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The environmental impact and sustainability of irrigation with coal-mine water

by

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Submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy
In the Faculty of Natural and Agricultural Science
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Co-Supervisor: Dr JM Steyn

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DECLARATION

I, the undersigned, declare that the thesis which I hereby submit for the degree of Doctor of Philosophy at the University of Pretoria, is my own work, except where acknowledged in the text, and has not previously been submitted for a degree in any form at this or any other tertiary institution

Yacob Ghebretinsae Beletse

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This thesis is dedicated:

To the glory of God and in thanks giving for my many blessings.

"Thus far has the lord helped us…Ebenezer" 1 Samuel 7:12

To my beloved son Israel and my wife Tsedal Tseggai:

You are God's gift to me.

"Every good gift and every perfect gift is from above…" (James1:17)

To my dear parents:

I hope that this achievement will complete the dream that you had for me all those many years when you chose to provide me with the best education you could.

"Children, obey your parents in the lord, for this is right…

and that you may enjoy long life on earth" Ephesians 6:1-3

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Weldu, Mussie, Tedros, Isacc, Solomon, Kibrom, Saba and Feven

" …with God all things are possible" Mathew 19:26

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THE ENVIRONMENTAL IMPACT AND SUSTAINABILITY OF IRRIGATION WITH COAL-MINE WATER

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ABSTRACT

The environmental impact and sustainability of irrigation with coal-mine water was investigated from an agricultural point of view on different coal-mines in the Republic of South Africa. Field trials were carried out on a commercial and plot scale, on sites that could offer a range of soil, crop, weather conditions and water qualities such as gypsiferous, sodium sulphate and sodium bicarbonate waters. Crop production under irrigation with gypsiferous mine water is feasible on a field scale and sustainable if properly managed. No symptoms of foliar injury due to centre pivot sprinkler irrigation with gypsiferous water were observed. The presence of high Ca and Mg in the water suppressed plant uptake of K. This could be corrected by regular application of K containing fertilizers. The bigger problem experienced was waterlogging due to poor site selection, especially during the summer months. The problem is not related to the chemistry of the gypsiferous water used for irrigation. Pasture production with Na_2SO_4 rich mine effluent was also feasible, at least in the short term, but would need a well-drained profile and large leaching fraction to prevent salt build up. Forage quality was not affected by the Na_2SO_4 water used. $NaHCO_3$ water was of very poor quality for irrigation and is not recommended for irrigation. Salt tolerant crops that are not susceptible to leaf scorching can be produced with this water, but only with very high leaching fractions and careful crop management. Regular gypsum application will be required to prevent structural collapse of the soil. Most of the salts applied will leach from the soil profile, and will probably need to be intercepted for treatment or reuse. The Soil Water Balance (SWB) model was validated successfully. The model predicted crop growth, soil water deficit to field capacity and soil chemistry reasonably well, with simulated results quite close to measured values. Soluble salts have to be leached from the soil profile, so that crop production can be sustainable, but will externalize the problem to the receiving water environment. To assess the environmental impact of irrigation with coal-mine water, it is valuable to develop a tool that can assist with prediction of offsite effects. SWB was validated for runoff quantity and quality estimations, and was found to give reasonable estimates of runoff quantity and quality. SWB also predicted the soil water and salt balance reasonably well. This gives one confidence in the ability of the model to simulate the soil water and salt balance for long-term scenarios and link the output of SWB to ground and surface water models to predict the wider impact of large scale irrigation. This will also link the findings of this work to other research oriented towards the management of mine water and salt balances on a catchment scale. It will also help authorities make informed decisions about the desirability and consequences of permitting mine water irrigation on a large scale. Irrigation with gypsiferous mine water can be part of finding the solution to surplus mine water problems. Appropriate irrigation management of mine water is essential for the long-term sustainability of irrigation.

Key words: Coal-mine water, irrigation, SWB model, modelling, soil salinity, $CaSO_4$, gypsiferous water, Na_2SO_4, $NaHCO_3$, sustainability, environmental impact

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LIST OF SYMBOLS AND ACRONYMS

AMD	Acid Mine Drainage
CBM	Coal bed methane
CEC	Cation Exchange Capacity
D	Wilmot's index of agreement
DOY	Day of the year
DRIS	Diagnosis and Recommendation Integrated Systems
EC	Irrigation water salinity
EC_e	Soil saturated paste extract
EC_{iw}	irrigation water salinity
ESP	Exchangeable Sodium Percentage
ET	Evapotranspiration
HDM	Harvestable Dry Matter
HDM	Harvestable Dry Matter
LAI	Leaf Area Index
LF	Leaching Fraction
LR	Leaching Requirement
MAE	Mean Absolute Error
r^2	Coefficient of determination
RD	Root Depth
RMSE	Root Mean Square Error
SAR	Sodium Adsorption Ratio
SCS-CN	Soil Conservation Services Curve Number
SD	Standard deviation
SR	Sufficiency Range
SWB	Soil Water Balance
TDM	Top Dry Matter
TDM	Top Dry Matter
TDS	Total dissolved salts
WFDs	Wetting Front Detectors

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CHAPTER 1

GENERAL INTRODUCTION

1.1 Introduction

South Africa's coal industry is the second biggest mining sector after gold, with sales contributing 16% to export revenue in 2003 (R20 billion in 2000) or 4% of the GDP. Mining impacts upon the natural water environment and its effect may be manifest throughout the life cycle of the mine, and even long after mine closure. According to Younger *et al.* (2004), the potential impacts of mining on the water environment are a) disruption of hydrological pathways, b) seepage of contaminated leachate into aquifers, c) disposal of saline mine water, and d) depression of the water table around the dewatered zone.

The impacts of mining arising from the disruption of hydrological pathways and seepage of contaminated leachate into aquifers tend to be relatively localised and limited compared to disposal of mine water (Younger *et al*., 2004). Disposal of mine water is a worldwide problem, occurring wherever operating mines, both underground and opencast workings are found (Pulles *et al*., 1995). The quality of the mine water depends largely on the chemical properties of the geological materials that come into contact with it (Thompson, 1980). Salts in solution usually cause such waters to be unsuitable for direct discharge into river systems and can limit other potential down stream uses.

Management options for saline mine water in South Africa are discussed in detail by Pulles (2006) and are summarized as (1) pollution prevention at source, (2) reuse and recycling of polluted water to minimize the volume of polluted water being discharged, (3) treatment of effluents should be implemented if the problem cannot be solved through prevention, reuse and recycling, (4) discharge of treated effluent, which is considered as the last resort. Pulles (2006) also reports that utilization of poor quality water for irrigation could be considered as a water reuse strategy that may have application, especially in the post closure phase.

Coal-mines in South Africa have adopted these water management strategies; however, some have excessive volumes of water, and not all of it can easily be taken care of following the four hierarchial management options (Gunther, 2006).

Reasonable estimates of volumes of mine-water stored and generated are available for a number of active mines in the central Witbank Coalfields (Mpumalanga Province, South Africa), which is one of the biggest Coalfields in the country. Grobbelaar *et al*., (2004) indicate that 360 Mℓ d^{-1} may be generated after closure of the entire Mpumalanga Coalfields. For the Olifants Catchment, a volume of 170 Mℓ d^{-1} is suggested. Not all this water will report to the same locality, and several sub-areas where water will decant from the mines are envisaged. The expected discharge at each decant position ranges between 12 and 40 Mℓ d^{-1}. These volumes of decant water have the potential to support in excess of 6 000 ha of irrigation in the Olifants Catchment alone. On a site-specific scale, Kleinkopjé Colliery (Witbank, Mpumalanga) for instance, has 12 x 10^6 m^3 of water stored underground, and it is estimated from pumping and water level data that the daily water make is in the order of 14 Mℓ d^{-1} (Grobbelaar *et al*., 2004). This is sufficient to sustain an irrigated system of some 500 to 700 ha, depending on the particular cropping system chosen (Jovanovic *et al*., 2002). If the proposed Waterberg Coal Bed Methane (CBM) operation (Waterberg Coalfields, Limpopo Province) is found to be feasible and commissioned, a total volume of 2 million m^3 of mine water will be generated per year, and this will continue for 30 years.

Most mines in these coalfields produce waters dominated by calcium and magnesium sulphates, and have near neutral pH values. The southern fields have high pH and also carbonates such as calcite and dolomite that make waters alkaline (Usher *et al*., 2003). Treatment of these mine waters will minimize pollution of water resources. However, this needs complex technologies with associated high costs to bring the water quality to a condition acceptable for release into natural watercourses. Interest has been growing in finding ways that can decrease the production of contaminated water and make its treatment less costly.

In the early 80s, the potential to use gypsiferous mine-water for irrigation of field crops was first evaluated in South Africa by Du Plessis (1983), using the steady-state chemical equilibrium model of Oster & Rhoades, (1975). Du Plessis (1983) predicted the amount of salt that would leach, and could potentially contaminate groundwater, and found that irrigating with gypsum rich water would result in lower soil- and percolate salinity compared to irrigation using a chloride rich water of otherwise similar ionic composition. This could be attributed to precipitation of gypsum in the soil. The increased sodium hazard caused by gypsum precipitation was not expected to seriously affect soil physical properties and crop yield using a typical gypsiferous mine-water for irrigation (Du Plessis, 1983).

The potential use of mine-water for agricultural crops was tested in a series of field trials from 1993-2000 (Jovanovic *et al*., 1998; Annandale *et al*., 1999; Annandale *et al*., 2001). The results of these studies indicated that crops were able to tolerate the salinity of gypsiferous waters and were grown successfully on a commercial scale, at least in the short term (Annandale *et al*., 2001; Jovanovic *et al*., 2002). The long-term crop performance and environmental impact, that is, the field scale sustainability of irrigation with mine water, however, had to be evaluated. Since long-term field experiments are expensive, time-consuming and produce only site-specific information, computer simulation models were required to predict the performance of various crops irrigated with different water qualities, on different soil types and under different climatic conditions. The Soil Water Balance (SWB) model is a crop growth-soil salinity model developed and validated during previous studies (Annandale *et al*., 1999), and was found to offer detailed insight into water and salt balances in space and time. However, short-term experiments may not provide conclusive evidence that these waters can be sustainably used for agricultural crops, and this raised several research questions for further study. The critical research questions raised were as follows:

1. According to Jovanovic *et al*. (1998), higher crop yields could be obtained under irrigation with gypsiferous mine water compared to dry land production, and dry season production is also possible under irrigation. This conclusion was drawn only for crops irrigated with lime treated acid mine drainage (gypsum rich water). What if the composition and concentration of the coal-mine water, the soil type and weather were different to those in their studies? Will it still be possible to grow crops and what management practices would be required? What would the effect of prolonged use of different qualities of coal-mine water on the soil chemical and physical properties, crop yield and plant nutrition?

2. Annandale *et al*. (2001), from their three years of commercial scale field experiments, concluded that possible nutritional problems, like for example deficiencies in K, Mg and NO_3, occurring due to Ca and SO_4 dominating the system, can be solved through fertilization management. What are the most limiting nutrients in crops irrigated with different qualities of coal-mine water? Could one use standard fertilization recommendations on such soils irrigated with different qualities of coal-mine water?

3. According to Annandale *et al*. (2001), soil salinity of irrigated soils increased compared to the beginning of the trial, and saturated extract electrical conductivity fluctuated around 200 mS m^{-1}, which is typical for a saturated gypsum solution. Did gypsum precipitate in these irrigated fields? If so, how much gypsum precipitated in these coal-mine water irrigated soils?

4. According to Annandale *et al*. (2001), the SWB model was validated for the sites where the field trials were carried out, and these validations were done for a few seasons by simulating single growing periods at a time. Could SWB be improved to simulate actual crop rotations in order to validate the sustainability of irrigation with different qualities of coal-mine water from the point of view of crop production and soil chemical properties?

5. The impact of irrigation with gypsiferous mine water on groundwater quality was assessed, and the groundwater quality did not show significant deterioration over the monitoring period (Annandale *et al*., 2001). In order to study the impact of soluble salts or redisolved precipitated gypsum from irrigated sites on surface water quality, SWB needs to be able to simulate runoff reliably. Is there enough confidence in the simulated runoff output values of SWB to be used for large scale impact assessment by geohydrological modellers?

In order to answer these critical questions, a research project titled “The environmental impact and sustainability of irrigation with coal-mine water” was initiated.

The objectives of this research were:

1. To investigate the sustainable use of different qualities of coal-mine water for the production of various crops under different soil and climatic conditions;

2. To investigate the impact of irrigation with gypsum rich mine water on the chemical properties of the soil and ascertain whether or not there is precipitation of gypsum in these irrigated soils;

3. To study any nutrient imbalances in plant tissues that could occur as a result of ions in the irrigation water, and to evaluate the suitability of standard fertilization recommendations for mine water irrigated soils;

4. To evaluate the SWB model for its accuracy in simulating several crop rotations and to evaluate the sustainability of irrigation with coal-mine water from the point of view of crop production and soil chemical properties, using measurements taken during the experiment and relevant outputs generated by SWB, and

5. To improve and validate the runoff quantity and quality estimates of SWB, to ensure this is simulated reliably.

1.2 Research approach

The general approach was to establish several commercial and plot scale experimental sites in the Republic of South Africa, that could offer a range of soil, wheather, crop and water quality conditions. The commercial scale experiments were set up in the Mpumalanga Province, close to Witbank (Kleinkopjé Colliery) and near Secunda (Syferfontein Colliery), and in the Free State Province, near Vereeniging (New Vaal Colliery). Kleinkopjé (Anglo Coal) included three centre pivot irrigated fields of between 20 and 30 ha each, and at New Vaal, also an Anglo Coal-mine, a single 10 ha pivot was set up. The Sasol mine, Syferfontein, had a 20 ha pivot site. Figure 1.1 is regional map of Republic of South Africa showing the location of the research sites.

