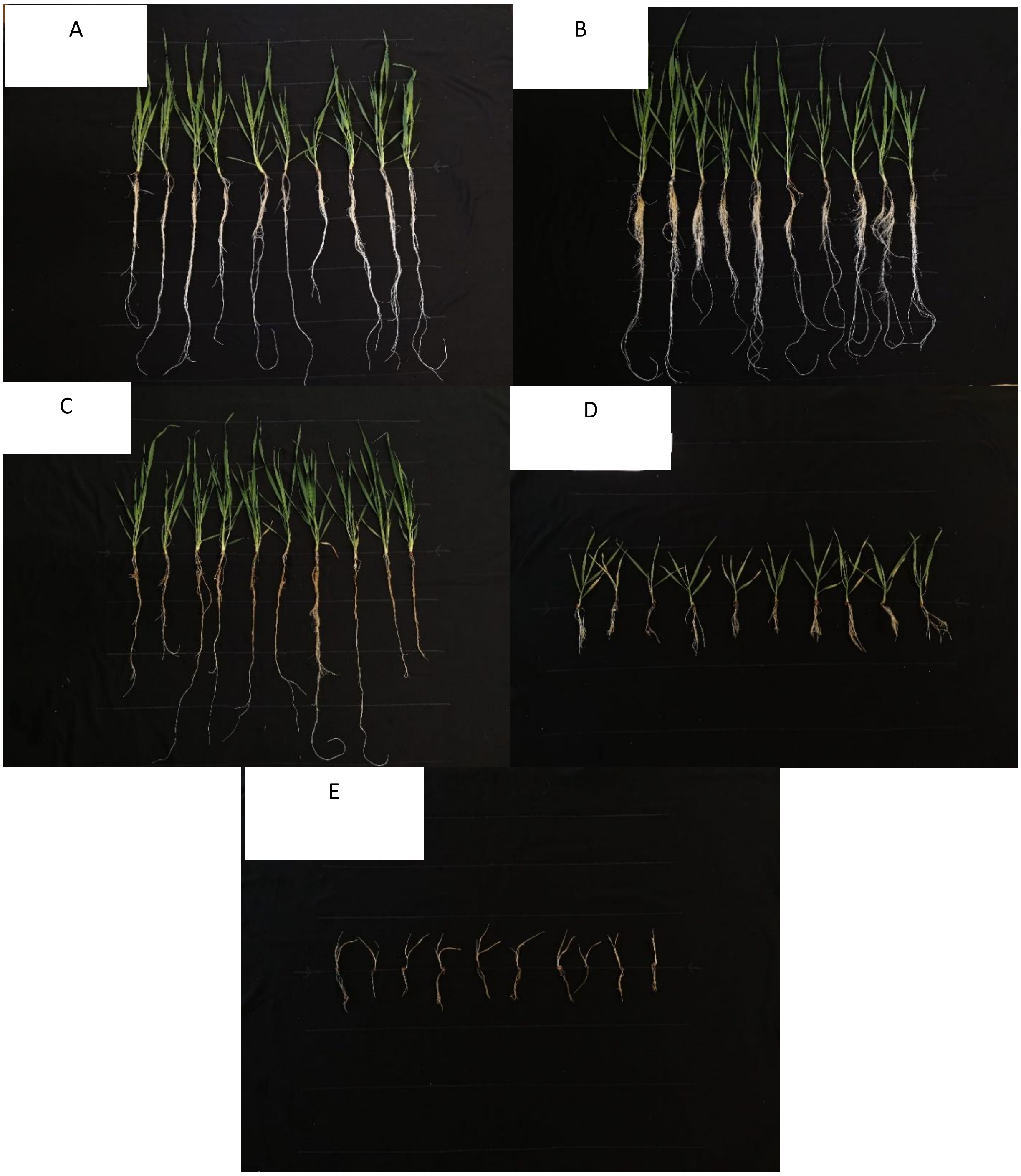

FIGURE 4.12: Wheat seedling growth as affected by an increase in salinity; a) 120 (control), b) 220, c) 580, d) 1430, and e) 2500 mS m^{-1}

To estimate the threshold and slope values, the Maas and Hoffman (1977) two-piecewise linear regression method was used. This estimates the relative yield or growth (Y_r) by using

$$Y_r = 100 - b\,(EC_e - a) \qquad (4.1)$$

where a is the salinity threshold (in dS m^{-1}) and b is the slope (% per dS m^{-1}). TABLE 4.6 shows the slope and threshold values for relative seedling growth of the different crops studied in terms of mS m^{-1} (1 dS m^{-1} = 100 mS m^{-1}) . FIGURE 4.13 also shows the crop response curve which is expected for crops under salinity stress. Barley was found to be the most salt tolerant during seedling growth and oats the least. EC_e was estimated by halving the treatment solution EC values as suggested by Marschner (1986) and Maas (1993).

TABLE 4.6: Salt tolerance parameters for seedling growth of annual temperate crops grown in sulphate rich waters

Crop	**Threshold Solution EC (mS m^{-1})**	**Threshold EC_e (mS m^{-1})**	**Slope % decrease per 100 mS m^{-1} (EC)**
Annual Ryegrass	272	136	6.3
Barley	435	218	8.4
Oats	48	24	6.3
Stooling Rye	248	124	5.5
Wheat	302	151	6.1

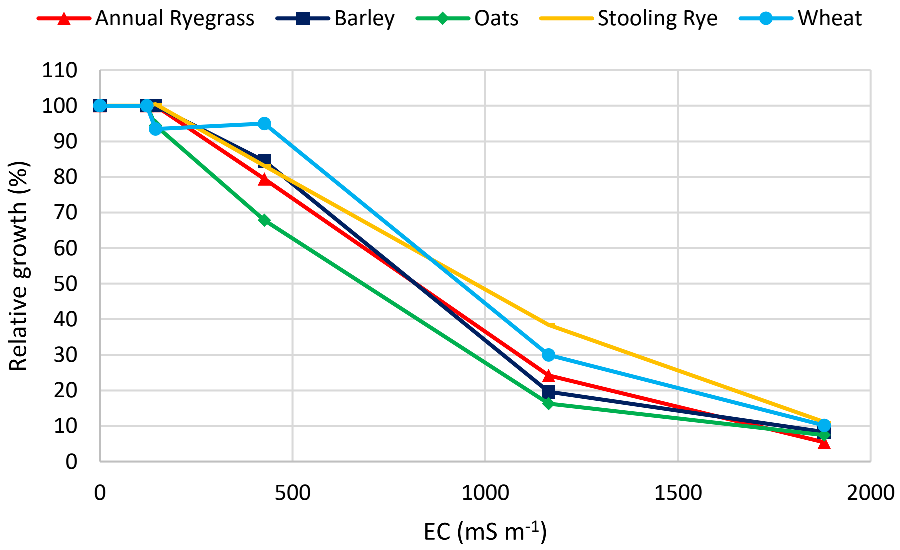

FIGURE 4.13: Crop growth response in the seedling stage for annual ryegrass, barley, oats, stooling rye and wheat

FIGURE 4.14 shows the individual growth response curves as measured compared to the published values. Oats is not shown as the slope and threshold values are unknown. Although the response curve follows the typical S-curve for observed data as discussed by Van Genuchten and Gupta (1993), it is clear that the measured values are far lower than the published values. This is as expected, as the published thresholds were obtained by measurements made during a later growth stage and thus cannot actually be compared to the findings of this investigation. However, the magnitude of the difference with published values for full cycle (mature) crops, are unexpected. There are several possible explanations for this result, as discussed below for the vegetative growth stage.

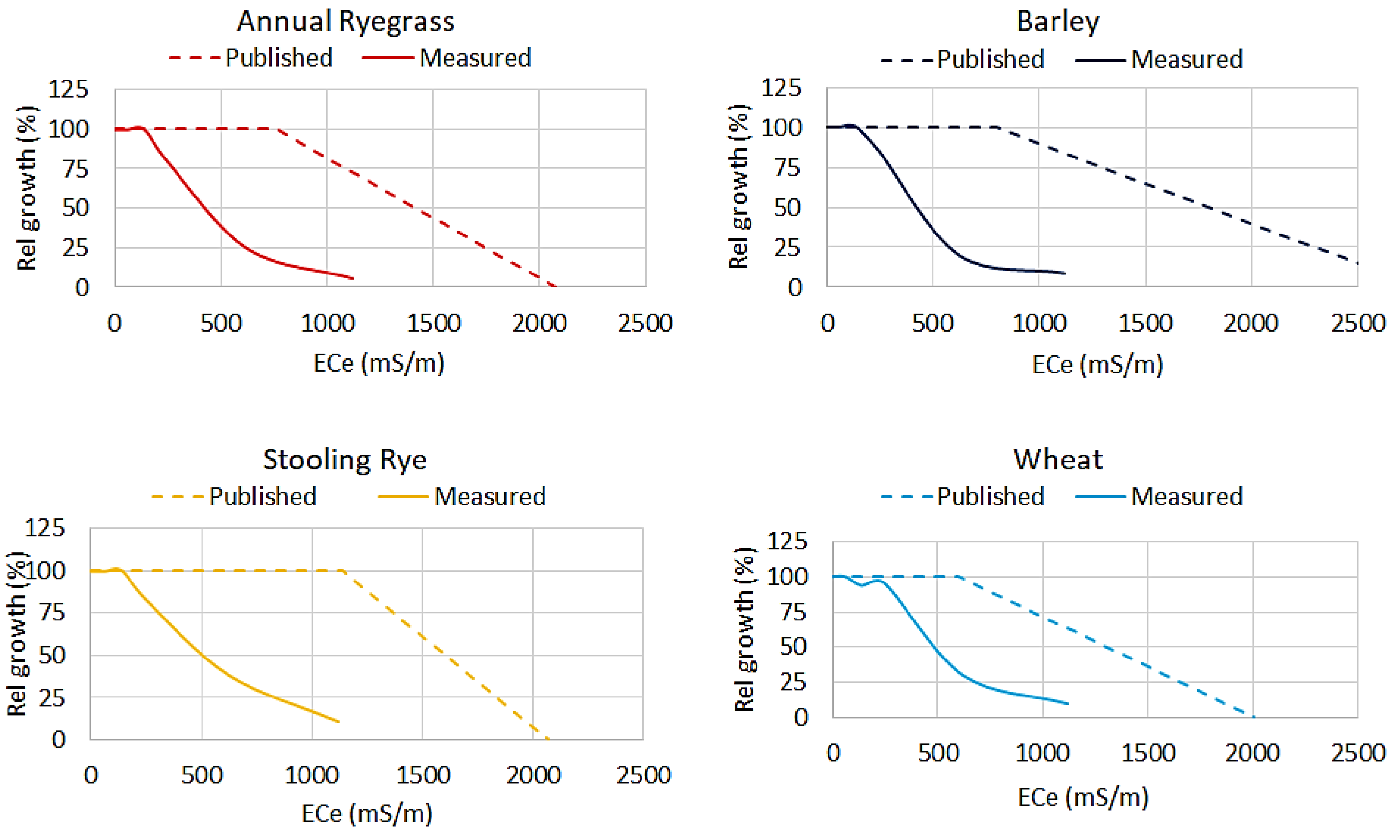

FIGURE 4.14: Slope-threshold graphs for annual ryegrass, barley, stooling rye and wheat showing the measured (seedling growth) and published values

4.3.3 Vegetative growth

FIGURE 4.15 shows the average EC as measured over the growing season for vegetative growth. The figure shows that at lower sulphate concentrations (EC_{120}, EC_{150} and EC_{480}), there was less variation between the highest EC and the lowest EC level of that treatment. The EC was measured before the daily top up, thus it is expected that these EC measurements are to be at a daily peak and therefore weekly measurements (after replacing the solutions) represents the lowest EC readings.

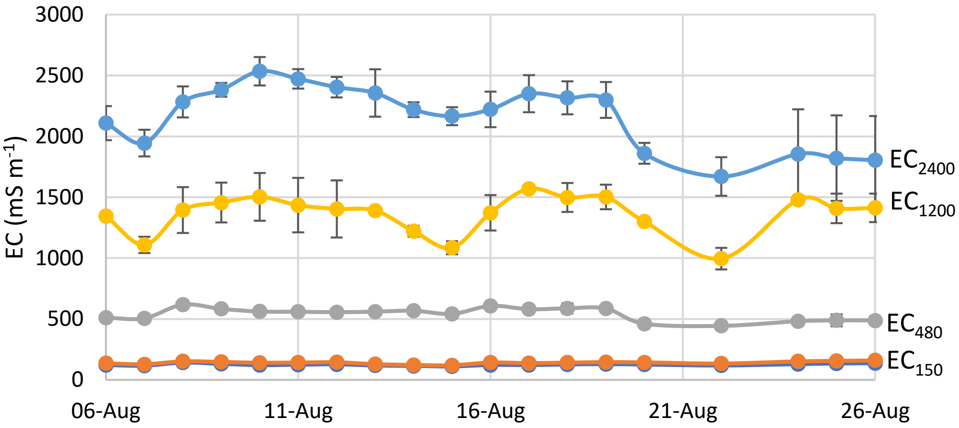

FIGURE 4.15: Average EC (mS m^{-1}) measured over the vegetative growth phase

Root to shoot ratios for salinities exceeding 1200 mS m^{-1} were significantly different from the control (FIGURE 4.16 and TABLE 4.7) except for stooling rye which showed no significant difference for any of the treatments. Overall, the root to shoot ratios increased with an increase in salinity. An increase in the root to shoot ratio is indicative of less favourable conditions (Harris 1992), such as salinity stress. The results also show that salinity has an effect on the growth of all crops, as the shoot mass decreases significantly as the salt concentration increases. The reduction in growth could be related to an increase in osmotic stress (Zeng and Shannon 2000) which reduces the uptake of water and nutrients (Grattan and Grieve 1999, Horie et al. 2012), thus negatively affecting cell differentiation and elongation, as well as leaf growth and expansion (Munns and Tester 2008) resulting in smaller plants. Plants regulate transpiration rates by opening and closing their stomata, however, under osmotic stress (induced by salinity) stomatal closure is stimulated resulting in a reduction in transpiration and photosynthesis (Jia et al. 2002, Hniličková et al. 2017). This reduces the overall carbon dioxide assimilation and the photosynthetic rate, which in turn negatively affects the growth and development of the plant (James et al. 2002, James et al. 2008).