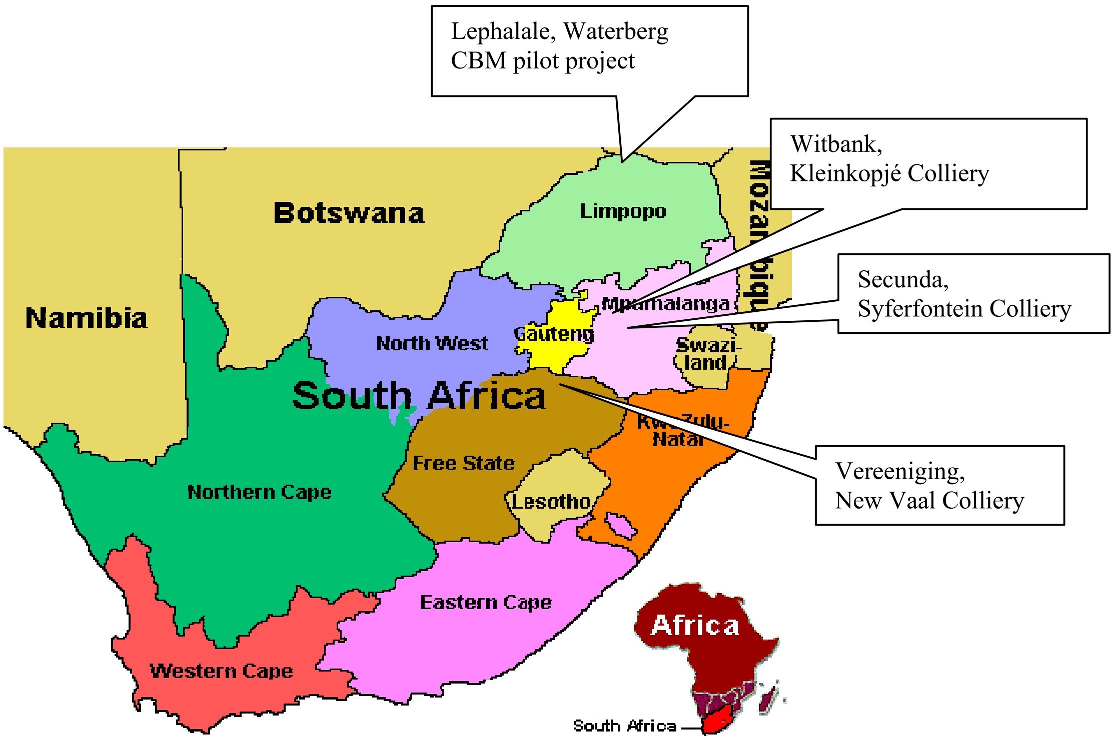

Figure 1.1 Regional map of irrigation mine water research sites

In the commercial scale studies at Kleinkopjé, agronomic field crops such as maize, wheat and potatoes were selected, depending on the interest of the mines and/or commercial farmers managing the fields. An intensive cycle of 3 vegetable crops (peas/sweetcorn/pumpkins) was also attempted at New Vaal, but waterlogging was problematic due to poor site selection. Perennial pastures were planted at Syferfontein due to the highly saline irrigation water and very heavy clay soil. Due to the installation of a conveyer belt between Kriel and Sasol that ran through middle of the irrigated field, the trials at Syferfontein were discontinued after two years of monitoring. The plot scale experimental site was set up in the Limpopo Province, 25 km north of Lephalale (Ellisras), at the Anglo Coal, Waterberg Coal Bed Methane (CBM) Pilot Project. In this experiment, drip and sprinkler irrigation systems were used on a 0.14 ha trial site, and test crops were selected based on their salinity tolerance and adaptation to the hot climate of the Waterberg area. The crops studied were: cotton, barley, Bermuda grass and ryegrass. Water qualities, soils, cropping systems investigated are summarized in Table 1.1

Table 1.1 Summary of water qualities, soils and cropping systems

	Kleinkopjé (Anglo Coal)	New Vaal (Anglo Coal)	Syferfontein (Sasol)	Waterberg (Anglo Coal)
Water quality	$Ca/Mg/SO_4$	$Na/Ca/SO_4$	Na_2SO_4	$NaHCO_3$
(mS m^{-1})	EC = 300-500	EC = 110	EC = 370	EC = 750
Soil	Clay loam	Sandy soil	Heavy clay	Sandy clay
Cropping system	Maize-wheat-potatoes (17 seasons)	Maize-wheat-vegetables (7 seasons)	Pasture species (9 harvests)	Barley-ryegrass, cotton-Bermuda grass (2005/2006)

Each mine generates different water qualities depending on the geological properties of the site. This is useful to assess the sustainability of irrigation with different water qualities as well as to validate the chemical equilibrium subroutine of the SWB model. Kleinkopjé generates two waters of similar qualities, both being rich in $CaSO_4$ and $MgSO_4$ (Jacuzzi and Tweefontein waters). Water from Jacuzzi was replaced during the project with water from New Vleishaft Dam, because of deteriorating pH. The electrical conductivity (EC) of New Vleishaft Dam water started off at around 250 mS m^{-1} in 1997, but climbed steadily to a value of 320 mS m^{-1} by the end of 2005 and started to decrease in 2006. At Tweefontein Pan, the EC started off a little higher than the New Vleishaft Dam water at around 300 mS m^{-1}, and was fairly stable for several years until 2001. An increase in EC to a level of 500 mS m^{-1} was observed by the end of 2005 at Tweefontein Pan, which decreased again in 2006. Syferfontein generates quite saline water (EC around 370 mS m^{-1}) with high concentrations of Na and SO_4. It is, of course, difficult to precipitate gypsum in the profile with a sodium sulphate dominated water quality. New Vaal generates water with an EC around 130 mS m^{-1}, and this water is predominantly rich in $CaSO_4$ with some NaCl. The Waterberg Coal Bed Methane (CBM) water is withdrawn from a depth of 250 m during methane gas production, and is very saline-sodic, dominated by $NaHCO_3$, with an EC around 800 mS m^{-1} and SAR of 85 (mmol $\ell^{-1})^{0.5}$.

It was also fortunate that crop response on a wide range of soil types could be monitored. Soils ranged from very sandy (<10% clay) at New Vaal and Waterberg, to a very heavy clay soil

(>60% clay) at Syferfontein. Soils at Kleinkopjé were medium textured. Soil profiles were also of varying depths, and were on both rehabilitated and unmined sites.

The approach was to monitor the crop growth, soil water and salt balance under these widely varying conditions, and then to attempt to model the dynamics of the system.

1.3 Thesis outline

The thesis is written in a series of Chapters, each contributing to the research questions and objectives stated above. A review of the existing local (South African) and international knowledge available on irrigation with saline and/or saline sodic water is presented in Chapter 2. In this Chapter, modelling the effects of saline sodic irrigation on crop growth, irrigation with mine water in southern Africa, runoff and drainage from mine water irrigated fields and possible impacts of mine water on surface waters are discussed. This chapter is followed by six more. Chapter 3 details field sites, location, experimental layout, water qualities, soil, weather, modelling and data processing. Chapter 4 is on production and plant nutrition of the crops under investigation. Chapter 5 covers the impact of irrigation with coal-mine water on soil chemical properties. Chapter 6 presents modelling of the field scale environmental impact of irrigation with coal-mine water from the point of view of crop production and soil chemical properties in the medium-term to long-term. Chapter 7 broadens the applicability of the field scale modelling by investigating surface runoff quantity and quality of mine water irrigated fields. Chapter 8 summarizes important results and makes recommendations for further studies.

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CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In open cast and underground coal mining operations, large volumes of coal-mine water from aquifers are released inadvertently through coalfaces. The coalfaces contain groups of minerals of metallic sulphides called pyrites, which can easily create sulphuric acid (acid mine water) when they come into contact with the released aquifer water (Gladney *et al*., 1983). This water is a major problem for coal-mines throughout the world (Kupchella and Hyland, 1993). The devastating effect of such waters is associated with its acidity (between pH 2 - 4). Some coal-mines also generate water qualities associated with calcium, magnesium, sodium, sulphate, carbonate and bicarbonate, with near neutral pH depending on the geology of the area.

Various studies show that some of these waters cannot be used for domestic purposes and/or released into natural streams, unless some form of water treatment is applied to nullify or neutralize its acid levels. Liming plants are usually used to treat the water and reduce its acidity levels to between pH 5 and 9.5 before the water can be utilized. However, the cost of running such liming plants is very high and thus, alternative methods have been sought. In most cases, after neutralization, the water is too saline to release to streams. These neutral mine waters need additional treatment, unless they can be utilized through some other technology, like irrigation of agricultural crops (Annandale *et al*., 1999).

A survey of literature reveals that agricultural use of mine water *per se* is limited; however, several reports are available on saline and/or sodic water use for irrigation of agricultural crops. Mine water is often very poor in quality, and can thus be classified as saline and/or sodic waters. The available literature on saline and/or sodic water, therefore, can be applied to the concept of coal-mine water irrigation, and in this literature review, the local (South African) and international knowledge available on irrigation with saline and/or sodic water is considered.

2.2 Soil and crop response to saline and saline-sodic water

Soils and crops respond to saline and saline-sodic irrigation either positively or negatively, depending on the composition and salt concentration of the water. For successful use of saline water for agriculture, therefore, selection of salt tolerant crops, suitable irrigation management strategies and the choice of appropriate irrigation systems is essential (Rhoades and Loveday, 1990).

2.2.1 Crop response to salinity

There are two ways in which saline waters affect plant growth: (1) when salts in the irrigation water decrease the osmotic potential of soil water and (2) when ions in the soil water exceeds a certain concentration value and become toxic to plants.

Effect of salinity on osmotic potential

Plants extract water from the soil when leaf water potential is less than total soil water potential. Total soil water potential is the sum of matric, osmotic and gravitational potential of the soil water. Salinity affects plant growth by decreasing the osmotic potential of the soil water. Plants close stomata when water is unavailable as a result of decreased osmotic potential in the soil water. Depending on the plant species, stomata begin to close when leaf water potential reaches -500 to -1500 kPa (Boyer, 1974), which leads to a reduction in photosynthesis. When leaf water potential reaches -1500 to -3000 kPa, the stomata are completely closed and photosynthesis ceases (Begg & Turner, 1976). Leaf enlargement and other growth processes begin to be affected at even higher (less negative) leaf water potential values than those which affect photosynthesis (Boyer, 1970 & Hsiao, 1973). According to Boyer (1974), plant growth may be reduced even if matric potential is close to zero, if the concentration of soluble salts in the soil water is high enough to lower osmotic potential to several hundred negative kPa. A matric potential close to zero implies that the soil water content is high. This indicates that a high salt concentration has the same impact on plant growth as low soil water content, the latter being associated with a low matric potential.

Toxicity

The concentration at which toxicity affects plant growth depends on the ion and plant species involved (Bernstein *et al*., 1974). Ions like boron, sodium and chloride in irrigation water can cause toxicity in certain crops. Ayers and Westcot (1985) present recommended maximum concentrations of trace elements in irrigation water. Specific ion effects may involve direct toxicity or nutritional imbalance (Berstein & Haward, 1958; Orcutt & Nilsen, 2000). The detrimental effects of ions can be observed at the level of enzyme activity, membrane function and several important metabolic process, including photosynthesis and respiration (Orcutt & Nilsen, 2000). Under saline conditions, which are characterized by low nutrient ion activities and extreme ratios of Na/Ca, Na/K, Ca/Mg and Cl/NO_3, nutritional disorders can develop and crop growth may be reduced. Nutrient imbalance may result from the effect of salinity on nutrient availability, competitive ion uptake, transport of or partitioning of ions within the plant, or may be caused by physiological inactivation of a given nutrient, resulting in an increase in the internal requirement for the essential element (Mengel & Kirkby, 1987). Excessive amounts of Na salts in soil water reduce Ca availability as well as transport and mobility of Ca to growing regions of the plant. Salinity can also directly affect ion uptake due to competition for uptake through cell membranes as Na decreases K, Cl and NO_3 uptake (Grattan & Grieve, 1994). Most of the works that has been done on toxicity are compiled in the hand books quoted here. Not much work has been done since then.

2.2.2 Soil salinity

As water is taken up by the crop or evaporates from the soil surface, salts are left behind and accumulate. Each plant has a maximum soil salinity level that it can tolerate without negatively influencing yield or crop quality due to osmotic and/or specific ion effects (Maas & Hoffman, 1977; Maas, 1987). The salts need to be leached below the root-zone and according to Ayers & Westcott (1985), the leaching requirement (LR) can be estimated as $LR= EC_{iw}/[5(EC_e-EC_{iw})]$ where EC_{iw} and EC_e refer to irrigation water salinity and the crop tolerance to soil salinity. LR is the amount of additional water to be applied in excess of crop water requirement to prevent salt accumulation. LR increases as the EC of the irrigation water increases. In addition, LR depends on the initial profile salt content of the soil, the required level of soil salinity after leaching, the depth to which leaching is required, and soil chemical and physical properties (Ayers & Westcott, 1985; Abrol *et al*., 1988; Hoffman & Durnford, 1999). It is, however, not necessary to achieve with every irrigation event and leaching is only needed once the levels of soil salinity approaches hazardous levels (Oster, 1994).

2.2.3 Soil sodicity

High salt concentration and toxic salt levels do not damage or affect the physical properties of a soil (Shainberg & Letey, 1984). Irrigation waters with high sodium levels, however, tend to produce soils with high exchangeable sodium levels. Such soils frequently crust, swell, disperse and decrease the infiltratrability. High Sodium Adsorption Ratio's (SAR) increase infiltration problems, but if the irrigation water also contains high levels of salinity, the infiltration hazard is lessened. Du Plessis & Shainberg (1985) carried out a study on infiltration rates of South African soils using a rainfall simulator and results confirmed that some soils are very susceptible to crust formation at exchangeable sodium percentages (ESP) as low as one. Sumner's (1993) study also showed that soils with very low levels of exchangeable sodium can exhibit sodic behaviour in the presence of low salinity water. Ayers & Westcot (1985) published guidelines to indicate the severity of expected infiltration problems based on SAR and EC of the irrigation water. A severe reduction in infiltration is likely to occur with the condition of relatively low EC and high SAR (Figure 2.1).

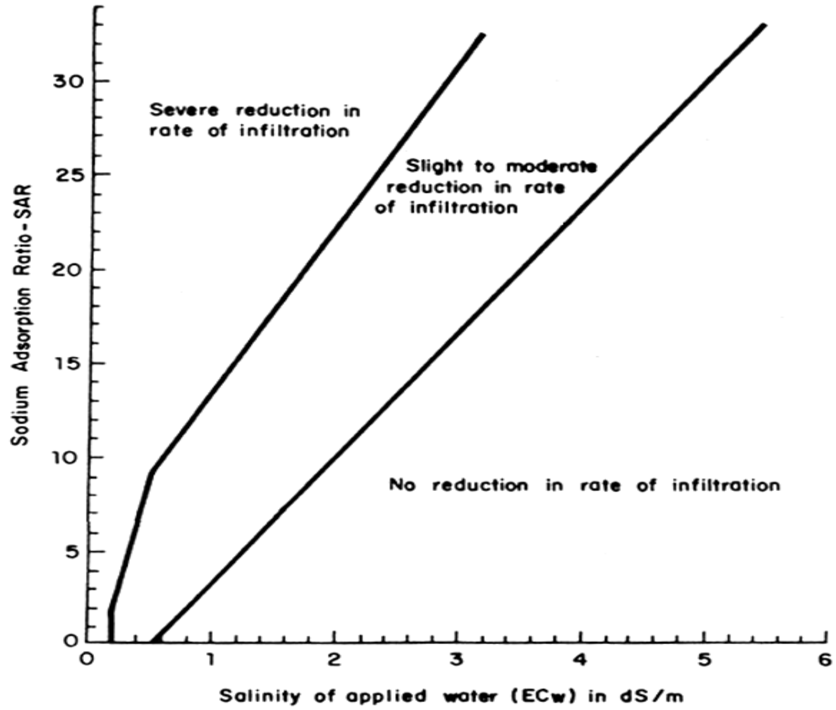

Figure 2.1 Potential for reduction in infiltration rates resulting from various combinations of EC and SAR of applied water (Ayers & Westcot, 1985)

Infiltration problems due to high SAR can be improved by adding gypsum to the soil or to the irrigation water. When the irrigation water comes into contact with gypsum, it dissolves into Ca and SO_4 ions that may slightly increase the salinity of the water, but simultaneously reducing the SAR. The Ca cations are then free to displace Na cations adsorbed onto the negatively charged clay particles, thereby enhancing flocculation, improving soil structure, and increasing the infiltratability.

The capacity of the SAR (SAR= Na/((Ca+Mg)/2)$^{\wedge 1/2}$) and ESP (ESP = (Na/ (Ca + Mg + Na + K))*100) equations to predict sodicity hazard from irrigation water quality and soil exchange sites is often complicated by evapotranspiration and changes in calcium solubility in the soil water that take place due to precipitation or dissolution (Ayers & Westcot, 1985). Shainberg & Letey (1984), and Rhoades & Loveday (1990), also noted that the change in the concentration of irrigation water and soil solution during a growing period are more important parameters than ESP for predicting the effect of sodicity hazard to the soil. Suarez (1981) introduced adjSAR to estimate the tendency of $CaCO_3$ to dissolve or precipitate, following irrigations and this parameter improved the capacity of SAR and ESP to predict soil physical problems. The permeability hazard, however, can be evaluated according to the relationship described by Rhoades & Loveday (1990) between adjSAR and the EC of the irrigation water.

2.3 Modelling the effects of saline-sodic water irrigation on crop growth

The need to assess sustainable use of coal-mine water for irrigation with regard to crop production, and the effect on soil chemical and physical properties, increased over the last decade (Annandale *et al*., 2007b). Such relations between irrigation water quality, crop growth, irrigation management and fertilization under different soil and cropping systems is complex, and needs well designed long-term field experiments. Long-term field experiments of such complex interactions, of course, are time consuming and expensive. Annandale *et al*. (2001) developed a soil water and salt balance model called SWB (Soil Water Balance) to manage irrigation with these water qualities and to provide insights into long-term effects of such waters on crop growth, soil water and the salt balance. The idea of this computer modelling study was also to assess the feasibility of using mine water for large scale irrigation, and predict the quantity and quality of irrigation return flows to groundwater and river systems. The model, however, would benefit from field-scale testing for a range of soil types, irrigation water qualities and cropping practices. In the following section, root zone modelling will be discussed. Return flows from mine water irrigated fields will be discussed in section 2.5.

2.3.1 Root zone modelling

The root zone is a dynamic region in a soil profile, with continual changes in water content, plant uptake of water and salts (Suarez, 2001). Water and solute movement, and root water uptake in this region are modelled in detail to accurately simulate the soil water and salt balance (Cardon & Letey, 1992b). There are several detailed root zone-salinity management models available in the literature. Clarke (1973) categorized such models into four groups: stochastic conceptual, stochastic empirical, deterministic conceptual and deterministic empirical. A model is considered as stochastic if any of the variables in its mathematical expression are described by a probability distribution. A model is termed deterministic if all variables are of from random variations. Models are conceptual if their functional form is derived from consideration of physical processes, and empirical if not. Addiscott & Wagenet (1985) also classified available models into deterministic and stochastic with the same definitions as that of Clarke (1973). SWB is a deterministic conceptual model.

The most recent review of model classification is by Hoffman *et al*. (1990), who classified them as transient and seasonal models. The seasonal models consist of equations that relate the amount of applied water to the seasonal yield, yield to average root zone salinity, yield to evapotranspiration (ET) and average root zone salinity to leaching fraction (LF) (Letey *et al*., 1985, Knapp, 1999). These models assume steady-state conditions and do not include crop response to variation in water content, weather, and soil salinity in space and time (Bresler, 1986). According to Bresler & Hoffman (1984) such models are not suitable for irrigation management under saline conditions. Examples of this type of model are WATSUIT (Rhoades, 1987) and SWAM (Singh *et al*., 1996). Research carried out by Letey *et al*. (1985) and Prendergast (1993) also report that these models may sometimes give results that could agree with observed field data, but have limited applications.

The transient models simulate water and solute movement in soil (Wagenet & Hutson, 1989; Cardon & Letey, 1992a). Water and solute movement in the soil, and root water uptake, are modelled in detail. However, the crop growth description is simple and does not consider interactions with environmental variables and agronomic management (Cardon & Letey, 1992b) an example of this is SWAP93 (Van Dam *et al*., 1997). According to Majeed *et al*., (1994), applications of such models for management of irrigation with saline water require a mechanistic description of relevant processes in the soil-water-plant-atmosphere continuum and proper interaction of these processes with crop growth. The Root Zone Water Quality Model (RZWQM) (RZWQ Team., 1998) and the SWB model are a few examples of mechanistic models in the USA and in southern Africa. Soil Water Balance (SWB) (Annandale *et al*., 1998) is a mechanistic, multi-layer, daily time step, soil water-salt balance-generic crop growth model, locally developed and parameterised for many crops.

Simunek *et al*. 2003 also recently reviewed various approaches for modeling preferential and non-equilibrium flow and transport in the vadose zone. The existing root zone water flow modelling approaches differ in terms of their underlying assumptions and complexity. They range from relatively simplistic models to more complex physically based models. According to Larsson and Jarvis (1999), the limited availability of comprehensive data sets has so far restricted the field validation of preferential flow models.

The applicability of the existing models to irrigation with mine water depends on the degree to which the models accurately represent the natural processes. For example, UNSATCHEM (Suarez, 2005) has unique features such as prediction of CO_2 concentration in the root zone, consideration of the effects of soil chemistry on hydraulic properties and inclusion of a kinetic model to describe the calcite dissolution and precipitation. SWB simulations have been found to be satisfactory for gypsum precipitation when compared to the out puts of UNSATCHEM.

2.3.2 Application of root zone modelling

Models have been used extensively to simulate field conditions for understanding basic processes and the long-term effects of various management options on the soil water and salt balance at field scale (Annandale *et al*., 2007a; Gates *et al*., 2002; Sarwar & Bastiaanssen, 2001). Particularly, validated mechanistic models have some advantages over long-term field experiments with respect to synthesizing information inexpensively and quickly. However, the reliability of model results is contingent upon the degree to which the models accurately represent the natural processes. Thus, model results must be compared to results from field experiments to ascertain the degree of model performance.

In most root zone model applications, the model is calibrated using a single season's experimental results and then evaluated with data from other years. This type of evaluation may not be effective if weather conditions are similar in all the study years. Another technique is to calibrate the model in one location and evaluate it in another location. Preferably, model evaluation should cover a broad range of management effects and locations. Good model predictions depend on model input parameters and model concepts as well as representative experimental data (Singh, *et al*., 1996). Evaluation of a model can only be objective if model users can give representative model input parameters. Some model parameters cannot be measured in one single experiment; therefore calibration of certain parameters is possible to achieve desired output (Donigian *et al*., 1995).

As noted above, model calibration and validation are necessary and critical steps in any root zone model application. Model performance and calibration/validation are evaluated through qualitative and quantitative measures, involving both graphical comparisons and statistical tests (Donigian, 1995). Comparisons of simulated and observed variables should be performed for daily, monthly, and annual values. Statistical procedures can include error statistics, correlation and model-fit efficiency coefficients, and goodness-of-fit tests.

2.3.3 Field scale application of the SWB model

The theory, classification and validation of root zone modelling approaches in general have been discussed. In this section, the SWB model is considered as an example of a root zone model that has been widely applied to field conditions in the southern Africa.

Model description

Soil Water Balance (SWB) is a mechanistic, multi-layer, daily time step, soil water-salt balance-generic crop growth model, developed from NEWSWB, a modified version of the model published by Campbell & Diaz (1988).

The first components of the soil water balance, which are calculated on a daily time step, are canopy interception of water and surface runoff. Water infiltration and redistribution can then be calculated using either a cascading soil water balance or a finite-difference water movement module based on Richards' equation. In the case of the cascading water balance, salt redistribution is determined assuming complete mixing of irrigation and rainfall with the soil solution of the topsoil layer, and similarly for the solution percolating to the next lower soil layer and so on. Any water that passes beyond the bottom layer is assumed lost to deep percolation. The amount of salt leached is then calculated from the amount and quality of the drained water.

Chemical equilibrium is calculated on a daily time step per soil layer, using the model published by Robbins (1991). The model of Robbins (1991) solves chemical equilibrium by iteration. Within each iteration, activity coefficients and ion activities are calculated for Ca, Mg, Na, H, SO_4, HCO_3 and CO_3, and the solution phase is equilibrated with solid phase lime and gypsum, if present. EC is calculated from individual ion concentrations (McNeal *et al*., 1970) for each soil layer. The SWB model ends the iteration procedure when the change in EC between the previous and the following loop is < 0.01 mS m^{-1}.

Potential evapotranspiration (PET) is calculated as a function of daily average air temperature, vapour pressure deficit, radiation and wind speed, adopting the internationally standardized FAO Penman-Monteith methodology (Allen *et al*., 1998). The two components of PET (potential evaporation and potential transpiration) are estimated from canopy cover. Actual transpiration is determined on a daily basis as the lesser of root water uptake or maximum loss rate (supply or demand limited). Total soil water potential is used to determine the amount of water available for crop transpiration in each soil layer. The osmotic effect on crop growth is simulated by adding osmotic potential to the matric and gravitational soil water potentials. Osmotic potential is calculated as a function of ionic concentration (Campbell, 1985). The daily dry matter increment (DM_i) is taken as the minimum of the water supply limited (Tanner & Sinclair, 1983) and radiation limited DM_i (Monteith, 1977). A stress index, the ratio between actual and potential transpiration, is used as a limiting factor for canopy growth.

Required weather and management input data are planting date, latitude, altitude, rainfall and irrigation water amounts and quality, as well as maximum and minimum daily temperature. In the absence of measured data, SWB estimates solar radiation, vapour pressure and wind speed according to the FAO recommendations (Allen *et al*., 1998). Required soil input data are volumetric field capacity, permanent wilting point and a runoff curve number to calculate runoff based on the SCS method (Stewart *et al*., 1976). In addition, initial volumetric soil water content, the content of soluble and exchangeable ionic species, as well as initial gypsum and lime are required for each soil layer.

If cascading redistribution is used, a drainage factor (fraction of water above field capacity that cascades daily to the next layer) and a drainage rate upper limit (maximum amount of water that can percolate from the bottom layer in a day) needs to be entered. The SWB model is written in Delphi v. 7.0 (Inprise Corp.) and runs in a user-friendly Windows 95 environment. The SWB model includes a database of specific crop growth parameters for 137 species (Annandale *et al*., 2007b).

Model application

Jovanovic *et al*. (1998), used SWB to predict the soil water and salt balance of lime treated acid mine water irrigated crops. Simulations were done using calculated crop growth co-efficients fitted measured data of water balance and crop growth. The predictions of the crop growth, soil water content and soil solution EC_e for single season simulations gave good agreement with observed data. Annandale *et al*. (2001) recommended that the SWB model should be further refined and validated for a range of soil types, irrigation water qualities and cropping practices. Further improvements and refinements should also be made to the runoff subroutine of the model. Beletse *et al*. (2004) also validated SWB for pastures irrigated using sodium sulphate rich mine water. Results showed that crop growth, soil water content and soil solution EC_e were well simulated, and good agreement was found between observed and predicted values. SWB model output of return flow from mine water irrigated areas was used as input into a groundwater model and the authors concluded that the impact of irrigation with mine water on ground water was simulated quite well (Annandale *et al*., 2006).

2.4 Irrigation with mine water in southern Africa

South Africa is the leading country in terms of mining in the southern part of Africa and mining contributes about 8% to the economy of the country. Coal mining in South Africa, in particular, is a very important industry, with a total of 65 collieries operating throughout the country (Pulles *et al*., 1995), and is the largest foreign exchange earner after gold.

Many of South Africa's largest coal-mines are located within the Witbank Coalfields in the Mpumalanga Province (Jones & Wagner, 1997). These coalmines consist of both underground and opencast workings. A large amount of low water quality is generated from these coal-mining activities and is in excess for coal beneficiation, road wetting, slurry dams and other activities. Pulles, *et al*. 2001 investigated the over all water balance of the South African coal mining industry and indicated that on average 133 ℓ of water is used for each ton of coal that is mined. They also reported that on average a mine use 77 963 m^3 day^{-1} for coal beneficiation and 13 064 m^3 day^{-1} for road wetting.