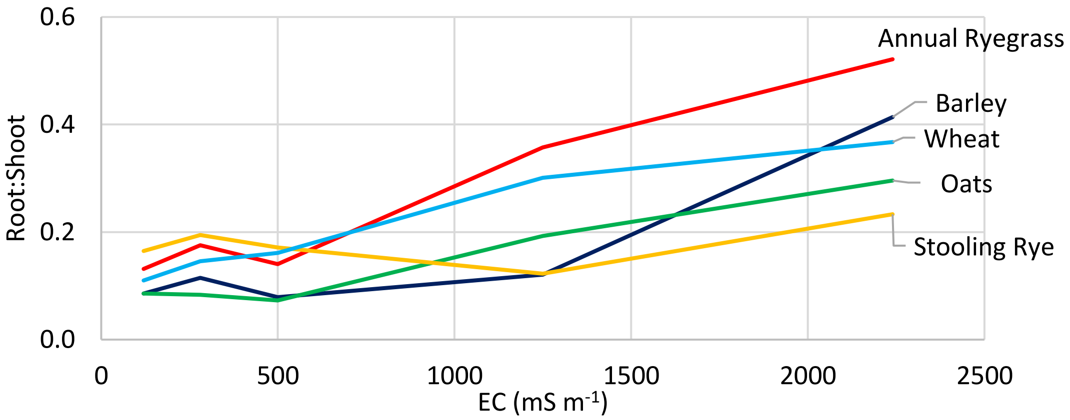

FIGURE 4.16: Root to shoot ratio measured for vegetative growth

TABLE 4.7: Growth parameters for the vegetative stage of annual temperate crops grown in sulphate rich waters

Crop	Treatment EC (mS m^{-1})	Dry mass of roots (g)	Dry mass of shoots (g)	Relative top growth %	Root:shoot
Annual Ryegrass	130	9.9	75.7	100	0.13
	150	10.7	61.0 **	81 *	0.18
	480	5.0 **	35.5 **	47 **	0.14
	1200	0.6 **	1.7 **	2 **	0.36 *
	2400	0.3 **	0.7 **	1 **	0.52 **
Barley	130	12.7	149.5	100	0.09
	150	15.4 *	134.0	90	0.12
	480	7.3 **	92.2 **	62 **	0.08
	1200	1.4 **	11.9 **	8 **	0.12
	2400	1.0 **	2.6 **	2 **	0.41 **
Oats	130	11.0	127.3	100	0.09
	150	10.3	122.7	96	0.08
	480	5.6 **	77.4 **	61 **	0.07
	1200	0.8 **	4.2 **	3 **	0.19 **
	2400	1.0 **	3.3 **	3 **	0.30 **
Stooling Rye	130	11.6	70.0	100	0.16
	150	12.3	64.2	92	0.19
	480	7.9 **	46.2 **	66 **	0.17
	1200	1.5 **	12.1 **	17 **	0.12
	2400	0.7 **	2.8 **	4 **	0.23
Wheat	130	5.0	46.0	100	0.11
	150	8.1 **	55.9	122 *	0.15
	480	5.8	37.1	81 *	0.16
	1200	0.8 **	2.6 **	6 **	0.30 **
	2400	0.8 **	2.3 **	5 **	0.37 **

Note: * - significant difference (LSD>5%) compared to control of that species
** - highly significant difference (LSD>1%) compared to control of that species

The differences in plant growth can be seen in FIGURE 4.17. Here it is clear that there is quite a significant difference as the salinity increases. In FIGURE 4.17E, it can be seen that the plants showed signs of necrosis at treatments exceeding an EC of 500 mS m^{-1}. The plants started showing signs of stress after two weeks of treatment. The differences for salinities below 480 mS m^{-1} were not as significant as for salinities exceeding 1200 mS m^{-1}.

FIGURE 4.17: Stooling rye vegetative growth as affected by an increase in salinity; a) 130 (control), b) 150, c) 480, d) 1200, and e) 2400 mS m^{-1}

Salinity causes elemental nutritional deficiencies or imbalances due to extreme ion ratios (such as Ca^{2+}/Mg^{2+}, Na^{+}/K^{+} and Ca^{2+}/Na^{+}) in solution. The resulting effects of salinity on nutrient imbalances include change in nutrient availability, uptake or distribution (Maas and Grattan 1999). TABLE 4.8 shows the elemental composition after plant (leaves) digestion. Although the P concentration decreased with an increase in salinity (except for barley and oats, where it increased), the differences were not as pronounced as for the other elements. Ca, Mg, K and Na concentrations were significantly affected with an increase in salinity. Ca concentrations decreased significantly as salinities exceeded 480 mS m^{-1} and the Mg concentrations increased. This is evidence that the effects observed cannot be solely related to salinity, as increased Mg clearly decreased Ca concentration which is known to happen if there is an excess of Mg (Kobayashi et al. 2005). This resulted in a higher Mg/Ca ratio, which not only interferes with the uptake of Ca (Kobayashi et al. 2005, Tuna et al. 2007) but can also affect uptake of other essential nutrients. K concentrations also decreased significantly as salinity (or rather Mg) levels increased, and this is also evident in a study done by Kobayashi et al. (2005). These levels are also far lower than expected as it is usually measured to be around 2% (Srinivasan et al. 2007) of the plant mass and not ~0.5% as in seen in this trial. This is another sign that the plants could have struggled due to a nutrient deficiency or that the abnormally high Mg content suppressed both Ca and K uptake and leads to a reduction in growth (Kobayashi et al. 2005). High SO_4 concentrations can also suppress nutrient uptake, like NO^{3-}, which is essential for plant growth (Martinez and Cerda 1989). The increased SO_4 concentration could reduce plant growth by limiting leaf expansion, reducing transpiration and slowing down photosynthesis (Munns 1993, Munns and Tester 2008).

TABLE 4.8: Elemental composition of dried leaves after the vegetative stage of annual temperate crops grown in sulphate rich waters

Crop	Treatment EC (mS m^{-1})	K (mg kg^{-1})	P (mg kg^{-1})	Mg (mg kg^{-1})	Na (mg kg^{-1})	Ca (mg kg^{-1})	SO_4 (mg kg^{-1})
Annual Ryegrass	130	385	99	52	13	101	129
	150	375	83	32	14	113	137
	480	289 *	76 *	125	9	44 **	197
	1200	175 **	46 **	493 **	13	26 **	1392 **
	2400	249 **	64 **	567 **	15	39 **	1775 **
Barley	130	290	59	32	16	126	141
	150	254 *	51	35	9 *	237 *	301
	480	193 **	53	147 *	5 **	48 *	355
	1200	252 *	68	276 **	9 *	25 *	777 **
	2400	320	74 *	451 **	20	52	1416 **
Oats	130	277	46	27	12	66	104
	150	277	47	22	9 *	86 *	119
	480	196 **	52	164	5 **	40 *	428
	1200	206 **	61 **	484 **	13	36 **	1480 **
	2400	200 **	53	722 **	12	35 **	2236 **
Stooling Rye	130	307	52	47	5	118	117
	150	292	65	32	4	130 **	129
	480	284	68	144	3	38 **	278
	1200	197 **	79 *	265 *	4	23 **	642
	2400	193 **	49	567 **	9 *	33 **	1741 **
Wheat	130	215	70	40	3	61	104
	150	184	60	35	3	98 *	178
	480	173 *	72	143 *	2	33 *	371
	1200	233	67	553 **	9 **	44	1734 **
	2400	247	66	682 **	11 **	39	2097 **

*Note: * - significant difference (LSD>5%) compared to control of that species*
*** - highly significant difference (LSD>1%) compared to control of that species*

TABLE 4.9 shows the slope and threshold values for relative seedling growth of the different crops studied. FIGURE 4.18 also shows the crop response curve which was obtained for crops under salinity stress. Wheat was found to be the most salt tolerant during seedling growth and oats was found to be the least salt tolerant during vegetative growth. The previously published threshold values are much higher than the thresholds found in this experiment, and could be due to the growth medium, high sulphate concentrations, average growth temperature, or time of year when the experiment was carried out.

TABLE 4.9: Salt tolerance parameters for vegetative growth of annual temperate crops grown in sulphate rich waters

Crop	Threshold EC (mS m^{-1})	Threshold EC$_e$ (mS m^{-1})	Slope % decrease per 100 mS m^{-1}
Annual Ryegrass	176	88	8.3
Barley	30	15	6.6
Oats	21	11	6.9
Stooling Rye	45	23	6.4
Wheat	247	124	9.9

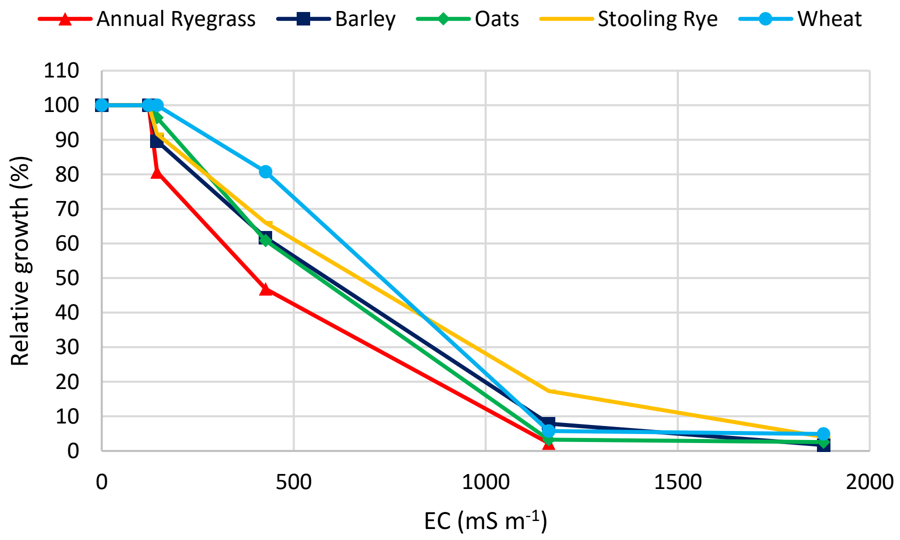

FIGURE 4.18: Crop growth response of annual temperate cereal crops in the vegetative stage

FIGURE 4.19 shows the individual growth response curves as measured compared to the published values. Oats is not shown as the slope and threshold values are unknown. As mentioned before, the response curve follows the typical S-curve for observed data, and again the measured values are far lower than the published values. It is worth mentioning that the typical piecewise linear threshold-slope model as described by Maas and Hoffman (1977) is known to be variety-specific, as well as dependent on various factors like the soil type, environmental conditions (temperature and humidity), and water management practices (Van Genuchten and Gupta 1993). Thus, simply comparing measured values from this investigation to published values is not a reliable practice as the outcome is limited due to multiple role-playing variables. Van Genuchten and Gupta (1993) also stated that there is certain discrepancies at higher salinities which leads to a so-called ‘tailing phenomena’ that can be found in many salt tolerance data sets and thus simply cannot be described with the piecewise linear threshold-slope model.