Mine water is unsuitable for direct discharge to the river systems except in periods of high rainfall when an adequate dilution capacity is present and controlled release is permitted (Pulles *et al*., 1996). A number of alternative desalinization treatment technologies were investigated (van Zyl, *et al*., 2000) where treated mine water must meet more stringent quality requirements (eg. <200 mg ℓ^{-1}). The capital cost of this process varied between R4 million/M ℓ/d and R10 million/M ℓ/d and the running cost between R2/m^3 and R5/m^3.

South Africa is a dry country with an average annual rainfall of only 464 mm, compared with a world average of 860 mm (Scott *et al*., 1998). Sixty five percent of the country has an annual rainfall of less than 500 mm, usually regarded as the absolute minimum for successful summer season dry-land farming. For this reason the available marginal and low quality water resources, such as mine water generated during mining operations, are becoming under an increasingly important consideration for irrigation purposes.

South Africa is the first country to test mine water for irrigation of agricultural crops in the region. The possible utilization of mine water for irrigation of agricultural crops was first evaluated by Du Plessis in 1983. He observed that gypsum rich water would be more suitable for irrigation than NaCl water (other water of similar concentration but with other ions). Large amounts of wastewater could possibly be made available to the farming community and utilised for the irrigation of highly productive soils in the coalfields of the Mpumalanga Province in South Africa, where water resources for irrigation are already under extreme pressure (Annandale *et al*., 2007b). In Botswana, studies have been done to consider the effects of the use of mine wastewater for irrigation (Jovanovic *et al*., 2001). Government has reserved this right to use this plan in future (Rahm *et al*., 2006). However, investigations are, in general, ongoing regarding the feasibility of wastewater use in agriculture (Rahm *et al*., 2006).

2.4.1 Composition of mine water

Throughout coal mining operations (open cast and underground), large volumes of mine water are produced and the composition of the mine water depends on the geology of the area. The water produced could be highly acidic (acid mine drainage (AMD)), which is characterized by low pH (pH<4) and elevated concentrations of dissolved heavy metals (Johnson, 2000).

Mining companies commonly use lime to treat the AMD. The water that results after treatment is rich in $CaSO_4$, $MgSO_4$, or Na_2SO_4 and pH remains between 5.0 and 9.5. Neutral pH waters at high total dissolved salts rich in Ca, Mg, Na and SO4 are also produced. Example of this is indicated in Table 2.1.

Table 2.1 Average mine water quality for Witbank (Annandale *et al*., 1999)

Analyses	Field	
(mg ℓ^{-1})	Major and Jacuzzi	Tweefontein
Al	0.3	0.01
Ca	513	405
Mg	158	196
Na	51	47
Fe	0.3	0.08
Mn	6	0.01
SO_4	2027	1464
Cl	18	32
HCO_3	143	68
TDS	2917	2212
pH	6.4	7.0
EC (mS m^{-1})	294	205

The listed water chemistries in Table 2.1 reflect a typical analysis of mine water for Kleinkopjé Colliery. As can be noted from Table 2.1, the lower the pH of water, the greater the presence of dissolved salts is likely to be. This is attributed to the fact that the salts dissociate and go into solution at reduced pH values. This can also explain the high TDS value of the water.

2.4.2 Gypsum precipitation in a soil – the opportunity to remove salt from the soil water system

The concept of gypsum precipitation in a soil arose as an opportunity in the South African coal mining industry that reduces salt leaching when lime treated AMD water was first used for irrigation of agricultural purposes (Meiring, 1983). This concept, which is protecting the environment by precipitating gypsum from the soil water system could be an opportunity in reducing salt leaching. The mechanism is that when this water is irrigated to a soil, crops concentrate up the soil solution through water uptake, gypsum precipitates and changes into solid phase.

Several studies have been undertaken worldwide, on the precipitation and dissolution of gypsum in soil but few in soils irrigated with gypsiferous waters. The studies indicated that gypsum precipitates when it reaches its saturation index. This index shows the status of a solution phase and is quantified by comparing its ion activity product (IAP) to solubility product (K_{sp}) of the solid phase.

Numerous studies indicate that gypsum precipitation in a soil is controlled by Ca concentration, pH and saturation of CO_3 and HCO_3. A high amount of Ca, low pH and amount of CO_3 and HCO_3 in a soil water system lead to increased precipitation of gypsum. pH level 3-5 is favourable for gypsum precipitation, but pH < 2 solubilizes gypsum. pH 3-5 also controls Ca desorption from a solid phase and, CO_3 and HCO_3 concentrations in the system.

The largest impact of this gypsum rich mine water on the environment could be salinization of water resources. Du Plessis (1983) evaluated, using a steady-state chemical equilibrium model (Oster & Rhoades, 1975), the amount of salt that would leach from a soil, and could potentially contaminate groundwater. In his study he was able to explain that when irrigating with gypsiferous water, soil salinity and percolate water salinity was lower compared to when a chloride rich water of otherwise similar ionic composition was used for irrigation. Using a field scale model, Annandale *et al*. (1999) predicted that low soil salinity and percolate salinity could be maintained by irrigating crops using gypsiferous water. Both studies indicated that percolate salinity could be reduced as a result of gypsum precipitation in the soil (Jovanovic *et al*., 2001)

Annandale *et al*. (2001) carried out a field trial and indicated that by irrigating with gypsiferous mine water, a large fraction of the salts can be removed from the soil water system through precipitation of gypsum in the soil profile, as the soil solution is concentrated by root water uptake. This could reduce the likelihood of off-site environmental pollution.

Annandale *et al*. (2002) also described that the use of gypsum-rich mine water for irrigation of agricultural crops was a ‘simple technology’ principle. Salt leaching is considered to be limited as (1) Ca and SO_4 ions precipitate out as gypsum (2) redissolution of gypsum is a slow process (3) even after redissolution, gypsum occurs as soluble Ca and SO_4 that rarely gets adsorbed to the ion exchange site once the base saturation of the exchange complex is reached, and can easily leach from the soil system.

2.4.3 Crop production using coal-mine water

Coal-mine water is usually saline water that can be of various compositions of $CaSO_4$, Na_2SO_4, $MgSO_4$ or $NaHCO_3$ and commonly is dominated by cations such as Ca, Mg and Na, as well as dominant anions such as SO_4, HCO_3 and Cl. Not much work has been done on the effect of mine waters on crop growth and soil properties (Annandale *et al*., 2001), several studies have been made of saline irrigation waters that mainly consist of NaCl as the salinization agent (Grattan & Grieve, 1999). A number of studies have also examined crop response under solutions of various anionic compositions, particularly SO_4 and HCO_3, in controlled conditions in glasshouses. The effect of SO_4 and HCO_3 on crop growth will be discussed in this section as the irrigation waters used in this study are predominantly $CaSO_4$, sodium sulphate (Na_2SO_4) or sodium bicarbonate ($NaHCO_3$) rich. In addition, Annandale *et al*. (2001) report possible nutritional problems, like for example deficiencies in K, Mg and NO_3, that can occur due to using mine water irrigation for irrigation. Therefore, a portion of the following section will focus on the effect of salinity on crop nutrition, specifically of N, K and Mg.

Irrigation with $CaSO_4$ water

Effect of sulphate on crop growth

The threshold sulphate concentration which most crops can tolerate is 4800 mg l^{-1}(Mengel & Kirkiby, 1987). Sulphate is not toxic to plants, but its effect on plant growth is related to the cation associated with the SO_4 ion. Sulphate affects the associated cation by causing an ionic effect, unavailability of nutrients and hindering mobility or transport of other nutrients. The ionic effect of SO_4 on Ca, for example, is to decrease the Ca concentration through precipitation. The availability of nutrients is then influenced by the formation of gypsum. For instance, in Na_2SO_4 rich systems Ca availability is reduced through formation of gypsum. SO_4 reduces the uptake of other ions such as Mo and NO_3 (Martinez & Cerdá *et al*., 1989). The tolerance of most crops to sulphate toxicity is prevented through a series of metabolic processes. It is therefore unlikely that excess sulphate would influence growth through ion toxicity (Rennenberg, 1984).

Crops such as maize, sorghum, pearl millet and Lucerne are more sensitive to $CaSO_4$ rich water in the seedling growth stage than crops where tolerance is mainly connected to ionic effects of Na and Cl. Mentz (2001) observed that crops which are tolerant to salinity, tolerated high SO_4 concentrations.

Soil irrigated using $CaSO_4$ rich mine water in South Africa (Du Plessis, 1983; Annandale *et al*., 1999, Annandale *et al*., 2001; Annandale *et al*., 2002, Jovanovic *et al*., 2002) stabilised at a relatively low EC_e. The EC oscillated at around 200 mS m^{-1}, which is typical for a saturated gypsum solution (Annandale *et al*., 1999; Jovanovic *et al*., 1998). Du Plessis (1983) also reported that irrigating with lime treated acid mine water did not pose a problem to soil physical properties. The use of high concentration $CaSO_4$ rich waters for irrigation of agricultural crops is believed to be beneficial for crop growth as salt build up is restricted by the low solubility and precipitation of gypsum. Gypsum precipitated in a soil provides calcium, which is needed to flocculate clays in acid and alkaline soils (Shainberg *et al*., 1989, Sumner 1993, Sumner and Miller 1992).

Irrigation with $NaSO_4$

Sodicity is one of the most important problems related with Na_2SO_4 water that limits crop productivity. Its effect is complicated by indirect means such as induced nutritional imbalances and impairment of soil physical conditions (Maas, 1987). The effect of Na containing waters on crop production is discussed in detail in section 2.2.1.

Irrigation with $NaHCO_3$ water

Effect of bicarbonate on crop growth

HCO_3 affects plant growth through a decrease in the solubility of nutrients. The decrease in solubility is caused by the increase of pH associated with increasing concentrations of carbonates (Grattan & Grieve, 1999). For example, the concentration of soluble Fe in soil decreases 1000 fold per unit increase in pH. Zinc, Cu, and Mn are also less soluble at alkalinity-induced high pH (Barber, 1995). The high pH caused by alkalinity may directly inhibit growth of sensitive plants, as demonstrated in Lupinus species (Tang & Robson, 1993). However, in most instances it is not the pH, but the high concentration of HCO_3 that is the major factor for plant growth inhibition (Lee & Woolhouse, 1969) due to its toxic effect. This was demonstrated by maintaining maize plants growing in solution at pH 8.0 with and without HCO_3. The high pH without high HCO_3 did not cause any negative effect on root and shoot elongation (Lee & Woolhouse, 1969).

Plants respond to elevated HCO_3 concentrations with decreased shoot growth. Shoot growth inhibition is associated with a decrease in number of leaves, fresh and dry mass, and shoot elongation. Sunflower (Alcántara *et al*., 2000), tomato, and petunia (Bailey & Hammer, 1986), chrysanthemum (Kramer & Peterson, 1990), apple (Zhou *et al*., 1984), rice (Yang *et al*., 1994), sorghum, maize and barley (Alhendawi *et al*., 1997), grapevine (Römheld, 2000), olive, peach (De LaGuardia & Alcántara, 2002), pea (Zribi & Gharsalli, 2002), and roses (Fernández-Falcón *et al*., 2006), exhibited stunted growth when growing in either soil or nutrient solution containing a high concentration of HCO_3. The detrimental concentration for HCO_3 reported varies between 4 and 20 mM.

Salinity effect on Nitrogen (N), Potassium (K) and Magnesium (Mg) availability

There is no clear evidence indicating that N applied to saline soils improves plant growth or yield. A number of laboratory and greenhouse studies have shown that salinity can reduce N accumulation in plants (Cram 1973; Pessarakli & Tucker, 1988; Feigin *et al*., 1991; Pessarakli, 1991; Al-Rawahy *et al*., 1992). Many attributed this reduction to Cl antagonism of NO_3 uptake (Bar *et al*., 1997; Feigin *et al*., 1987) while others attributed the response to salinity's effect on reduced water uptake (Lea-Cox & Syvertsen, 1993). The form in which N is supplied to salt-stressed plants can also influence salinity-N relations as well as affect salinity's relation with other nutrients (Lewis *et al*., 1989; Martinez & Cerdá, 1989). NH_4

supplied maize (Lewis *et al*., 1989), melon (Feigin, 1990) and pea, *Pisum sativum* L. (Speer *et al*., 1994) plants were found to be more sensitive to salinity than NO_3 supplied plants when grown in solution cultures.

According to Lewis *et al*. (1989), addition of Ca to growing media improved the growth rate of the plants in the NO_3 treatment, but not those treated with NH_4. Martinez and Cerdá (1989) also found that Cl uptake was reduced in cucumber when only NO_3 was added to the solution but when half the NO_3 in the solution was replaced by NH_4, Cl accumulation was enhanced. These investigators further noted that when NO_3 was the only N-source, accumulation of K in the plant was increased under saline conditions. As the NH_4/ NO_3 ratio was increased, plants accumulated more Na and Cl and less Ca and K in their leaves. Numerous other studies with a wide variety of crops have also shown that K concentration in plant tissue declines as the Na-salinity or as the Na/Ca ratio in the root media is increased (e.g. Francois, 1984; Graifenberg *et al*., 1995).

Most salinity-nutrition studies have given little attention to magnesium nutrition as affected by salinity (Grattan & Grieve, 1994). Calcium is a strong competitor of Mg, and the binding sites on the root plasma membrane appear to have less affinity for Mg than for Ca (Marschner, 1995). Thus, high concentrations of Ca often result in increased leaf-Ca along with a marked reduction in leaf-Mg (Bernstein & Hayward, 1958). For example Ruiz *et al*. (1997) found that NaCl salinity reduced leaf Mg concentrations in citrus. However increases in salinity are not always associated with decreases in leaf Mg. Bernstein *et al*. (1974) found that increases in salinity (NaCl + $CaCl_2$) only reduced leaf Mg concentration in beet and had little or no effect in leaves from five other vegetable crops that they examined.

It has been known for several decades that solutions with a Mg/Ca ratio greater than one, such as those that result by diluting sea-water, reduces the growth of maize (Key *et al*., 1962). In eucalyptus, Mg-salts were found to reduce root growth more than Na-salts (Marcar & Termaat, 1990) and this effect was associated with low concentrations of calcium in the root. Calcium-induced Mg deficiency has been observed in sesame (Nassery *et al*., 1979).

2.5 Runoff and drainage from mine water irrigated fields

Runoff and drainage could be the main means of salt transport from coal-mine water irrigated fields to water resources. A rainfall event that is greater than the water holding capacity and is greater than the infiltration rate of the soil initiates surface runoff, which carries salts watercourses. Drainage that occurs through natural lateral flow or vertical percolation of excess water below the root zone could also be another means of salt transport. The salinization of water resources through drainage and runoff, therefore, could be a major concern regarding the sustainability of irrigation with coal-mine water.

Factors influencing runoff and drainage

Runoff

Several factors can affect surface runoff, such as precipitation (amount, intensity and duration)**,** soil type**,** soil water content**,** vegetation and topography (Mishra & Singh, 2003). Infrequent torrential rainfall easily erodes salts from the soil surface, while soft drizzly rain infiltrates into the soil resulting in minimal salt transport by surface runoff. Porous soils such as sands are well-drained soils which can absorb water more quickly than fine-textured (clay) soils and have a lower runoff potential than poorly-drained soils (less-porous). Antecedent soil water content also is very important in runoff generation, as wet soils generate more runoff than dry soils (Gómez-Plaza *et al*., 2001). Topography is an additional factor affecting water velocity, infiltration rate, and overland flow rate. Cropping promotes slope stability, and reduces adding salt and sediment load into streams. Runoff can be minimized by increasing soil surface storage and by increasing the infiltration rate of the soil, by leaving crops residues as well as mulching.

Drainage

Drainage occurs when the plant/soil system is unable to use or store the amount of water it receives over a period of time. Rainfall, soil properties and vegetation affect the extent of drainage.

Soil properties such as clay mineralogy, clay content (or texture), CEC/clay ratio, bulk density, soil structure, porosity, hydraulic conductivity and water holding capacity are key determinants of drainage (Silburn & Freebairn 1992; Keating *et al*. 2001, 2002; Yee Yet & Silburn 2002, 2003). For instance, drainage tended to be highest at low clay contents, lowest at medium clay contents and intermediate at high clay contents. Sandy soils drainage is usually higher than for clay soils.

Cropping system also affects the pattern of soil water use and storage (Freebairn *et al*., 1986, 1996). Deep drainage is generally greater under annual crops and pastures than native perennial vegetation (Walker *et al*., 1999; Cocks, 2001; Heng *et al*., 2001). Management of soil surfaces (tillage) and crop residues (stubble) also affects drainage. Evidence of greater solute movement under zero tillage than under conventional tillage has been noted in a number of studies (Dalal 1989; Turpin *et al*., 1998; Turpin *et al*., 1999; McGarry *et al*., 2000). Modelling studies (Walker *et al*., 2002 ; Keating *et al*., 2002) have compared farming systems in terms of their susceptibility to drainage. They generally find drainage under annual wheat > (greater than) annual sorghum> perennial pasture>native vegetation in Australia.

Reduction of drainage in rainy seasons could be difficult as it is dependent on the rapid development of annual crop root systems. However, perennial species such as trees generally have deeper rooting systems which can be much more effective in abstracting soil water and reducing drainage (Huda & Ong, 1989). Since trees have deeper root systems than annual crops and use water outside the rooting zone of annual crops, they have been used as companion species for crops in agroforestry systems.

Runoff and drainage measurements

Runoff and drainage quantity and quality measurements are necessary to quantify the magnitude of the salt loads from coal-mine water irrigated fields. Runoff quantity and quality can be measured by erecting runoff weirs at the lowest end of the irrigated field, where the runoff water converges. Since the carrying out of field experiments to measure salt transport and design appropriate management solutions is expensive, different techniques are used to estimate runoff quantity and quality. The most commonly used is the Soil Conservation Services Curve Number (SCS-CN) method which was developed in 1950 by the United States

Soil Conservation Services (US-SCS) (Mishra & Singh, 2003). This method is characterized by the following equation:

$$Q = (P - I_a)^2 / (P - I_a + S)$$

Where

Q is Runoff (mm)

P is Precipitation (mm)

I_a is Initial Abstraction (stored, intercepted, and infiltrated water) (mm) and approximated as 0.2S, S is a parameter derived from the following equation where

$S = (1000/CN) – 10$

CN is Curve number

The equation simplifies to:

$Q = (P - 0.2S)^2 / (P + 0.8S)$

CN is the slope of the line between rainfall and surface runoff. The US-SCS determines the values for these curve numbers. They are derived from hydrologic soil group, land use and antecedent soil water content conditions.

Soils are divided into four hydrologic soil groups. Group A has low runoff potential (i.e., runoff is unlikely), having a final infiltration rate of > 7.62 mm hr^{-1}. Group B has moderate infiltration rates when wet, having final infiltration rates between 3.81 and 7.62 mm hr^{-1}. Group C has low infiltration rates when wet (i.e., is likely to provide surface runoff), having infiltration rates between 1.27 and 3.81 mm hr^{-1}. Group D has a high runoff potential, having infiltration rates < 1.27 mm hr^{-1} (SCS, 1971). Antecedent soil water content conditions assess how wet the soils were before the storm. The higher the antecedent soil water content, the greater the surface runoff. This SCS-CN approach, however, does not consider the quality of runoff.

Drainage can be measured using direct methods, for instance, lysimeter, which is a device to measure the volume of the percolating past the bottom of profile flow of water with or without application of tension, or to obtain water samples from the soil (Titus & Mahendrappa, 1996).

Indirect methods include using Darcy's law (Bond, 1998), salt balance, water balance (Zhang *et al*., 2002; Ward *et al*., 2001), groundwater response (Cook & Herczeg, 1998; Allison & Hughes, 1983), the hydraulic water potential gradient and soil hydraulic conductivity (Jury *et al*., 1991), soil water balance modelling (Annandale *et al*., 2006; Rhoades & Loveday, 1990; Zhang *et al*., 2002) and chloride balance (Lidón *et al*., 1999). Annandale *et al*. (2006), used boreholes drilled inside and in close proximity to the mine irrigated fields, to measure salts moving through a profile. Accurate determination of drainage using a water balance (Wagenet, 1986) relies heavily on how accurately the evapotranspiration can be measured or estimated. Evaporation when not limited by water deficits or other crop growth limitations, runoff and drainage can be estimated with reasonable accuracy using climate data and crop coefficients (Doorenbos & Pruitt, 1984; Jensen *et al*., 1990; Allen *et al*., 1994).

Annandale *et al*. (2006), for instance, used a mechanistic soil water balance model to estimate leachate from coal-mine water irrigated fields to investigate the impact of large scale irrigation on groundwater resources.

The hydrological cycle plays a dominant role in the movement of salts. Drainage and runoff measurements/estimates are, therefore, very site and season specific, varying from year to year depending on the total amount of rainfall, but also on its seasonal distribution. Extrapolation of field measurements is further complicated by the diversity of soils and crops, and the lack of information on the interaction between crop, soil and climate variability as they affect water use and water loss.

Beven, 1989 and Wagener *et al*. 2001, have reviewed a large body work on runoff hydrology. Their study suggests that physically based models cannot predict runoff generation in the field adequately as they are not good descriptors of runoff processes, except under some special circumstances. In the assessment of irrigation with coal mine water for large scale irrigation, a reliable runoff model is required to ascertain whether surface waters are impacted. Crop models are believed to be effective tools in the extrapolation of research findings over time, soil type and climatic region. However, the acceptance of outcomes from simulation studies is dependent on the confidence in the models used to predict crop growth, water use, soil water dynamics and deep drainage. Soil water balance model output coupling with groundwater and surface water models, could be helpful in the assessment of water resource pollution induced from agriculture. Therefore, modifying the runoff component of the SWB model is an appropriate method for this study given the available data, goals of the study and goals of the larger research program.

Possible impact of mine water irrigation on surface water

This section focuses on the aspects that were directly related to the objectives of the research. Therefore, it includes a review on the impact of mine water on the water resources of the Olifants Catchment.

There are a large number of mining operations exploiting a wide variety of minerals in the Olifants Catchment. Available evidence suggest that lime treated AMD and AMD leakages are likely to be a threat to water resources, especially to the water quality of all streams and rivers (Vermeulen *et al*., 2008). The largest impact of freely releasing lime treated AMD onto the environment could be to salinization of the water resources. Whereas AMD that leaks from closed or abandoned mines have a serious impact on the productivity of ecosystems by affecting biological organisms within the streams (IIED, 2002). One of the worst features of AMD could also be its persistence in the environment and it has the potential for severe long-term, (possibly several decades long (IIED, 2002)), impacts on surface and groundwater, and on aquatic life.

This serious impact caused by mining or attributable to mining has been the subject of concerted research and management for several decades in South Africa. Coaltech 2020 is a collaborative research programme which has been formed by the major coal companies, Universities, CSIR, NUM and the state to address the specific needs of the Coal Mining Industry in South Africa using local and international knowledge and skills. This is one of the programmes that is attempting to derive appropriate and cost effective management strategies that will help resolve these problems.

As part of this programme, Annandale et al. (2006) and Vermeulen *et al*. (2008) investigated the impact of irrigation with mine water on groundwater resources for the first time at field scale in southern Africa. Out put of the SWB model was used during the groundwater modelling. According to Annandale et al. (2006), irrigating large areas with gypsum rich mine water could be feasible and sustainable if careful attention is paid to the specificity of each situation. They also advised that large errors can be made in designing such irrigation schemes if the amount of deep drainage leaving the root zone, the storage capacity between the base of the root zone and the underlying aquifer systems, and the hydraulic characteristics of the aquifers are not properly matched. Percolation from irrigation in excess of what the underlying aquifers can transmit from the site, will lead to rising water tables, and over time, water logging and salinization of the root zone. This will necessitate the installation of expensive drainage systems, or ultimately, result in the failure of the irrigation scheme.

Vermeulen *et al*. (2008) also reported that the overall water quality trend in the deeper aquifer indicated no significant water quality deterioration over the monitoring period. Some exceptions occurred on a very sandy soil, with consistent water quality degradation, but none of the boreholes outside the pivot areas show any meaningful change in water quality due to leaching from irrigated area. In the short to medium term, the evidence from groundwater monitoring shows that irrigation with mine water does not hold significant threats to the regional groundwater quality. The hydraulic and attenuation factors preventing the salts in the mine water used for irrigation from being mobilized down the soil profile and into the aquifer are important considerations in this process. From this study they concluded that irrigation with gypsiferous mine water, if properly managed, could seriously be considered as part of the solution towards the challenge of responsible management of the considerable volumes of mine water available during mining and post closure

Saline water irrigated fields could generate runoff salts during large rainfall events. The magnitude of runoff salt depends on the soil type, slope and rainfall intensity and soil salinity (Gilfedder & Walker, 2001; Rhoades *et al*., 1997). Thus, the salt discharge by surface runoff from mine water irrigated fields needs to be quantified and used to validate models like SWB to better understand the impact of large-scale irrigation on surface water resources.

Knowledge gap

In conclusion, a large body of knowledge exists regarding the irrigation of crops with saline and sodic waters. The use of saline water for irrigation requires selection of salt tolerant crops, sound irrigation water management and the maintenance of favourable soil chemical and physical properties to ensure adequate infiltration and salt leaching. However, there will be several uncertainties when it comes to crop and soil response, to the long-term impact of irrigation with the unusual water qualities emanating from coal-mines.

Several of the studies available in the literature have been done using of saline irrigation waters that mainly consist of NaCl as the salinization agent (Grattan & Grieve, 1999). A number of studies have also examined crop response under solutions of various anionic compositions, particularly SO_4 and HCO_3, in controlled conditions in glasshouses. Coal-mine water is usually saline water that can be of various compositions of $CaSO_4$, Na_2SO_4, $MgSO_4$ or $NaHCO_3$ and commonly is dominated by cations such as Ca, Mg and Na, and anions such as SO_4, HCO_3 and Cl. In view of these uncertainties the literature could not answer all the research questions as these waters are atypical of waters used in most studies. Thus, an assessment of the suitability of poor quality mine waters for irrigation and its long-term impacts on crops and soils is worth investigating in view of possible future uses of these mine waters.

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CHAPTER 3

FIELD SITES, MONITORING AND MODELLING

3.1 Introduction

In this Chapter, a detailed description of the field sites, the monitoring undertaken and modelling and data processing, is presented. For the *field site* description, the location and experimental layout, the soil conditions, irrigation water qualities and cropping systems are also described. This will highlight the wide range of conditions investigated in this study. Under *monitoring*, the equipment used and the measurements taken on atmospheric evaporative demand, crop growth and nutritional status, soil water balance components and salt balance measurements are described. Finally, in the brief description of the *modelling* section, the approach taken to process the data and model the root zone soil water and salt balance, is given.

3.2 Field site locations and experimental layout

The study was carried out at four mines: Kleinkopjé Colliery near Witbank, New Vaal Colliery near Vereeniging, Syferfontein near Secunda and Waterberg CBM pilot project near Lephalale. Two irrigation systems were designed for the Waterberg CBM irrigation trial: drip and sprinkler that were set up on separate blocks. The remaining sites were centre pivot irrigated.

3.2.1 Kleinkopjé

This Anglo Coal-mine is located in Mpumalanga Province (Latitude 26^{o}28’S, Longitude 28^{o}75’E, Altitude 1570 m). Pivot Major (30 ha) and Pivot Tweefontein (20 ha), abbreviated as TWF, is on rehabilitated open cast soils. These two fields have been irrigated with mine water since 1997. Pivot Four (30 ha) is a virgin site that has been irrigated since the winter season of 1999. Figure 3.1 shows the position of the pivots (Pivot Major, Pivot TWF and Pivot Four) and Figure 3.2 shows the experimental layout of Pivot Major, Pivot Four and Pivot TWF. Figure 3.2 includes the position of intensive monitoring sites and runoff weirs. During the 2000/01summer season at Kleinkopjé, two adjacent intensive monitoring stations were installed in the maize fields of all three pivots. Two adjacent intensive monitoring stations were also installed during the 2001/02 season in Pivot Four, which was planted to potatoes at the time. In all other seasons at Kleinkopjé, as well as the other sites, a single intensive monitoring station was installed in each field.