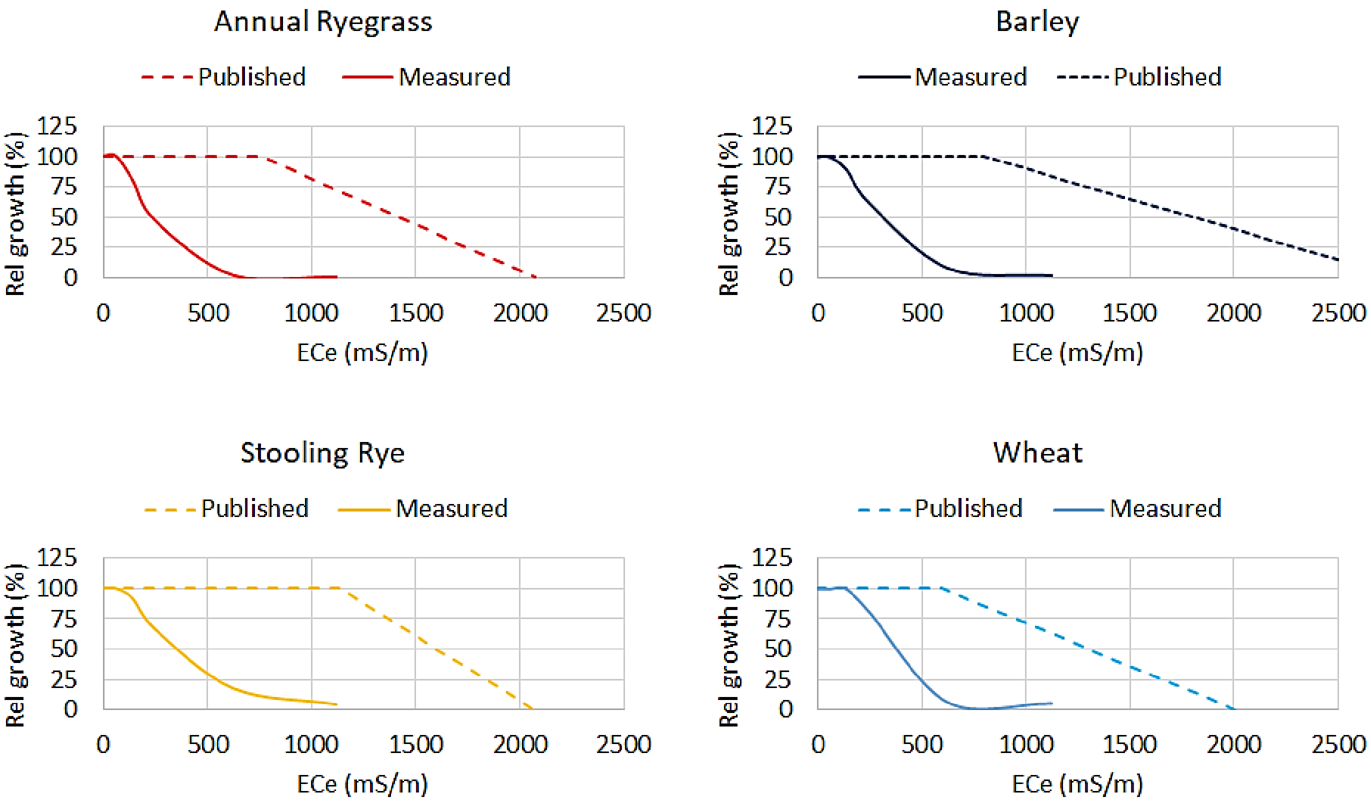

FIGURE 4.19: Slope-threshold relationships for annual ryegrass, barley, stooling rye and wheat showing measured (during vegetative growth phase) and published values

4.4 Conclusions and summary

In this study, it was observed that sulphate salt concentrations above 600 mS m^{-1} significantly reduced germination of annual temperate crops. In the seedling growth stage, increasing sulphate concentration resulted in an increase in root to shoot ratio, and a decrease in relative growth. There was no significant difference in average vegetative dry mass per plant between the first two treatments (as these treatments weren’t significantly different to start with), however, further increasing sulphate salinity concentration resulted in a significant reduction after the first two treatments.

It can be concluded that increasing sulphate salinity reduces germination, seedling and vegetative growth of annual temperate crops, especially when dominated by Mg. After exceeding the threshold obtained in this experiment, a linear reduction in relative growth was found for both seedling establishment and vegetative growth. In general, annual temperate cereal crops are more sensitive to sulphate salinity during the vegetative growth stage compared to the seedling stage at the same sulphate salinity concentrations. This was clear as the vegetative growth stage had lower thresholds and higher slopes than the seedling growth stage.

Although the results from this study may give the idea that irrigation with sulphate rich waters is not viable, other studies have proven otherwise. This is mainly due to the type of sulphate used, and as proven in other studies Ca dominated sulphates are not as detrimental as Mg dominated sulphate. Crop and cultivar selection, climatic conditions, irrigation method, soil and water quality are but a few of the parameters that need to be studied when considering irrigation with saline sulphate waters. Another important parameter to look at it, is nutritional requirements and signs of deficiencies as these could lead to a 'false' crop response to salinity as deficiencies often give the same results as salt stress. It is also worth mentioning that the assumption made regarding EC and EC_e of the treatment solution may be incorrect as it only applies to soil solution and not water culture experiments.

Recommendations for future studies include;

- Looking at Cl salinity and SO_4 salinity in a comparison study;
- Including more treatments and replications;
- Using Ca and Na dominated sulphates instead of just Mg;
- Revisiting the Maas and Hoffman (1977) trials and ensuring that the same procedure is followed.

4.5 References

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APPENDIX A1

Fertilizer regime and budget

TABLE A1.1: Fertilizers applied to field at Mafube unmined site

		N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	S (kg ha^{-1})	Cost (R per ha)
Pre-plant broadcast	9.1.2 (38) 0.5% Zn @ 500 kg ha^{-1}	161.3	17.9	35.8	-	R 2 572.59
Planting fertilizer	3.2.1 (38) 0.5% Zn @ 200 kg ha^{-1}	38.0	25.3	12.7	-	R 1 343.00
Top Dressing	None	-	-	-	-	R 0.00
TOTAL COST FOR 2016/17 SEASON		**R 199.3**	**R 43.2**	**R 48.5**	**-**	**R 3 915.59**
Pre-plant broadcast	9.1.2 (38) 0.5% Zn @ 500 kg ha^{-1}	142.5	15.8	31.6	-	R 2 526
Planting fertilizer	4.3.4 (36) 0.4% Zn + 3.9% S @ 250 kg ha^{-1}	32.7	24.5	32.7	9.75	R 1 400
Top Dressing	Urea 46% @ 250 kg ha^{-1}	115	-	-	-	R 1 088.75
TOTAL COST FOR 2017/18 SEASON		**R 290.20**	**R 40.30**	**R 64.30**	**R 9.75**	**R 5 014.75**

TABLE A1.2: Pre-planting herbicide sprays at Mafube unmined site

Herbicide/Insecticide	Quantity	Cost per hectare
Eptam Super (EPTC)	2 L ha^{-1}	R 196.00
Guardian S (840 EC)	700 mL ha^{-1}	R 62.89
Insectido (50 g L^{-1})	200 mL ha^{-1}	R 13.40
Allbuff	2 L per 2000 L water	R 2.90
Boron (10%)	2 L ha^{-1}	R 51.00
TOTAL COST FOR 2016/17 SEASON		**R 326.19**
Galago (480)	265 mL ha^{-1}	R 52.47
Guardian S (840 EC)	1.2 L ha^{-1}	R 98.40
Atrazine 500 (Atraflo)	2 L ha^{-1}	R 73.80
Lamda (5EC)	100 mL ha^{-1}	R 6.30
Correcto	100 mL ha^{-1}	R 3.40
Liquibor (10%)	2 L ha^{-1}	R 56.00
TOTAL COST FOR 2017/18 SEASON		**R 290.38**

TABLE A1.3: Post-emergence herbicide sprays at Mafube unmined site

Herbicide	Quantity	Cost per hectare
Terbuzine (600)	2.5 L ha^{-1}	R 119.67
Acetochlor (900 EC)	682 mL ha^{-1}	R 44.67
Campertop (225)	800 mL ha^{-1}	R 63.20
Allbuff	2 L per 2000 L water	R 2.90
TOTAL COST FOR 2016/17 SEASON		**R 230.44**
Galago (480)	200 mL ha^{-1}	R 39.60
Acetochlor (900EC) no safener	682 mL ha^{-1}	R 40.92
Terbuzine/Cheetah 600	2 L ha^{-1}	R 75.00
Lamda (5EC)	120 mL ha^{-1}	R 7.56
Correcto	100 mL ha^{-1}	R 3.40
TOTAL COST FOR 2017/18 SEASON		**R 166.48**

TABLE A1.4: Post-emergence fungicide sprays at Mafube unmined site, 2016/17 season

Fungicide	Quantity	Cost / hectare
Spanta S.C.	500 mL ha^{-1}	R 107.75
Performer	500 mL ha^{-1}	R 14.25
TOTAL COST FOR 2016/17 SEASON		**R 122.00**

TABLE A1.5: Beestepan Boerdery Costing Report

DIRECT INPUT COSTS	**2017**	**2018**	
	Dryland	**Irrigated**	**Dryland**
Fertilizer and Minerals	3915.59	5014.75	2200.00
Lime (incl transport)	-	-	-
Herbicides & Insecticides	556.63	394.05	394.05
Fungicides	122	-	-
Seed	1727.68	2706.30	1691.44
Fuel	1441.59	1528.09	1528.09
Repairs and Maintenance	1577.65	1672.31	1672.31
Rent	450	477.00	477.00
Depreciation	1625.43	1722.96	1722.96
Fixed improvements	74.01	78.45	78.45
Wages (temporary staff)	367.27	389.31	389.31
Interest paid	-	-	-
INDIRECT FIXED COSTS	**2017**	**2018**	
	Dryland	**Irrigated**	**Dryland**
Salaries (Permanent staff)	2675.83	2836.38	2836.38
Medical Aid (Providend Fund)	209.37	221.93	221.93
Electricity	326.97	346.59	346.59
Transport for Contractors	80.88	85.73	85.73
Insurance and Licences	85.68	90.82	90.82
Silo cost and Packaging	3.67	3.89	3.89
Telephones	24.86	26.35	26.35
Statutory levies and WCC	130.86	138.71	138.71
Sundry Operating Expenses	118.45	125.56	125.56
TOTAL COST PER HECTARE	**R 15514.42**	**R 17859.17**	**R 15980.09**

Note: Irrigation and pumping costs (estimated at R5000 per ha) are covered by Mafube Colliery
2018 costs are calculated based on 2017 costs plus 6% inflation

TABLE A1.6: Profits and losses per year for dryland and irrigated yields

	2017	**2018**	
	Dryland	**Irrigated**	**Dryland**
Yield (t ha^{-1})	5.4	13	5.4
Cost per ha	R 15514	R 17859	R 15980
Cost per ton	R 2873	R 1374	R 2959
Avg SAFEX Price per ton (May - July)	R 1885	R 2070	
Earnings per ha	R 10179	R 26910	R 11178
Profit/Loss per ton (excl pumping costs)	Loss of R 5335	Profit of R 9051	Loss of R 4802
Profit/Loss per ton (incl pumping costs of R5000 per ha)	-	Profit of R 4051	-

APPENDIX A2
Soil analysis results

TABLE A2.1: Soil sampling GPS coordinates

Sample no	Longitude	Latitude
S01	25°48'30.8" S	29°45'49.1" E
S02	25°48'30.8" S	29°45'45.3" E
S03	25°48'28.1" S	29°45'46.2" E
S04	25°48'26.0" S	29°45'45.9" E
S05	25°48'27.5" S	29°45'42.5" E
S06	25°48'24.3" S	29°45'44.6" E
S07	25°48'22.5" S	29°45'43.7" E
S08	25°48'19.9" S	29°45'46.6" E
S09	25°48'21.7" S	29°45'46.9" E
S10	25°48'23.1" S	29°45'49.5" E
S11	25°48'19.8" S	29°45'52.3" E
S12	25°48'23.4" S	29°45'53.8" E
S13	25°48'26.2" S	29°45'50.9" E
S14	25°48'27.5" S	29°45'52.9" E

TABLE A2.2: Total soluble salt content (mg kg^{-1}) before and after irrigation

	Poorly drained west						Well drained east					
	30 cm		60 cm		90 cm		30 cm		60 cm		90 cm	
	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
Ca (mg kg^{-1})	21	69	27	61	35	89	22	73	26	50	35	95
Mg (mg kg^{-1})	9	20	7	21	9	26	8	22	8	21	7	29
Na (mg kg^{-1})	0.20	7	3	8	4	9	0.40	7	0.60	7	0.80	12
K (mg kg^{-1})	11	3	1	3	1	1	11	4	5	7	3	2
P (mg kg^{-1})	0.85	0.18	0.33	0.24	0.21	0.05	1	0.42	0.63	0.86	0.21	0
Al (mg kg^{-1})	93	32	18	58	22	8	62	53	34	100	0.46	0.07
Mn (mg kg^{-1})	0.64	0.17	0.18	0.21	0.31	0.16	0.64	0.23	0.53	0.35	0.42	0.17
Fe (mg kg^{-1})	30	11	6	19	6	3	26	22	14	40	0.20	0
Cu (mg kg^{-1})	0.06	0.02	0.02	0.03	0.01	0.01	0.06	0.03	0.03	0.05	0.01	0.01
Zn (mg kg^{-1})	0.13	0.03	0.07	0.05	0.06	0.02	0.15	0.05	0.10	0.12	0.07	0.01
Cl (mg kg^{-1})	15	5	10	4	8	9	8	3	10	6	9	4
SO_4 (mg kg^{-1})	40	222	64	213	92	296	49	247	59	191	88	336

TABLE A2.3: Total extractable salt content (mg kg^{-1}) before and after irrigation

	Poorly drained west						Well drained east					
	30		60		90		30		60		90	
	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
Ca (mg kg^{-1})	624	553	597	566	616	606	437	402	470	388	465	452
Mg (mg kg^{-1})	149	143	146	147	154	146	96	115	101	116	83	110
Na (mg kg^{-1})	17	22	24	24	26	23	16	12	16	16	16	19
K (mg kg^{-1})	100	42	39	35	39	30	85	40	56	31	46	24
P (mg kg^{-1})	25	10	6	7	3	3	42	19	12	11	6	2
Al (mg kg^{-1})	798	796	973	827	974	887	748	684	939	711	987	760
Mn (mg kg^{-1})	32	16	10	12	11	8	21	14	11	11	16	7
Fe (mg kg^{-1})	63	52	32	44	27	30	64	43	28	32	22	19
Cu (mg kg^{-1})	3	2	2	2	2	2	3	2	3	2	2	2
Zn (mg kg^{-1})	10	2	7	1	7	0.60	18	3	16	2	21	0.40
SO_4 (mg kg^{-1})	77	202	119	239	204	283	86	178	116	210	220	271