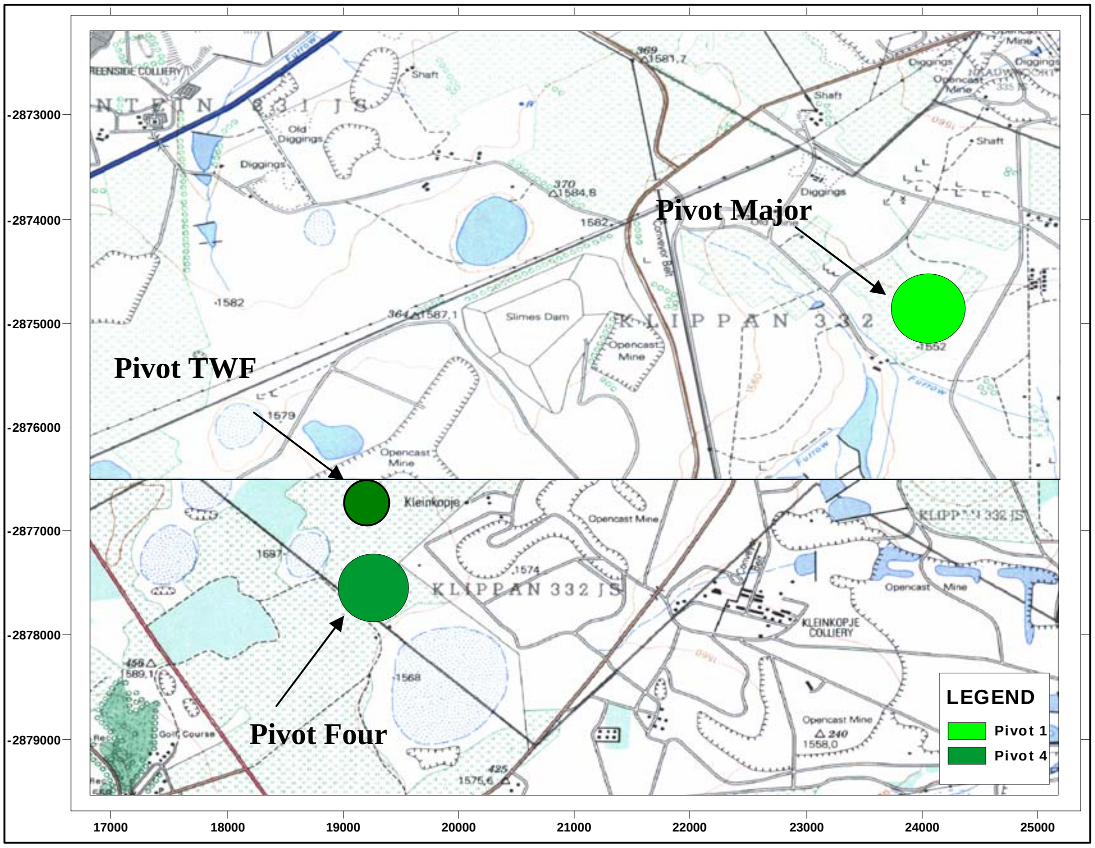
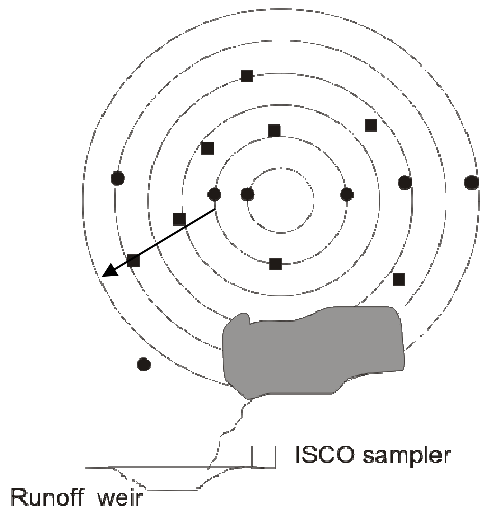
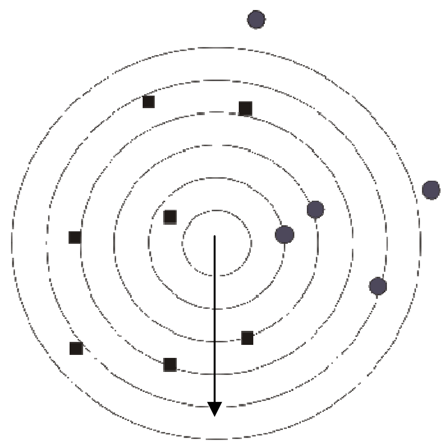


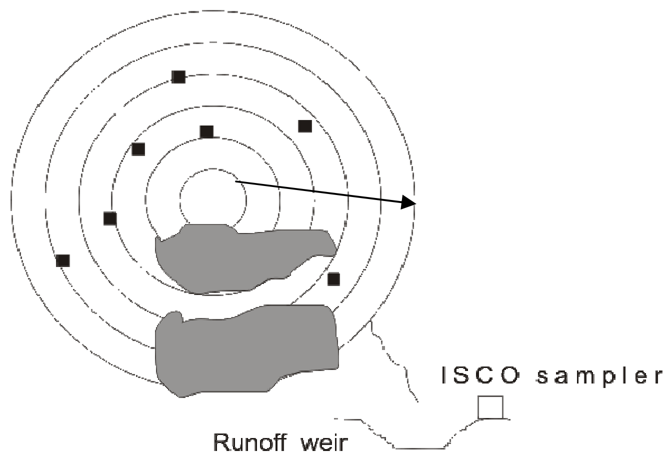
Figure 3.1 Topographic map of the Kleinkopjé area, indicating the position of Pivot Major, Pivot Four and Pivot TWF



a) Pivot Major (30ha)



b) Pivot Four (30ha)



c) Pivot TWF (20ha)

Wheel tracks

Intensive monitoring station and plant and soil sampling sites

Areas occasionally waterlogged during summer

Main direction of slope

Figure 3.2 Experimental layout of the irrigated fields at Kleinkopjé

3.2.2 New Vaal

This Anglo Coal-mine is in Free State Province (Latitude 26°42' S, Longitude 27°55' E, Altitude 1432 m), and is located on the Southern bank of the Vaal River. The 10 ha field is placed close to the river in an area that had been mined in the past by underground mining method. Figure 3.3 shows the position of the field and Figure 3.4 shows the experimental layout of the Pivot. Monitoring at this site started in November 2001. This site was already erected before by the mines before the experiment was started. Unfortunately, the positioning of this site was inappropriate, as internal drainage problems plagued the research.

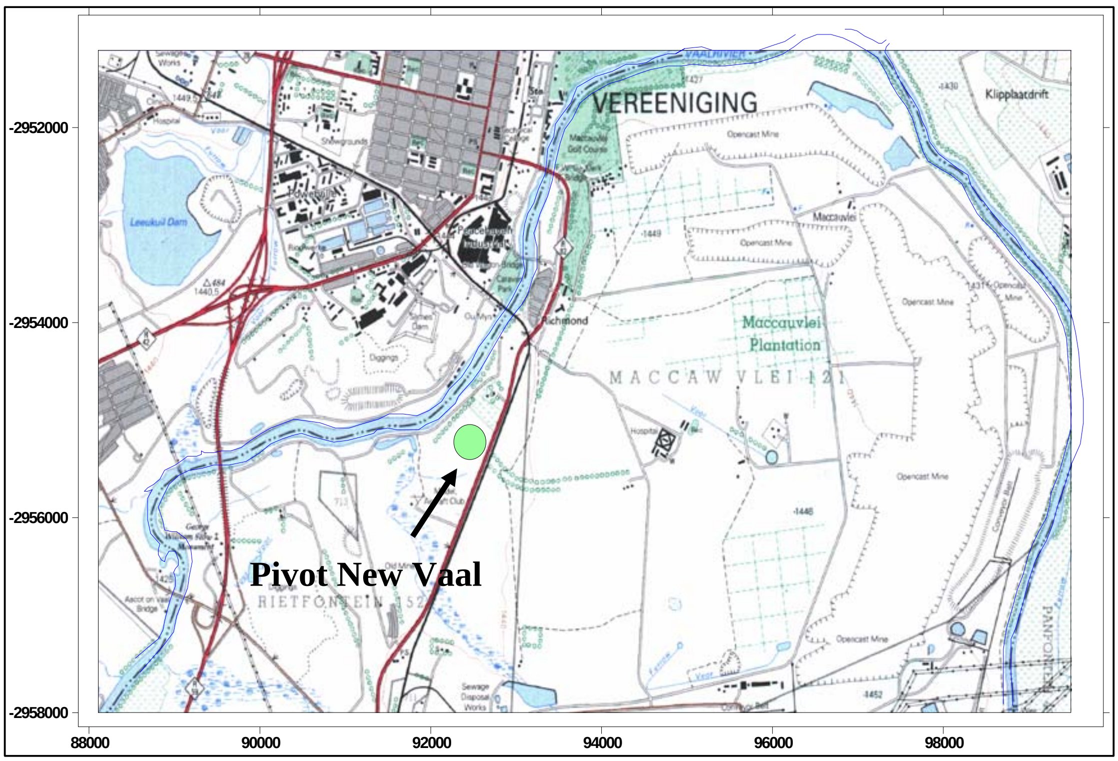
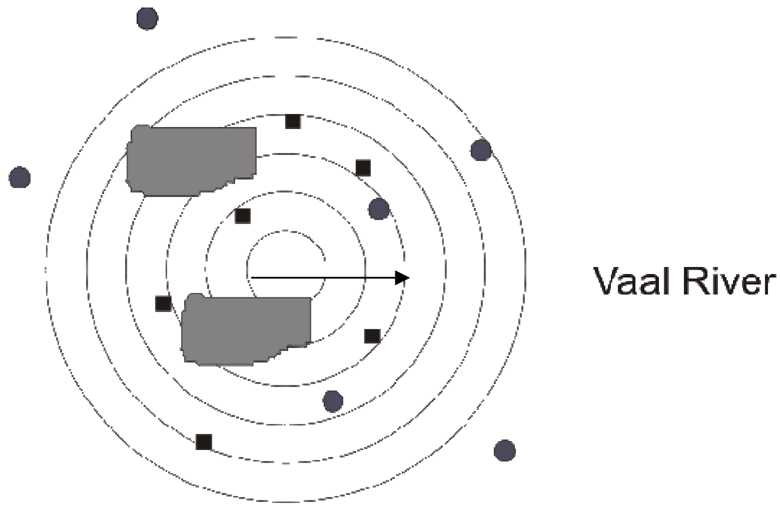


Figure 3.3 Topographic map of the New Vaal area



Wheel tracks

Intensive monitoring station and plant and soil sampling sites

Areas occasionally waterlogged during summer

Main direction of slope

Figure 3.4 Experimental layout of the irrigated fields at New Vaal

3.2.3 Syferfontein

This Sasol Coal-mine is in Mpumalanga Province (Latitude 23°64’ S, Longitude 29°20’E, Altitude 1570 m). The 20.6 ha field had received some irrigation with mine water before the trial commenced, so the research did not begin with pristine conditions. Figure 3.5 shows the regional setting of the irrigation site and Figure 3.6 shows experimental layout of this field, which includes intensively monitored plots.

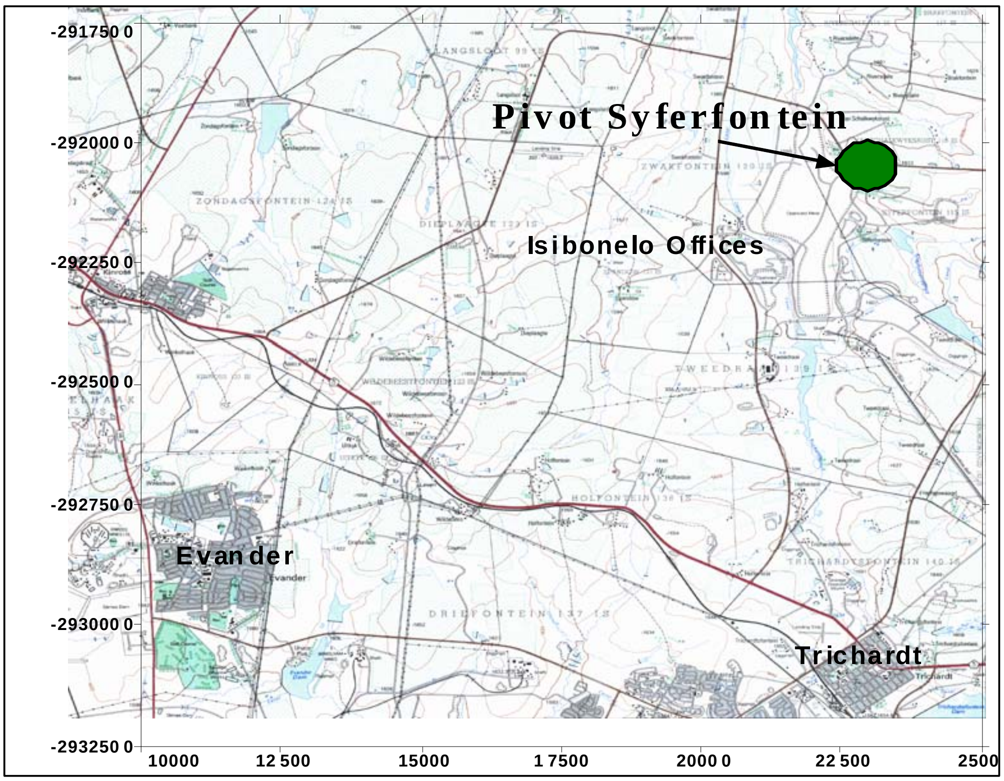


Figure 3.5 Regional setting of Syferfontein irrigation site

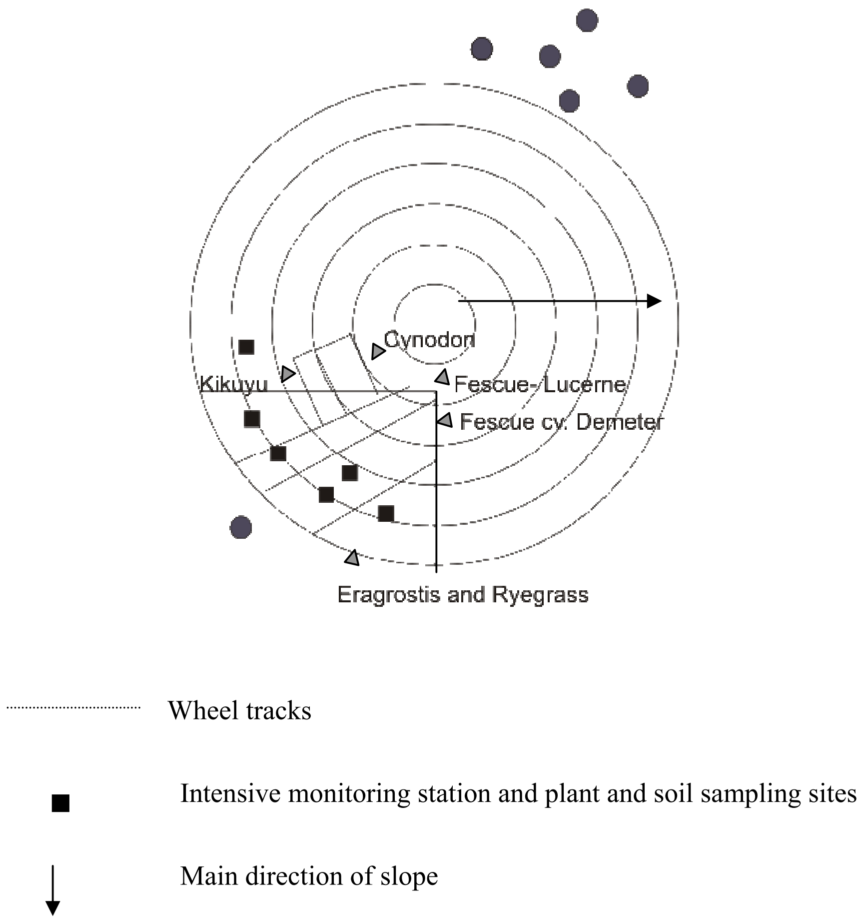


Figure 3.6 Experimental layout of the irrigated fields at Syferfontein.

3.2.4 Waterberg

The Waterberg CBM pilot project is in the Limpopo Province (Latitude 23°68'N, Longitude 27°70'S and Altitude 839 m), located 30 km North West of Lephalale (Ellisras). The irrigation site selected was in the natural veld approximately 100 m from the CBM production water reservoir. The total area of the site was 1440 m^2. Figures 3.7 to 3.10 show a schematic diagram and experimental layout of the drip and sprinkler irrigation systems.

$46B_1$	FCR_1	$23R_2$	$23B_1$	FCB_2	$46R_3$
FCB_1	FCR_4	$46B_2$	FCR_2	FCR_2	$46R_4$
$46R_1$	$23R_1$	FCB_4	$23B_2$	$46R_2$	$23B_3$
FCB_3	$23R_4$	$46B_3$	$23B_4$	$46B_4$	$23R_3$

24 m

30 m

FC irrigation to field capacity (FC)

23 leaching fraction of 23% that applies 30% more water than that needed to return the profile to FC

46 leaching fraction of 46% that applies 85% more water than that needed to return the profile to FC

R Ryegrass/rye

B Barley

The subscript indicates replicate number.

Figure 3.7 Schematic layout of the drip irrigation trial treatment (winter 2005) at Waterberg

Figure 3.8 Drip irrigation system layout for the CBM irrigation trial at Waterberg

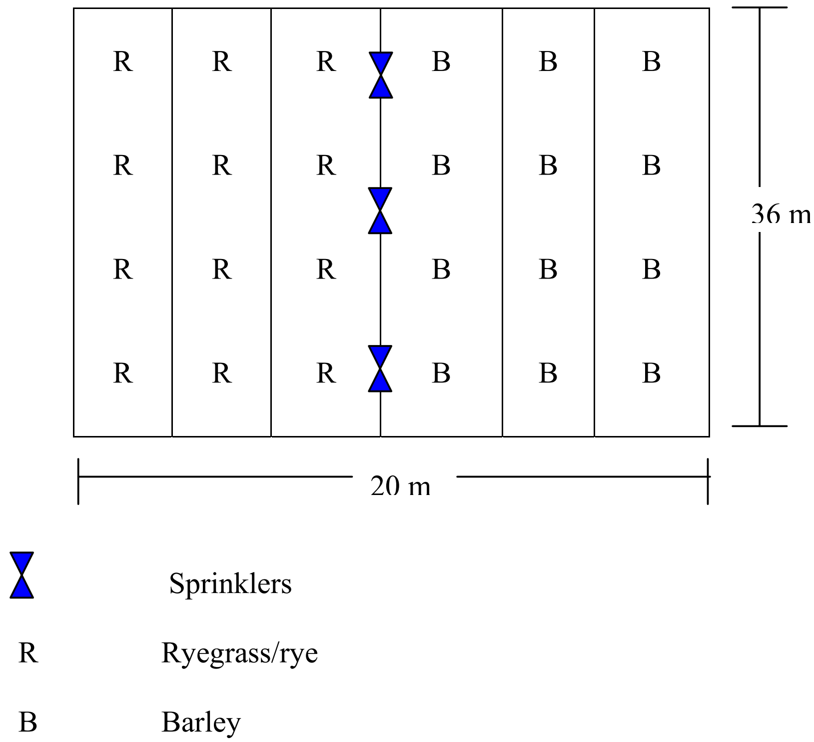


Figure 3.9 Schematic presentation of the line source Sprinkler irrigation system layout (winter, 2005) at Waterberg

Figure 3.10 Line source irrigation system layout for the CBM water irrigation trial at Waterberg

3.3 Cropping systems

The cropping systems include 18 growing seasons for TWF, 17 growing season for Major and 15 seasons of different cropping systems at Pivot Four, 7 growing seasons at New Vaal and nine harvests at Syferfontein. In the Waterberg, two irrigation trials were carried out in the winter season 2005 and summer 2005/06 seasons. Each growing period included records of leaf area index (LAI), dry matter (DM), plant chemical analysis, and volumetric water content measurements with a neutron water meter (NWM) and soil solution chemical analysis results.

3.3.1 Kleinkopjé

The fields at Kleinkopjé were cropped to annual cash crops, and these included maize, wheat, sugarbeans and potatoes. The yields of maize and wheat are expressed as air-dry grain masses, whilst potato and sugarbeans are fresh mass. An example of maize irrigated with gypsum rich mine water is in Figure 3.11.

Figure 3.11 Maize irrigated with gypsiferous mine water at Pivot Major

3.3.2 New Vaal

At first wheat and maize were the crops of choice, and then an attempt was made to produce vegetables such as peas, sweetcorn, pumpkin and soybean. An example of Sweet corn grown at New Vaal is shown in Figure 3.12.

Figure 3.12 Sweetcorn irrigated with gypsiferous mine water at Pivot New Vaal

3.3.3 Syferfontein

Due to the heavy clay soil that would make cultivation extremely difficult, the mine decided to establish a perennial Fescue pasture. Five temperate and subtropical, annual and perennial pastures were then established as part of this research in small plots that were fenced off separately to prevent grazing animals from eating the fodder and damaging instruments (Figure 3.13). The pastures planted are listed in Table 3.1.

Figure 3.13 Fescue irrigated with sodium sulphate rich mine water at Syferfontein

Table 3.1 Annual and perennial, temperate and subtropical pasture crops planted (Syferfontein)

Planted pastures (Common name)	Scientific name	Classification
Fescue (cv. Iewag)	*Festuca arundinaceae*	Perennial Temperate
Lucerne (cv. SA standard)	*Medicago sativa*	Perennial Temperate
Fescue (cv. Demeter)	*Festuca arundinaceae*	Perennial Temperate
Eragrostis	*Eragrostis curvula*	Perennial Subtropical
Kikuyu	*Pennisetum clandestinum*	Perennial Subtropical
Ryegrass (cv. Midmar)	*Lolium* multiflorum *cv. Midmar*	Perennial Temperate

3.3.4 Waterberg

Salt tolerant crops of barley (*Hordeum vulgare* cv. Puma), and a mixture of an Italian ryegrass (*Lolium multiforum* cv. Agriton (Diploid)) and stooling rye (*Secale cereale* cv. Echo) were planted in the 2005 winter season (Figure 3.14), whereas cotton (*Gossypium hirsutum* cv. Opal) and Bermuda grass (*Cynodon dactylon* cv. K11) were planted in the summer 2005/06 season (Figure 3.15).

Harvests for the Waterberg CBM trial are presented for the winter 2005 and summer 2005/06 experiments. Barley and ryegrass were harvested before they reached maturity, as infiltration became problematic and ponding occurred. Bermuda grass was harvested when it reached the flowering stage and yield was determined. Cotton was harvested three times by hand from April to May 2006, and lint quality (uniformity (%), length (cm), micronaire (μg cm^2), strength (grams per tex)), seed cotton mass (g) were determined using a laboratory gin by Cotton South Africa, in Pretoria. Uniformity (%) shows the degree to which the fibres in a sample are uniform based on the ratio of mean length to the upper half mean length. Length (cm) describes the average length of cotton fibres after the ginning process. Micronaire (μg cm^{-2}) quantifies the mass of an individual cotton fibre taken in cross-section. Strength expresses the force required to break a bundle of fibres in grams per tex (a tex unit is equal to the weight in grams of 1,000 meters of fibre). Seed cotton (g) represents the mass of unginned cotton.

Figure 3.14 Barley irrigated with sodium bicarbonate rich CBM deep aquifer water at Waterberg (winter 2005)

Figure 3.15 Cotton and Bermuda grass irrigated with sodium bicarbonate rich CBM deep aquifer water at Waterberg (summer 2005/06)

3.4 Soil

This section discusses the soil classification, depth, texture and initial soil salinity of the irrigated fields at the different mines, summarised in Table 3.2.

Table 3.2 Soil classification, depth, texture and initial saturated soil salinity (EC_e) of the irrigated fields on the different mines.

Colliery and field		Soil classification	Soil depth (m)	Texture (%)	Initial EC_e ($mS\ m^{-1}$)
Kleinkopjé	Major	Bainsvlei, Clovelly	~ 1.0	Loamy sand (Clay 12%)	60 (1997/98)
	TWF	Witbank/rehab.	~ 0.9	Sandy loam (Clay 17%)	40 (1997/98)
	Pivot Four	Hutton	> 2.0	Sandy loam (Clay 14%)	50 (1999/00)
Syferfontein		Arcadia	~ 0.5	Clay (64%)	160 (2001/02)
New Vaal		Clovelly, Dundee, Oakleaf	> 1.4	Sand (98%)	10 (2001)
Waterberg CBM		Hutton	1.4	Loamy sand Clay (9%)	42 (2005)

All the fields except Pivot Four and Waterberg CBM irrigation trial, experienced poor internal drainage problems, which reduces yields. Pivot TWF showed a marked reduction in hydraulic conductivity at the soil-spoil interface, and this has resulted in regions of waterlogging, especially in the summer when we had less control over the water balance. The Syferfontein pivot was on a very heavy clay soil that naturally limits drainage, and therefore did not present an ideal site for irrigation. The Waterberg soil was a coarse sand with low percentage of clay and silt in the 0-20 cm. The clay percentage increased to 11% in the 60-80 cm depths. The biggest problems, however, were found on the site with the lightest texture of all, New Vaal. This was due to clay lenses and the level of the buffer dam next to the field (Figure 3.16).

Figure 3.16 Waterlogging at New Vaal during the early growth stage of Pumpkins

3.5 Water qualities

3.5.1 Kleinkopjé and New Vaal

The EC of New Vleishaft Dam water, which irrigates Pivot Major started off at around 250 mS m^{-1} in 1997, but climbed steadily to a value of 320 mS m^{-1} by the end of 2005 (Figure 3.17a). Sulphate levels over this period climbed from 1500 mg ℓ^{-1} to 3000 mg ℓ^{-1} (Figure 3.17d) whilst pH remained around 6.5, within the range that could favour good crop growth (Figure 3.17b). K, Na and Cl fluctuated between 5 and 30 mg ℓ^{-1} and Mg between 150 and 300 mg ℓ^{-1} over the growing period. Ca, however, remained quite stable at 500 mg ℓ^{-1}, during the trial period. Ca, SO_4 and Mg clearly dominated this water.

At Tweefontein pan, a dam which irrigates Pivot Four and Pivot TWF, the EC of the water started off a little higher than that of New Vleishaft Dam water in 1998, which was around 300 mS m^{-1} and was fairly stable for several years until 2001 (Figure 3.17a). A rapid increase in EC to a level of 500 mS m^{-1} was observed by the end of 2005 and decreased to 450 mS m^{-1} in 2006. pH remained around 7.5 and was higher than that of New Vleishaft Dam (Figure 3.17b). Sulphate levels over this period increased from 2500 mg ℓ^{-1} to 4000 mg ℓ^{-1} (Figure 3.17c). Ca increased from 400 mg ℓ^{-1} to 600 mg ℓ^{-1}. Mg fluctuated between 200 and 300 mg ℓ^{-1} over the growing period. Na, K and Cl, however, remained quite stable-with Na at 80 mg ℓ^{-1}, K at 25 mg ℓ^{-1} and Cl around 50 mg ℓ^{-1} during the trial period. The deterioration of water quality resulted from the increase of Ca, Mg and SO_4 concentrations in the water.

The dam, which irrigates pivot New Vaal, contains water with EC of around 130 mS m^{-1} and TDS around 1000 mg ℓ^{-1} (Figures 3.17a and 3.17e), and this water is predominantly rich in NaCl with some Ca and Mg. Na fluctuated between 15 and 300 mg ℓ^{-1} Cl between 6 and 132 mg ℓ^{-1}, Ca between 26 and 250 mg ℓ^{-1}, and Mg between 6 and 94 mg ℓ^{-1}. K was only present in small quantities in the irrigation water.