APPENDIX A3

Water quality

TABLE A3.1: Monthly averages for irrigation water sourced from Mafube Void 3

	Sep-17	**Oct-17**	**Nov-17**	**Dec-17**	**Jan-18**	**Feb-18**	**Mar-18**	**Apr-18**	**May-18**	**Jun-18**	**Jul-18**	**Aug-18**
TDS (mg L^{-1})	1835	1890	1839	1664	1887	1950	1920	1933			1945	
Alkalinity$_{total}$ as $CaCO_3$ (mg L^{-1})	197	163	107	78	20	35	63	110	204	255	229	265
Total N (mg L^{-1})	13	13	10	9	7	6	5	2	3	3	3	4
Cl (mg L^{-1})	29	30	29	24	18	19	20	15	19	21	19	19
F (mg L^{-1})	0.645	0.650	0.423	0.315	0.273	0.457	0.580	0.464	0.450	0.491	0.517	0.420
SO_4 (mg L^{-1})	1096	1106	1113	1036	1230	1265	1221	1181	1077	966	1018	982
Ca (mg L^{-1})	209	202	184	168	223	224	222	233	231	226	222	232
Mg (mg L^{-1})	154	153	154	133	158	159	159	171	157	151	150	155
Na (mg L^{-1})	88	85	84	69	56	58	58	52	55	63	64	37
K (mg L^{-1})	40	39	40	32	22	22	24	25	31	35	35	66
Fe (mg L^{-1})	<0.01	<0.01	0.070	<0.01	0.148	0.960	0.087	<0.004	<0.004	<0.004	<0.004	<0.004
Mn (mg L^{-1})	1.750	1.334	0.020	2.980	7.758	3.247	1.383	5.305	2.770	0.71	0.525	0.464
Al (mg L^{-1})	0.045	0.033	0.020	0.025	0.038	0.033	0.048	0.027	0.033	<0.002	<0.002	<0.002
Cd (mg L^{-1})								<0.002	<0.002	<0.002	0.007	<0.002
Co (mg L^{-1})								0.075	0.037	0.013	0.005	0.004
Cr (mg L^{-1})								<0.003	<0.003	<0.003	0.004	<0.003
Cu (mg L^{-1})								<0.002	<0.002	<0.002	<0.002	<0.002
Ni (mg L^{-1})								0.041	0.017	<0.002	0.006	<0.002
Pb (mg L^{-1})								<0.004	<0.004	<0.004	<0.004	<0.004
Zn (mg L^{-1})								0.024	0.012	0.014	0.02	<0.002
EC (mS m^{-1})	219	215	208	183	202	211	198	182	207	239	219	223
pH	8.17	8.15	8.16	7.95	7.26	7.51	7.56	8.08	8.38	8.3	8.39	8.55

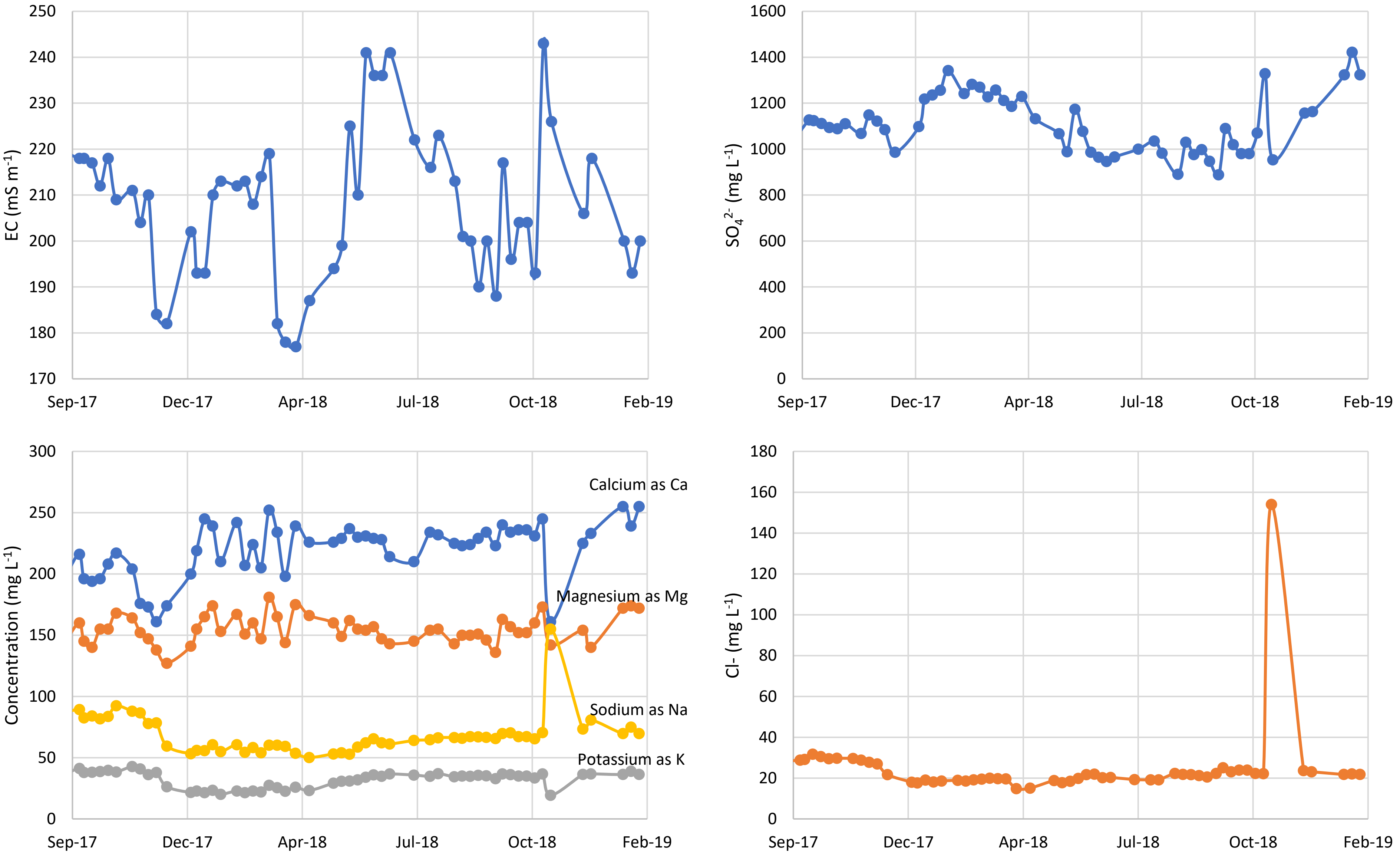


FIGURE A3.1: Constituent levels as measured for the irrigation water sourced from Mafube Void 3

TABLE A3.2: Yearly averages for surface water monitoring from Beestepan Dam

	2014	**2015**	**2016**	**2017**	**2018**
pH	7.5	7.3	6.7	7.5	8.4
EC (mS m^{-1})	112	114	146	79	57
TDS (mg L^{-1})	927	905	1297	626	419
$Alkalinity_{total}$ as $CaCO_3$ (mg L^{-1})	25	56	23	36	42
Total N (mg L^{-1})	0.967	0.950	1.975	1.053	72
Total P (mg L^{-1})	2.133	0.508	0.218	0.238	0.650
Ca (mg L^{-1})	87	77	127	57	40
Mg (mg L^{-1})	68	59	100	43	31
Na (mg L^{-1})	32	69	53	32	24
K (mg L^{-1})	9	13	12	9	6
Cl^- (mg L^{-1})	26	58	30	20	21
SO_4^{2-} (mg L^{-1})	576	468	776	324	191
F^- (mg L^{-1})	0.600	0.550	0.809	0.733	0.650
Al (mg L^{-1})	0.100	0.667	0.100	0.133	
Fe (mg L^{-1})	0.029	0.766	0.084	0.060	0.049
Mn (mg L^{-1})	8.110	5.954	9.908	1.071	0.177
Zn (mg L^{-1})			0.043	0.028	

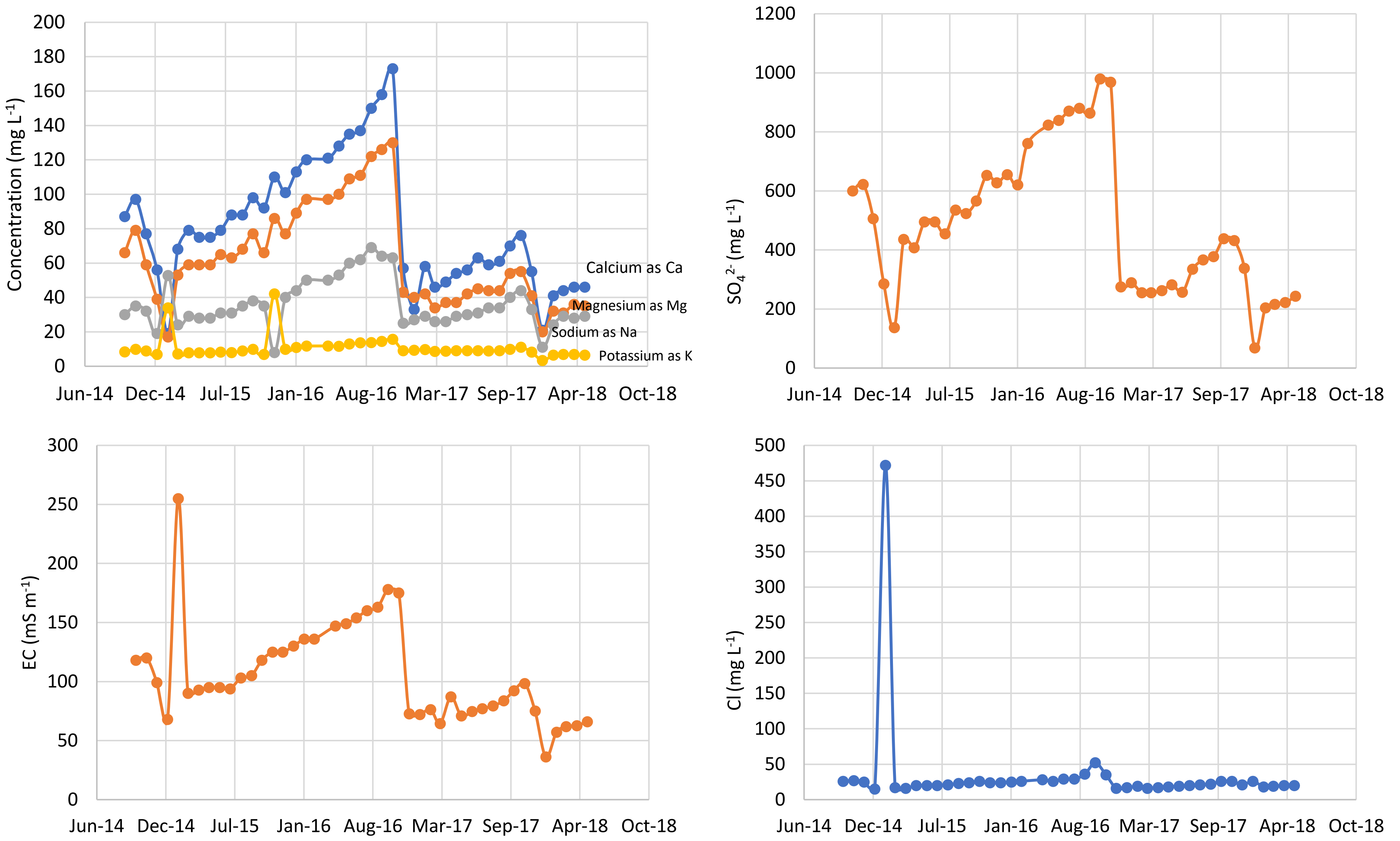


FIGURE A3.2: Constituent levels as measured for surface water monitoring from Beestepan Dam

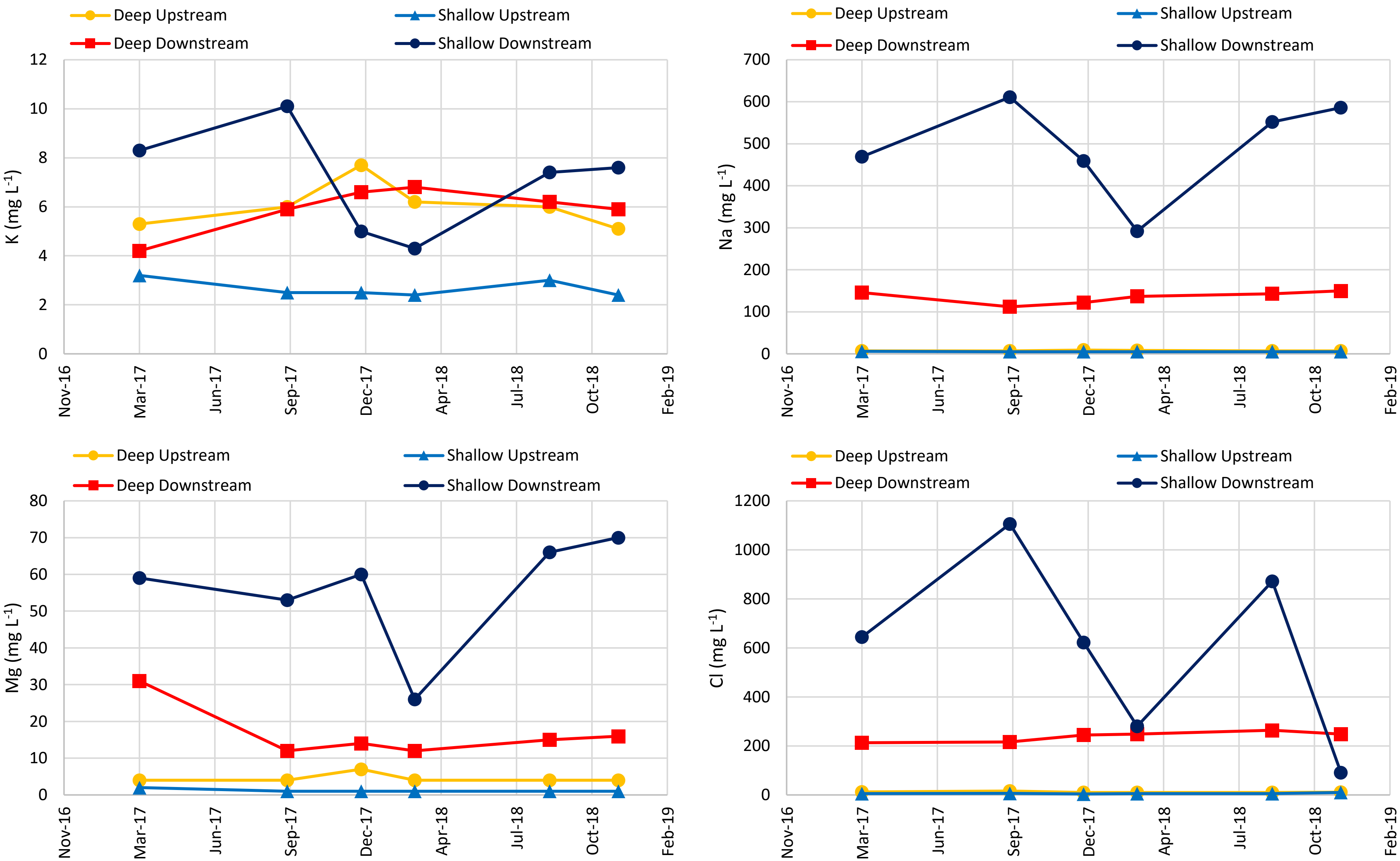


FIGURE A3.3: Constituent levels as measured for the four boreholes at Mafube unmined site in the 2017/18 summer season

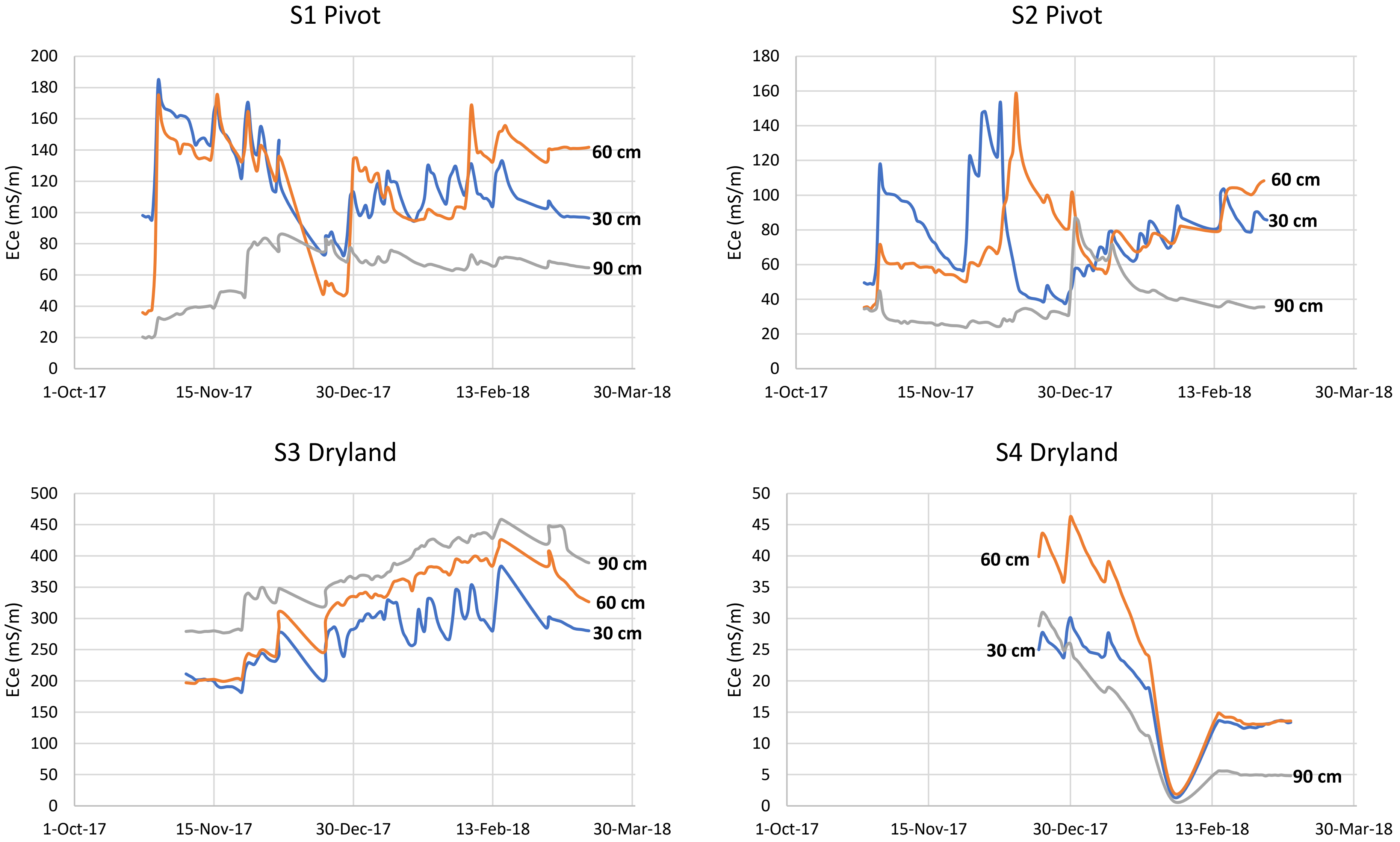


FIGURE A3.4: Soil salinity (ECe) as measured for the four monitoring sites at Mafube unmined site in the 2017/18 summer season

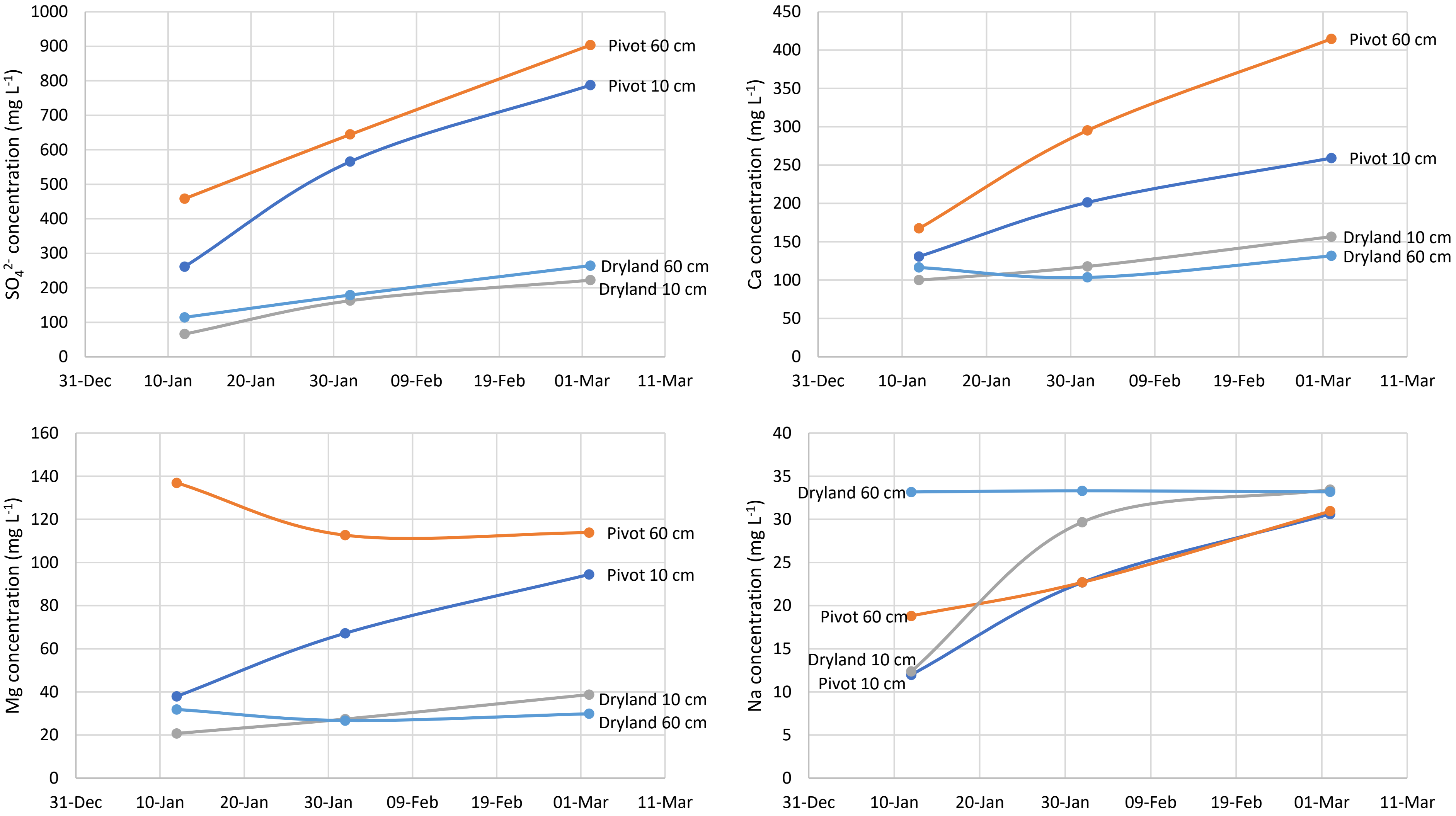


FIGURE A3.5: Constituent levels as measured for the pivot and dryland suction cups at Mafube unmined site in the 2017/18 summer season

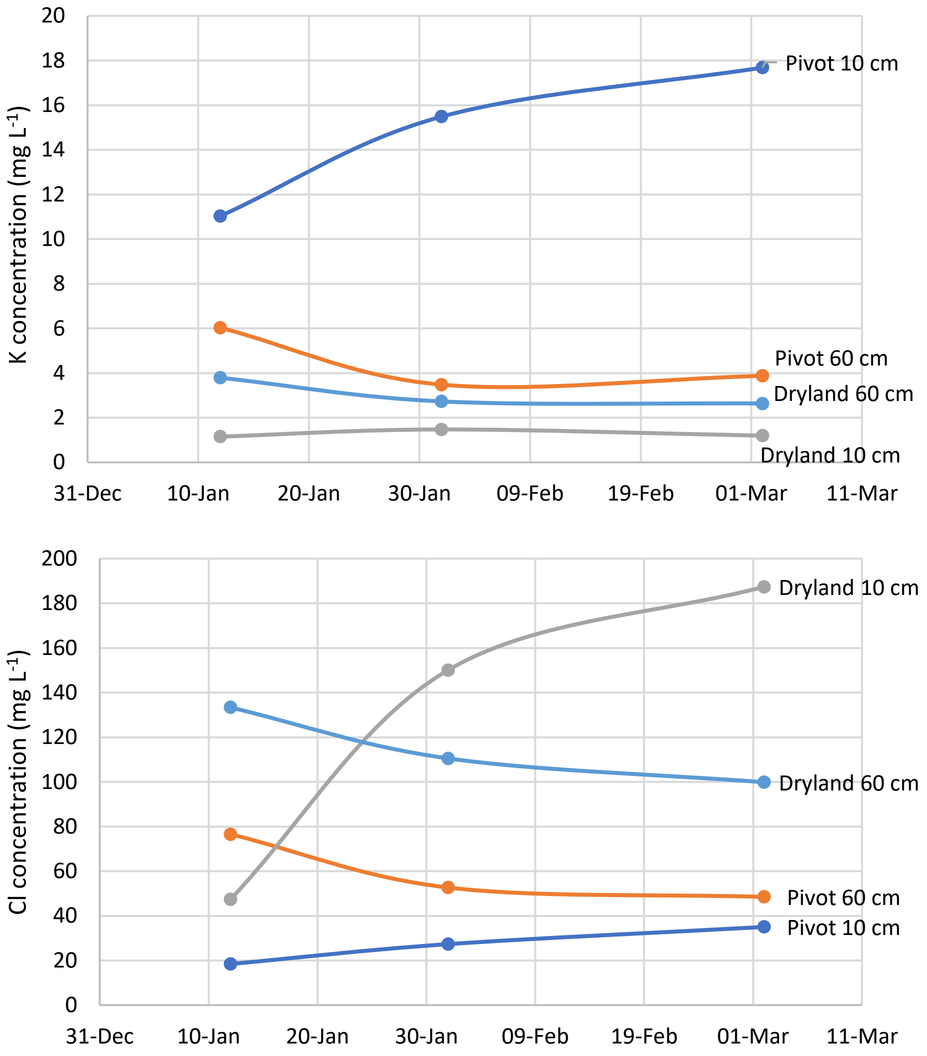


FIGURE A3.6: Constituent levels as measured for the pivot and dryland suction cups at Mafube Unmined Field in the 2017/18 summer season

APPENDIX B1
SWB Simulations

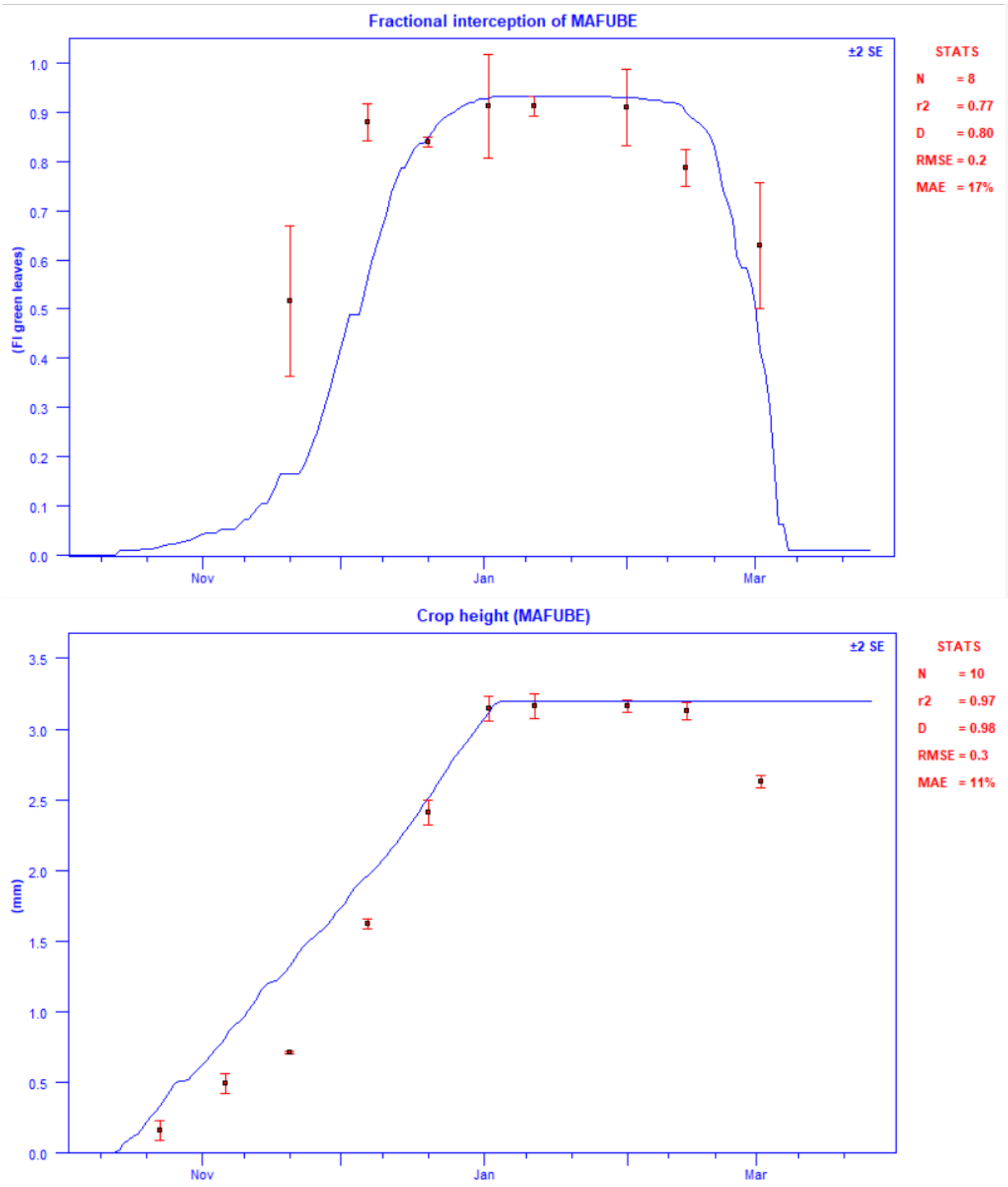
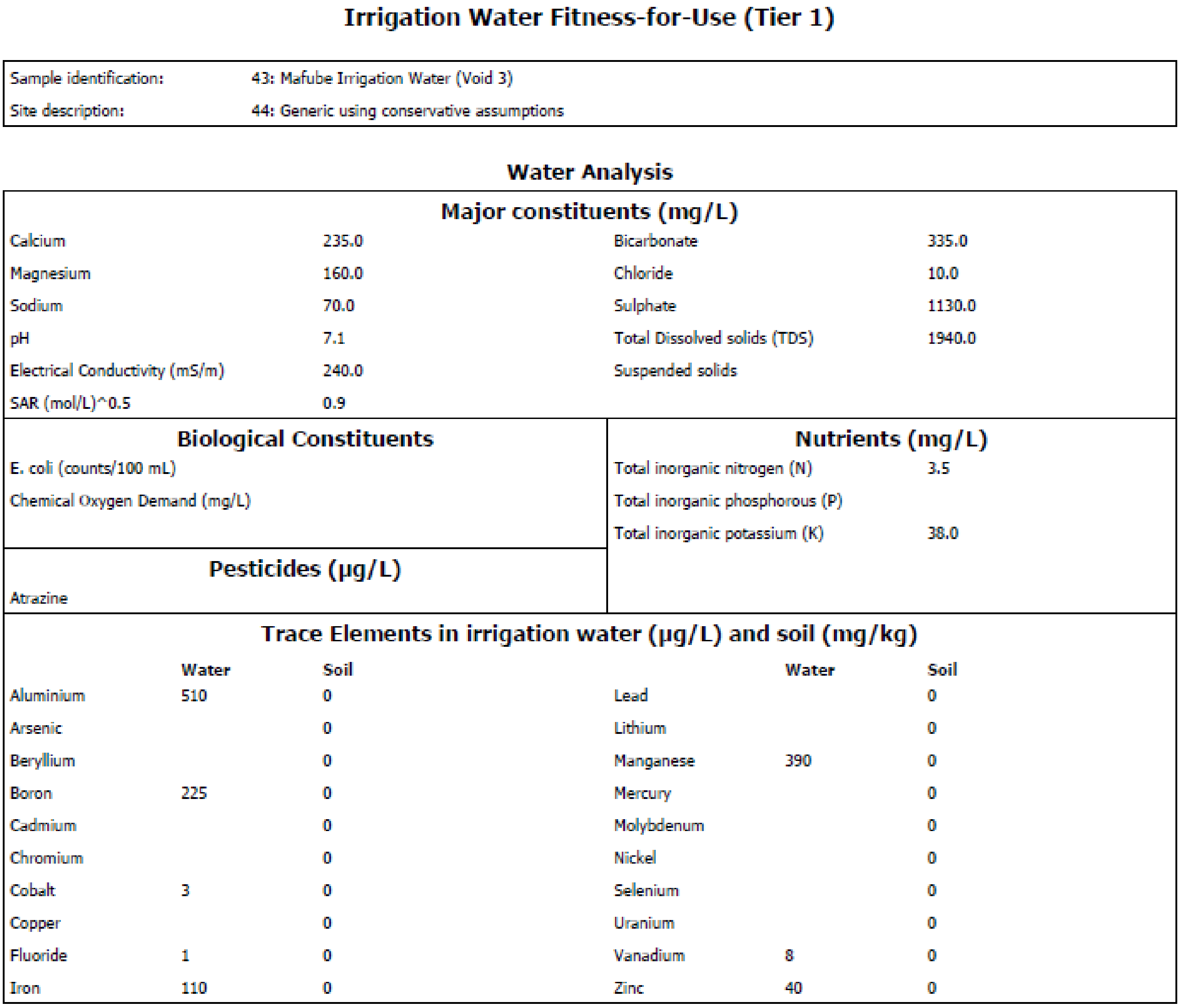


FIGURE B1.1: Measured (symbols) and simulated (lines) fractional interception (top), and crop height (bottom) simulating the effect of saline mine water irrigation

Note: N – number of observations, r^2 -coefficient of determination, D – Willmott's (1982) index of agreement, RMSE – root mean square error, MAE – mean absolute error

APPENDIX B2
SAWQG-DSS Simulations



Irrigation Water Fitness-for-Use (Tier 1)

Sample identification:	43: Mafube Irrigation Water (Void 3)
Site description:	44: Generic using conservative assumptions

Water Analysis

Major constituents (mg/L)

Calcium	235.0	Bicarbonate	335.0
Magnesium	160.0	Chloride	10.0
Sodium	70.0	Sulphate	1130.0
pH	7.1	Total Dissolved solids (TDS)	1940.0
Electrical Conductivity (mS/m)	240.0	Suspended solids	
SAR (mol/L)^0.5	0.9		

Biological Constituents

E. coli (counts/100 mL)	
Chemical Oxygen Demand (mg/L)	

Nutrients (mg/L)

Total inorganic nitrogen (N)	3.5
Total inorganic phosphorous (P)	
Total inorganic potassium (K)	38.0

Pesticides (µg/L)

Atrazine	

Trace Elements in irrigation water (µg/L) and soil (mg/kg)

	Water	Soil		Water	Soil
Aluminium	510	0	Lead		0
Arsenic		0	Lithium		0
Beryllium		0	Manganese	390	0
Boron	225	0	Mercury		0
Cadmium		0	Molybdenum		0
Chromium		0	Nickel		0
Cobalt	3	0	Selenium		0
Copper		0	Uranium		0
Fluoride	1	0	Vanadium	8	0
Iron	110	0	Zinc	40	0

Tier 1: Fitness-for-Use
Soil Quality

	Fitness-for-use	Root zone salinity (mS/m)	Predicted equilibrium root zone salinity (mS/m)
Root zone salinity	Ideal	0 - 200	
	Acceptable	200 - 400	
	Tolerable	400 - 800	451
	Unacceptable	> 800	

	Fitness-for-use	Degree of reduced Permeability	Qualitative indication of the impact on soil permeability as manifested by reduced:	
			Surface Infiltrability	Soil Hydraulic Conductivity
Soil Permeability	Ideal	None		None
	Acceptable	Slight	Slight	
	Tolerable	Moderate		
	Unacceptable	Severe		

	Fitness-for-use		Number of years of 1000 mm irrigation before Trace Elements reach accumulation threshold in topsoil			
Trace Element Accumulation	**Ideal**		> 200 years to reach soil accumulation threshold			
	Acceptable		150 to 200 years to reach soil accumulation threshold			
	Tolerable		100 to 150 years to reach soil accumulation threshold			
	Unacceptable		< 100 years to reach soil accumulation threshold			
	Trace Element	**Soil Accumulation Threshold (mg/kg)**	**No of years to reach Soil Accumulation Threshold**	**Trace Element**	**Soil Accumulation Threshold (mg/kg)**	**No of years to reach Soil Accumulation Threshold**
	Al	2500	980	Li	1250	No data
	As	50	No data	Mn	100	51
	Be	50	No data	Hg	1	No data
	Cd	5	No data	Mo	5	No data
	Cr	50	No data	Ni	100	No data
	Co	25	> 1000	Se	10	No data
	Cu	100	No data	U	5	No data
	F	1000	> 1000	Va	50	> 1000
	Fe	2500	> 1000	Zn	500	> 1000
	Pb	100	No data			

Tier 1: Fitness-for-Use
Yield and Quality of a Generic Sensitive Crop with 1000 mm irrigation p.a.

	Fitness-for-use	Relative crop yield (%)	Predicted relative crop yield (%) as affected by:			
			Salinity (EC)	Boron (B)	Chloride (Cl)	Sodium (Na)
Root Zone Effects	Ideal	90 - 100		97	100	100
	Acceptable	80 - 90				
	Tolerable	70 - 80				
	Unacceptable	<70	0			

	Fitness-for-use	Degree of leaf scorching	Degree of leaf scorching under sprinkler irrigation caused by:	
			Chloride (Cl)	Sodium (Na)
Leaf scorching when wetted	Ideal	None	None	
	Acceptable	Slight		Slight
	Tolerable	Moderate		
	Unacceptable	Severe		

	Fitness-for-use	Contribution to estimated N P K Removal by crop	% of estimated N P K removal at harvest and amount that is applied through irrigation (High nutrient concentrations may impact development of sensitive crops)					
			Nitrogen (N)		Phosphorous (P)		Potassium (K)	
			Removal (%)	Applied (kg/ha)	Removal (%)	Applied (kg/ha)	Removal (%)	Applied (kg/ha)
Contribution to NPK removal by generic sensitive crop	Ideal	0 - 10%				No data		
	Acceptable	10 - 30%						
	Tolerable	30 - 50%						
	Unacceptable	>50%	70	35			3800	380

Tier 1: Fitness-for-Use
Irrigation Equipment

Corrosion or Scaling of Irrigation Equipment

Fitness-for-use	Fitness for Use Category determined by the corrosion or scaling potential indicated by the Langelier Index			
	Corrosion (Langelier Index)		Scaling (Langelier Index)	
Ideal	-0.5 to 0	Not Corrosive	0 to +0.5	0.29
Acceptable	-0.5 to -1.0		+0.5 to +1.0	
Tolerable	-1.0 to -2.0		+1.0 to +2.0	
Unacceptable	<-2.0		>+2.0	

Clogging of Drippers

Fitness-for-use	Fitness for Use Category determined by the potential of a constituent to cause clogging of drippers									
	Suspended Solids (mg/L)		pH		Manganese (Mn) (mg/L)		Total Iron (Fe) (mg/L)		*E.coli* (10^6 per 100 mL)	
Ideal	<50	No data	<7.0		<0.1		<0.2	0.1	<1	No data
Acceptable	50 - 75		7.0 - 7.5	7.1	0.1 - 0.5	0.4	0.2 - 0.5		1 - 2	
Tolerable	75 - 100		7.5 - 8.0		0.5 - 1.5		0.5 - 1.5		2 - 5	
Unacceptable	>100		>8.0		>1.5		>1.5		>5	

Irrigation Water Fitness-for-Use (Tier 2)

Sample identification:	43: Mafube Irrigation Water (Void 3)
Site description:	45: Mafube Unmined site

Water Analysis

Major constituents (mg/L)

Calcium	235.0	Bicarbonate	335.0
Magnesium	160.0	Chloride	10.0
Sodium	70.0	Sulphate	1130.0
pH	7.1	Total Dissolved solids (TDS)	1940.0
Electrical Conductivity (mS/m)	240.0	Suspended solids	
SAR (mol/L)^0.5	0.9		

Biological Constituents

E. coli (counts/100 mL)	
Chemical Oxygen Demand (mg/L)	

Pesticides (µg/L)

Atrazine	

Nutrients (mg/L)

Total inorganic nitrogen (N)	3.5
Total inorganic phosphorous (P)	
Total inorganic potassium (K)	38.0

Trace Elements in irrigation water (µg/L) and soil (mg/kg)

	Water	Soil		Water	Soil
Aluminium	510	0	Lead		0
Arsenic		0	Lithium		0
Beryllium		0	Manganese	390	0
Boron	225	0	Mercury		0
Cadmium		0	Molybdenum		0
Chromium		0	Nickel		0
Cobalt	3	0	Selenium		0
Copper		0	Uranium		0
Fluoride	1	0	Vanadium	8	0
Iron	110	0	Zinc	40	0

Site Specific Characteristics

Crop

Crop	Maize (Mafube)
Plant date (DD/MM)	1/10

Irrigation management

Irrigation system	Pivot
Irrigation timing	Amount (mm) 10
Refill option	Field capacity

Soil

Soil texture	Sandy loam
Soil depth (m)	1.0
Initial water content	Wet (FC)
Profile available water (mm)	120
Plant available water (mm/m)	120
Field capacity (m/m)	0.22
Wilting point (m/m)	0.10
Bulk density (Mg/m3)	1.40

Weather station	WONDERFONTEIN (45 years)

Water Balance

Water balance components	Maize (Mafube)
Mean irrigation application (mm p.a.)	415
Mean rainfall (mm p.a.)	509
Mean evaporation (mm p.a.)	340
Mean transpiration (mm p.a.)	503
Mean evapotranspiration (mm p.a.)	843
Mean drainage (mm p.a.)	82
Effective leaching fraction (%)	8.9

Tier 2: Fitness-for-Use

Soil Quality of a Sandy loam soil with 395 mm irrigation p.a.

	Fitness-for-use	Root zone salinity (mS/m)	% of time root zone salinity is predicted to fall within a particular Fitness-for-use category
Root zone salinity	Ideal	0 - 200	100
	Acceptable	200 - 400	
	Tolerable	400 - 800	
	Unacceptable	> 800	

	Fitness-for-use	Degree of reduced Permeability	% of time soil permeability is predicted to fall within a particular Fitness-for-use category	
			Surface Infiltrability	Soil Hydraulic Conductivity
Soil Permeability	Ideal	None		72
	Acceptable	Slight	100	
	Tolerable	Moderate		18
	Unacceptable	Severe		10

	Fitness-for-use	Number of years of 395 mm irrigation before Trace Elements reach accumulation threshold in topsoil
Trace Element Accumulation	**Ideal**	> 200 years to reach soil accumulation threshold
	Acceptable	150 to 200 years to reach soil accumulation threshold
	Tolerable	100 to 150 years to reach soil accumulation threshold
	Unacceptable	< 100 years to reach soil accumulation threshold

Trace Element	Soil Accumulation Threshold (mg/kg)	No of years to reach Soil Accumulation Threshold	Trace Element	Soil Accumulation Threshold (mg/kg)	No of years to reach Soil Accumulation Threshold
Al	2500	> 1000	Li	1250	No data
As	50	No data	Mn	100	130
Be	50	No data	Hg	1	No data
Cd	5	No data	Mo	5	No data
Cr	50	No data	Ni	100	No data
Co	25	> 1000	Se	10	No data
Cu	100	No data	U	5	No data
F	1000	> 1000	Va	50	> 1000
Fe	2500	> 1000	Zn	500	> 1000
Pb	100	No data			

Tier 2: Fitness-for-Use
Yield and Quality of a Maize (Mafube) crop with 415 mm irrigation per season

	Fitness-for-use	Relative crop yield (%)	% of time yield is within relative crop yield category, as affected by:			
			Salinity (EC)	Boron (B)	Chloride (Cl)	Sodium (Na)
Root Zone Effects	Ideal	90 - 100	100	100	100	100
	Acceptable	80 - 90				
	Tolerable	70 - 80				
	Unacceptable	<70				

	Fitness-for-use	Degree of leaf scorching	Degree of leaf scorching under sprinkler irrigation caused by:	
			Chloride (Cl)	Sodium (Na)
Leaf scorching when wetted	Ideal	None	None	None
	Acceptable	Slight		
	Tolerable	Moderate		
	Unacceptable	Severe		

	Fitness-for-use	Contribution to estimated N P K Removal by crop	Mean applied N P K at harvest and % of time N P K removal at harvest is within fitness-for-use categories (High nutrient concentrations may impact development of sensitive crops)					
			Nitrogen (N)		Phosphorous (P)		Potassium (K)	
			Time (%)	Applied (kg/ha)	Time (%)	Applied (kg/ha)	Time (%)	Applied (kg/ha)
Contribution to NPK removal	Ideal	0 - 10%	100	14		No data		0
	Acceptable	10 - 30%						
	Tolerable	30 - 50%						
	Unacceptable	>50%					100	153

	Fitness-for-use	Excess infections per 1000 persons p.a.	Predicted excess infections per 1000 people p.a.
Microbial Contamination	Ideal	<1	No data
	Acceptable	1 - 3	
	Tolerable	3 - 10	
	Unacceptable	>10	

	Fitness-for-use	Atrazine load (Maize (Mafube), SaLm) (g/ha)	% of time Atrazine load is predicted to fall within particular fitness-for-use category
Qualitative Atrazine Damage	Ideal	<90	No data
	Acceptable	90 - 130	
	Tolerable	130 - 180	
	Unacceptable	>180	

Tier 2: Fitness-for-Use

Irrigation Equipment

Corrosion or Scaling of Irrigation Equipment

Fitness-for-use	Fitness for Use Category determined by the corrosion or scaling potential indicated by the Langelier Index			
	Corrosion (Langelier Index)		Scaling (Langelier Index)	
Ideal	0 to -0.5	Not Corrosive	0 to +0.5	0.29
Acceptable	-0.5 to -1.0		+0.5 to +1.0	
Tolerable	-1.0 to -2.0		+1.0 to +2.0	
Unacceptable	<-2.0		>+2.0	

Clogging of Drippers

Fitness-for-use	Fitness for Use Category determined by the potential of an irrigation water constituent to cause clogging of drippers									
	Suspended Solids (mg/L)		pH		Manganese (Mn) (mg/L)		Total Iron (Fe) (mg/L)		*E.coli* (10^6 per 100 mL)	
Ideal	<50	No data	<7.0		<0.1		<0.2	0.1	<1	No data
Acceptable	50 - 75		7.0 - 7.5	7.1	0.1 - 0.5	0.4	0.2 - 0.5		1 - 2	
Tolerable	75 - 100		7.5 - 8.0		0.5 - 1.5		0.5 - 1.5		2 - 5	
Unacceptable	>100		>8.0		>1.5		>1.5		>5	

Irrigation Water Fitness-for-Use (Tier 2)

Sample identification:	43: Mafube Irrigation Water (Void 3)
Site description:	44: Mafube Unmined site

Water Analysis

Major constituents (mg/L)

Calcium	235.0	Bicarbonate	335.0
Magnesium	160.0	Chloride	10.0
Sodium	70.0	Sulphate	1130.0
pH	7.1	Total Dissolved solids (TDS)	1940.0
Electrical Conductivity (mS/m)	240.0	Suspended solids	
SAR (mol/L)^0.5	0.9		

Biological Constituents

E. coli (counts/100 mL)	
Chemical Oxygen Demand (mg/L)	

Nutrients (mg/L)

Total inorganic nitrogen (N)	3.5
Total inorganic phosphorous (P)	
Total inorganic potassium (K)	38.0

Pesticides (µg/L)

Atrazine	

Trace Elements in irrigation water (µg/L) and soil (mg/kg)

	Water	Soil		Water	Soil
Aluminium	510	0	Lead		0
Arsenic		0	Lithium		0
Beryllium		0	Manganese	390	0
Boron	225	0	Mercury		0
Cadmium		0	Molybdenum		0
Chromium		0	Nickel		0
Cobalt	3	0	Selenium		0
Copper		0	Uranium		0
Fluoride	1	0	Vanadium	8	0
Iron	110	0	Zinc	40	0

Site Specific Characteristics

Crop

Summer crop	Maize (Mafube)
Plant date (DD/MM)	1/10
Winter crop	Wheat
Plant date (DD/MM)	1/5

Irrigation management

Irrigation system	Pivot
Irrigation timing	Amount (mm) 10
Refill option	Field capacity

Soil

Soil texture	Sandy loam
Soil depth (m)	1.0
Initial water content	Wet (FC)
Profile available water (mm)	120
Plant available water (mm/m)	120
Field capacity (m/m)	0.22
Wilting point (m/m)	0.10
Bulk density (Mg/m3)	1.40

Weather station	WONDERFONTEIN (45 years)

Water Balance

Water balance components	Maize (Mafube)	Wheat
Mean irrigation application (mm p.a.)	467	709
Mean rainfall (mm p.a.)	480	51
Mean evaporation (mm p.a.)	338	339
Mean transpiration (mm p.a.)	481	409
Mean evapotranspiration (mm p.a.)	819	747
Mean drainage (mm p.a.)	133	8
Effective leaching fraction (%)	14.0	1.1

Tier 2: Fitness-for-Use

Soil Quality of a Sandy loam soil with 1182 mm irrigation p.a.

	Fitness-for-use	Root zone salinity (mS/m)	% of time root zone salinity is predicted to fall within a particular Fitness-for-use category
Root zone salinity	Ideal	0 - 200	94
	Acceptable	200 - 400	6
	Tolerable	400 - 800	
	Unacceptable	> 800	

	Fitness-for-use	Degree of reduced Permeability	% of time soil permeability is predicted to fall within a particular Fitness-for-use category	
			Surface Infiltrability	Soil Hydraulic Conductivity
Soil Permeability	Ideal	None	32	91
	Acceptable	Slight	68	1
	Tolerable	Moderate		2
	Unacceptable	Severe		6

	Fitness-for-use			Number of years of 1182 mm irrigation before Trace Elements reach accumulation threshold in topsoil		
Trace Element Accumulation	**Ideal**			> 200 years to reach soil accumulation threshold		
	Acceptable			150 to 200 years to reach soil accumulation threshold		
	Tolerable			100 to 150 years to reach soil accumulation threshold		
	Unacceptable			< 100 years to reach soil accumulation threshold		
	Trace Element	Soil Accumulation Threshold (mg/kg)	No of years to reach Soil Accumulation Threshold	Trace Element	Soil Accumulation Threshold (mg/kg)	No of years to reach Soil Accumulation Threshold
	Al	2500	829	Li	1250	No data
	As	50	No data	Mn	100	43
	Be	50	No data	Hg	1	No data
	Cd	5	No data	Mo	5	No data
	Cr	50	No data	Ni	100	No data
	Co	25	> 1000	Se	10	No data
	Cu	100	No data	U	5	No data
	F	1000	> 1000	Va	50	> 1000
	Fe	2500	> 1000	Zn	500	> 1000
	Pb	100	No data			

Tier 2: Fitness-for-Use

Yield and Quality of a Maize (Mafube) crop with 467 mm irrigation per season

	Fitness-for-use	**Relative crop yield (%)**	**% of time yield is within relative crop yield category, as affected by:**			
			Salinity (EC)	**Boron (B)**	**Chloride (Cl)**	**Sodium (Na)**
Root Zone Effects	Ideal	90 - 100	100	100	100	100
	Acceptable	80 - 90				
	Tolerable	70 - 80				
	Unacceptable	<70				

	Fitness-for-use	**Degree of leaf scorching**	**Degree of leaf scorching under sprinkler irrigation caused by:**	
			Chloride (Cl)	**Sodium (Na)**
Leaf scorching when wetted	Ideal	None	None	None
	Acceptable	Slight		
	Tolerable	Moderate		
	Unacceptable	Severe		

	Fitness-for-use	**Contribution to estimated N P K Removal by crop**	**Mean applied N P K at harvest and % of time N P K removal at harvest is within fitness-for-use categories (High nutrient concentrations may impact development of sensitive crops)**					
			Nitrogen (N)		**Phosphorous (P)**		**Potassium (K)**	
			Time (%)	**Applied (kg/ha)**	**Time (%)**	**Applied (kg/ha)**	**Time (%)**	**Applied (kg/ha)**
Contribution to NPK removal	Ideal	0 - 10%	100	17		No data		0
	Acceptable	10 - 30%						
	Tolerable	30 - 50%						
	Unacceptable	>50%					100	182

Tier 2: Fitness-for-Use

Yield and Quality of a Wheat crop with 709 mm irrigation per season

Root Zone Effects	Fitness-for-use	Relative crop yield (%)	% of time yield is within relative crop yield category, as affected by:			
			Salinity (EC)	Boron (B)	Chloride (Cl)	Sodium (Na)
	Ideal	90 - 100	100	69	100	100
	Acceptable	80 - 90		20		
	Tolerable	70 - 80		7		
	Unacceptable	<70		4		

Leaf scorching when wetted	Fitness-for-use	Degree of leaf scorching	Degree of leaf scorching under sprinkler irrigation caused by:	
			Chloride (Cl)	Sodium (Na)
	Ideal	None	No scorching parameter	No scorching parameter
	Acceptable	Slight		
	Tolerable	Moderate		
	Unacceptable	Severe		

Contribution to NPK removal	Fitness-for-use	Contribution to estimated N P K Removal by crop	Mean applied N P K at harvest and % of time N P K removal at harvest is within fitness-for-use categories (High nutrient concentrations may impact development of sensitive crops)					
			Nitrogen (N)		Phosphorous (P)		Potassium (K)	
			Time (%)	Applied (kg/ha)	Time (%)	Applied (kg/ha)	Time (%)	Applied (kg/ha)
	Ideal	0 - 10%	2	20		No data		
	Acceptable	10 - 30%	98	25				
	Tolerable	30 - 50%						
	Unacceptable	>50%					100	269

Tier 2: Fitness-for-Use

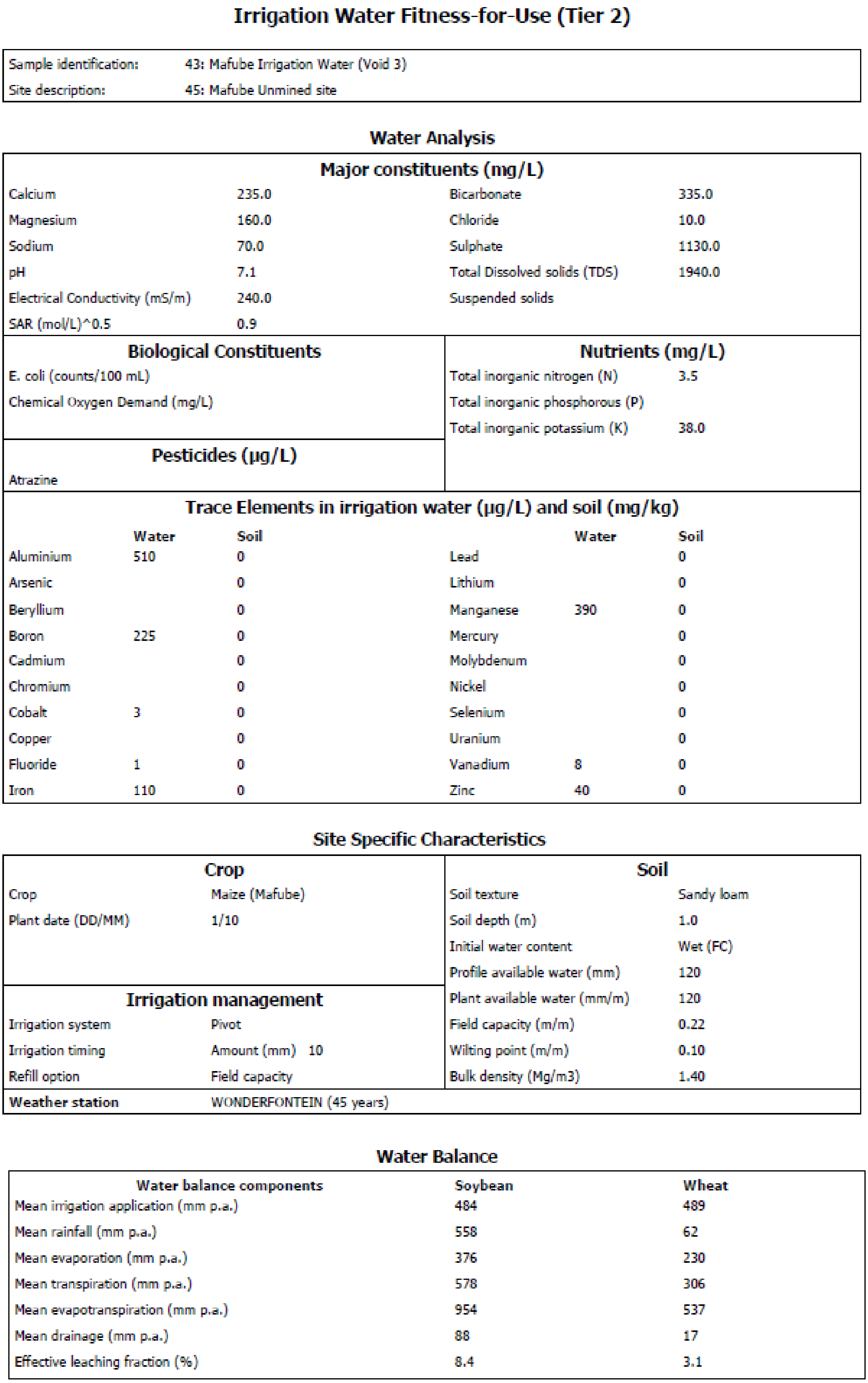
Irrigation Equipment

Corrosion or Scaling of Irrigation Equipment

Fitness-for-use	Fitness for Use Category determined by the corrosion or scaling potential indicated by the Langelier Index			
	Corrosion (Langelier Index)		Scaling (Langelier Index)	
Ideal	0 to -0.5	Not Corrosive	0 to +0.5	0.29
Acceptable	-0.5 to -1.0		+0.5 to +1.0	
Tolerable	-1.0 to -2.0		+1.0 to +2.0	
Unacceptable	<-2.0		>+2.0	

Clogging of Drippers

Fitness-for-use	Fitness for Use Category determined by the potential of an irrigation water constituent to cause clogging of drippers									
	Suspended Solids (mg/L)		pH		Manganese (Mn) (mg/L)		Total Iron (Fe) (mg/L)		*E.coli* (10^6 per 100 mL)	
Ideal	<50	No data	<7.0		<0.1		<0.2	0.1	<1	No data
Acceptable	50 - 75		7.0 - 7.5	7.1	0.1 - 0.5	0.4	0.2 - 0.5		1 - 2	
Tolerable	75 - 100		7.5 - 8.0		0.5 - 1.5		0.5 - 1.5		2 - 5	
Unacceptable	>100		>8.0		>1.5		>1.5		>5	



Irrigation Water Fitness-for-Use (Tier 2)

Sample identification:	43: Mafube Irrigation Water (Void 3)
Site description:	45: Mafube Unmined site

Water Analysis

Major constituents (mg/L)

Calcium	235.0	Bicarbonate	335.0
Magnesium	160.0	Chloride	10.0
Sodium	70.0	Sulphate	1130.0
pH	7.1	Total Dissolved solids (TDS)	1940.0
Electrical Conductivity (mS/m)	240.0	Suspended solids	
SAR (mol/L)^0.5	0.9		

Biological Constituents

E. coli (counts/100 mL)	
Chemical Oxygen Demand (mg/L)	

Nutrients (mg/L)

Total inorganic nitrogen (N)	3.5
Total inorganic phosphorous (P)	
Total inorganic potassium (K)	38.0

Pesticides (µg/L)

Atrazine	

Trace Elements in irrigation water (µg/L) and soil (mg/kg)

	Water	Soil		Water	Soil
Aluminium	510	0	Lead		0
Arsenic		0	Lithium		0
Beryllium		0	Manganese	390	0
Boron	225	0	Mercury		0
Cadmium		0	Molybdenum		0
Chromium		0	Nickel		0
Cobalt	3	0	Selenium		0
Copper		0	Uranium		0
Fluoride	1	0	Vanadium	8	0
Iron	110	0	Zinc	40	0

Site Specific Characteristics

Crop

Crop	Maize (Mafube)
Plant date (DD/MM)	1/10

Irrigation management

Irrigation system	Pivot	
Irrigation timing	Amount (mm)	10
Refill option	Field capacity	

Soil

Soil texture	Sandy loam
Soil depth (m)	1.0
Initial water content	Wet (FC)
Profile available water (mm)	120
Plant available water (mm/m)	120
Field capacity (m/m)	0.22
Wilting point (m/m)	0.10
Bulk density (Mg/m3)	1.40

Weather station	WONDERFONTEIN (45 years)

Water Balance

Water balance components	Soybean	Wheat
Mean irrigation application (mm p.a.)	484	489
Mean rainfall (mm p.a.)	558	62
Mean evaporation (mm p.a.)	376	230
Mean transpiration (mm p.a.)	578	306
Mean evapotranspiration (mm p.a.)	954	537
Mean drainage (mm p.a.)	88	17
Effective leaching fraction (%)	8.4	3.1

Tier 2: Fitness-for-Use

Soil Quality of a Sandy loam soil with 996 mm irrigation p.a.

	Fitness-for-use	Root zone salinity (mS/m)	% of time root zone salinity is predicted to fall within a particular Fitness-for-use category
Root zone salinity	Ideal	0 - 200	100
	Acceptable	200 - 400	
	Tolerable	400 - 800	
	Unacceptable	> 800	

	Fitness-for-use	Degree of reduced Permeability	% of time soil permeability is predicted to fall within a particular Fitness-for-use category	
			Surface Infiltrability	Soil Hydraulic Conductivity
Soil Permeability	Ideal	None	30	80
	Acceptable	Slight	70	2
	Tolerable	Moderate		8
	Unacceptable	Severe		10

	Fitness-for-use			Number of years of 996 mm irrigation before Trace Elements reach accumulation threshold in topsoil		
Trace Element Accumulation	**Ideal**			> 200 years to reach soil accumulation threshold		
	Acceptable			150 to 200 years to reach soil accumulation threshold		
	Tolerable			100 to 150 years to reach soil accumulation threshold		
	Unacceptable			< 100 years to reach soil accumulation threshold		
	Trace Element	Soil Accumulation Threshold (mg/kg)	No of years to reach Soil Accumulation Threshold	Trace Element	Soil Accumulation Threshold (mg/kg)	No of years to reach Soil Accumulation Threshold
	Al	2500	984	Li	1250	No data
	As	50	No data	Mn	100	51
	Be	50	No data	Hg	1	No data
	Cd	5	No data	Mo	5	No data
	Cr	50	No data	Ni	100	No data
	Co	25	> 1000	Se	10	No data
	Cu	100	No data	U	5	No data
	F	1000	> 1000	Va	50	> 1000
	Fe	2500	> 1000	Zn	500	> 1000
	Pb	100	No data			

Tier 2: Fitness-for-Use

Yield and Quality of a Soybean crop with 484 mm irrigation per season

Root Zone Effects	Fitness-for-use	Relative crop yield (%)	% of time yield is within relative crop yield category, as affected by:			
			Salinity (EC)	Boron (B)	Chloride (Cl)	Sodium (Na)
	Ideal	90 - 100	100	100		
	Acceptable	80 - 90				
	Tolerable	70 - 80				
	Unacceptable	<70				

Leaf scorching when wetted	Fitness-for-use	Degree of leaf scorching	Degree of leaf scorching under sprinkler irrigation caused by:	
			Chloride (Cl)	Sodium (Na)
	Ideal	None	No scorching parameter	No scorching parameter
	Acceptable	Slight		
	Tolerable	Moderate		
	Unacceptable	Severe		

Contribution to NPK removal	Fitness-for-use	Contribution to estimated N P K Removal by crop	Mean applied N P K at harvest and % of time N P K removal at harvest is within fitness-for-use categories (High nutrient concentrations may impact development of sensitive crops)					
			Nitrogen (N)		Phosphorous (P)		Potassium (K)	
			Time (%)	Applied (kg/ha)	Time (%)	Applied (kg/ha)	Time (%)	Applied (kg/ha)
	Ideal	0 - 10%	100	19		No data		0
	Acceptable	10 - 30%						
	Tolerable	30 - 50%						
	Unacceptable	>50%					100	204

Tier 2: Fitness-for-Use

Yield and Quality of a Wheat crop with 489 mm irrigation per season

	Fitness-for-use	Relative crop yield (%)	% of time yield is within relative crop yield category, as affected by:			
			Salinity (EC)	Boron (B)	Chloride (Cl)	Sodium (Na)
Root Zone Effects	Ideal	90 - 100	100	No parameters	No parameters	No parameters
	Acceptable	80 - 90				
	Tolerable	70 - 80				
	Unacceptable	<70				

	Fitness-for-use	Degree of leaf scorching	Degree of leaf scorching under sprinkler irrigation caused by:	
			Chloride (Cl)	Sodium (Na)
Leaf scorching when wetted	Ideal	None	No scorching parameter	No scorching parameter
	Acceptable	Slight		
	Tolerable	Moderate		
	Unacceptable	Severe		

	Fitness-for-use	Contribution to estimated N P K Removal by crop	Mean applied N P K at harvest and % of time N P K removal at harvest is within fitness-for-use categories (High nutrient concentrations may impact development of sensitive crops)					
			Nitrogen (N)		Phosphorous (P)		Potassium (K)	
			Time (%)	Applied (kg/ha)	Time (%)	Applied (kg/ha)	Time (%)	Applied (kg/ha)
Contribution to NPK removal	Ideal	0 - 10%	100	17		No data		
	Acceptable	10 - 30%						
	Tolerable	30 - 50%						
	Unacceptable	>50%					100	186

Tier 2: Fitness-for-Use

Irrigation Equipment

Corrosion or Scaling of Irrigation Equipment

Fitness-for-use	Fitness for Use Category determined by the corrosion or scaling potential indicated by the Langelier Index			
	Corrosion (Langelier Index)		Scaling (Langelier Index)	
Ideal	0 to -0.5	Not Corrosive	0 to +0.5	0.29
Acceptable	-0.5 to -1.0		+0.5 to +1.0	
Tolerable	-1.0 to -2.0		+1.0 to +2.0	
Unacceptable	<-2.0		>+2.0	

Clogging of Drippers

Fitness-for-use	Fitness for Use Category determined by the potential of an irrigation water constituent to cause clogging of drippers									
	Suspended Solids (mg/L)		pH		Manganese (Mn) (mg/L)		Total Iron (Fe) (mg/L)		*E.coli* (10^6 per 100 mL)	
Ideal	<50	No data	<7.0		<0.1		<0.2	0.1	<1	No data
Acceptable	50 - 75		7.0 - 7.5	7.1	0.1 - 0.5	0.4	0.2 - 0.5		1 - 2	
Tolerable	75 - 100		7.5 - 8.0		0.5 - 1.5		0.5 - 1.5		2 - 5	
Unacceptable	>100		>8.0		>1.5		>1.5		>5	