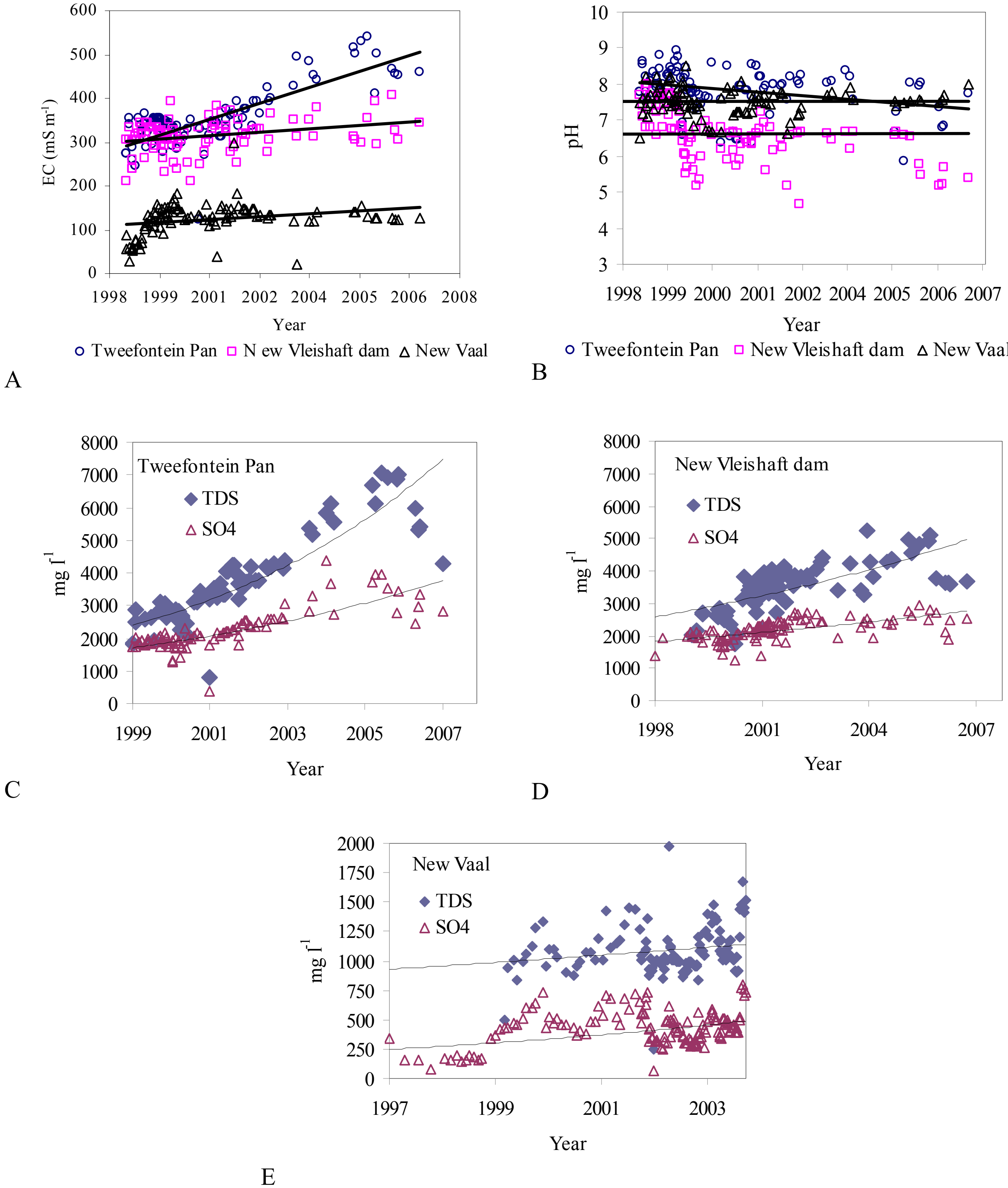


Figure 3.17 Irrigation mine water qualities of Kleinkopie and New Vaal

3.5.2 Syferfontein

At Syferfontein, water quality did not change during the experimental period (October 2001-May 2004) (Table 3.3).

Table 3.3 Typical irrigation water quality of the Syferfontein coal-mine

Chemical analysis	mg l^{-1}	mmol l^{-1}
Ca	32	0.8
Mg	87.6	3.7
Na	795.8	34.6
K	16.4	0.4
SO_4	1647	17.2
Cl	17.8	0.5
pH	8.9	-
EC	mS m^{-1}	372
SAR	(mmol $l^{-1})^{0.5}$	16.32

3.5.3 Waterberg

The CBM deep aquifer water had highly elevated levels of salinity and sodicity, relative to water resources routinely used for irrigation. TDS is very high (5.1 g ℓ^{-1}) and rich in sodium bicarbonate with low chloride levels and high sulphate. Concentrations of most trace elements are low (< 1 mg ℓ^{-1}). Crops vary in their response to irrigation water salinity. According to FAO irrigation water quality guideline, the EC of the CBM water is higher than the threshold level specified for severe restriction to crop growth (300 mS m^{-1}). The degree of restriction on use for this water is, therefore, severe for sensitive and moderately sensitive crops. For moderately tolerant and tolerant crops, the severity is related to the yield reduction.

The normal range of pH of irrigation water is 6.5-8.4. A pH value outside this range could cause a nutritional imbalance. pH of the CBM water remained around 7.5 during the trial period, which is in the range that could favour good crop growth.

The sulphate levels of the CBM water climbed from 0.1 mg ℓ^{-1} to 10 mg ℓ^{-1} in June 2006 (Figure 3.18). K fluctuated between 9 and 27 mg ℓ^{-1} and, Ca between 15 and 30 mg ℓ^{-1} over the growing period. Na, HCO_3, Mg and Cl, however, remained quite stable during the trial. Na and HCO_3 dominated the CBM irrigation water, thus caution is required to prevent precipitation of salts in irrigation systems, particularly with drip emitters.

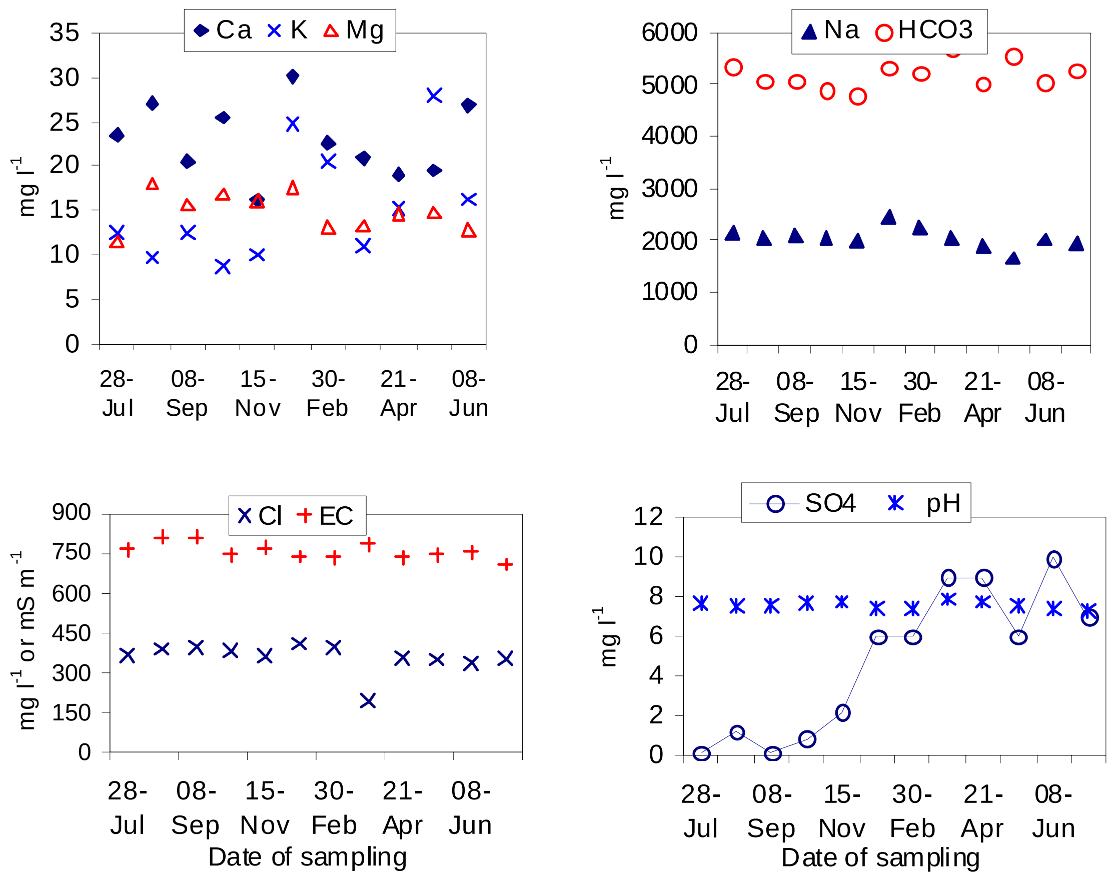


Figure 3.18 CBM irrigation water quality applied in winter 2005 and summer 2005/06

In the winter irrigation trial the crops were sprinkled using less saline water (EC = 70 mS m^{-1}) for about a week to alleviate the salt stress that could appear during the emergence and seedling stages. Irrigation with the CBM water (EC = 800 mS m^{-1}) followed after a week of less saline water irrigations, as the Reverse Osmosis-treatment plant that was giving clean water was unexpectedly out of order. The EC measured for this period of time is presented in Figure 3.19.

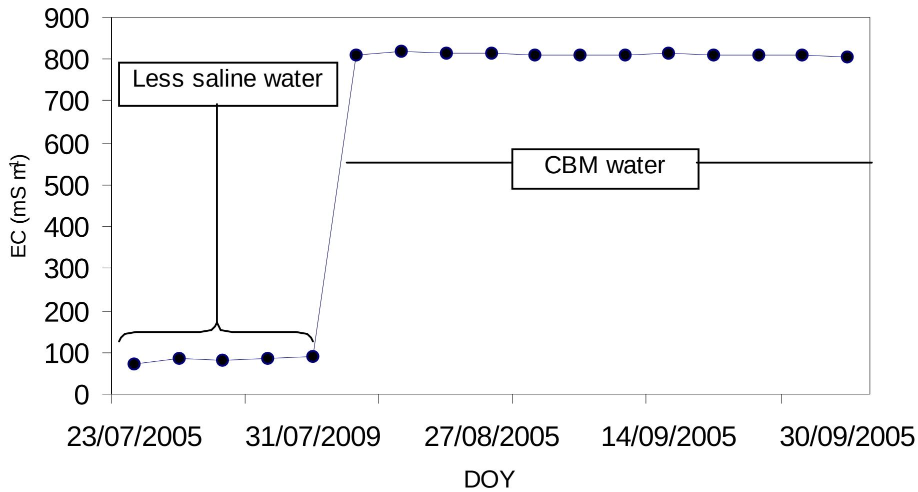


Figure 3.19 EC of the less saline water and CBM water irrigated in winter 2005

In the summer experiment, crops were also irrigated with less saline water for about 8 weeks, whereafter CBM water was applied for the rest of the growing period (Figure 3.20).

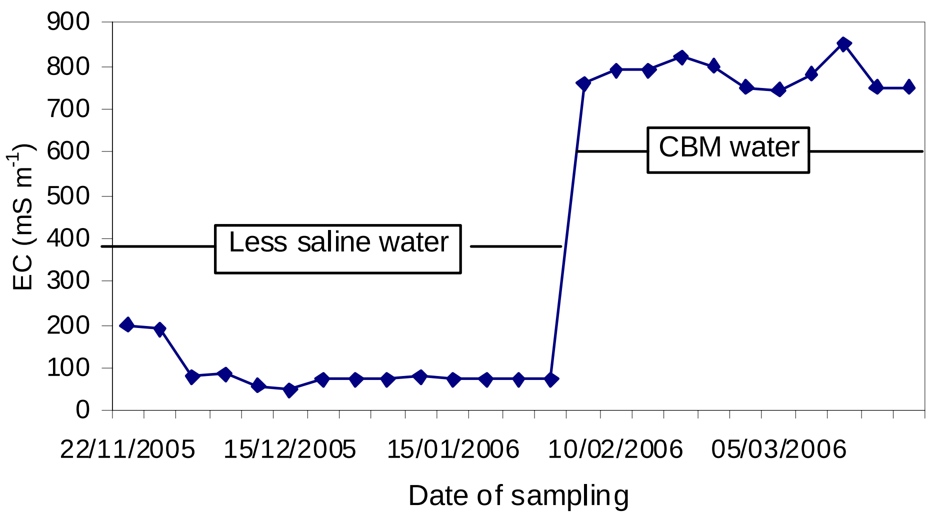


Figure 3.20 EC of the less saline water and CBM water irrigated in summer 2005/06

3.6 Monitoring the field water and salt balance

In all the fields intensive monitoring stations were installed to monitor the soil water and salt balance during the cropping seasons. The intensive monitoring station's instrumentation and measurements made are described here.

3.6.1 Atmospheric Evaporative Demand

An automatic weather station was set up close to the cropped areas for each site. At all the sites where weather stations were set up, they were surrounded by grass and was on a slight slope (Figure 2.20). The sites were assumed to be representative for the area where each pivot was located.

The following metrological data were recorded with the weather stations:

- Temperature and relative humidity with a CS-500 Vaisala temperature and humidity probe;
- Solar radiation with a Li-Cor LI-200 pyranometer (LiCor, Lincoln, Nebraska, USA);
- Wind speed with an R.M. Young cup anemometer (R.M.Young, Michigan, USA); and
- Rainfall amount and intensity with a tipping bucket (Texas Electronics Inc.) rain gauge.

Weather data were recorded every 10 s with a Campbell Scientific CR10X data logger. Temperatures were averaged hourly.. Daily average, maximum and minimum data were also recorded. The datalogger program was set up to calculate and output hourly and daily average vapour pressure and saturation vapour pressure. Solar irradiance was averaged hourly and total daily radiant flux density calculated. Wind speed was averaged, maximized and minimized daily.

3.6.2 Crop growth and nutritional status

During the field trial period, growth analysis was done at various stages of crop development for each site. Plant samples were taken from 1 m^2 areas at representative places, with 3 replications every 10-14 days. Two essential measurements were made, namely, leaf area index and above-ground dry matter (DM) accumulation. Leaf area index (LAI) was calculated from leaf area determined with a leaf area meter (LI-3100, LiCor, Lincoln, Nebraska, USA) and dry matter of partitioned plant parts (leaf, stem, flower and seed) was determined after four to five days of oven drying at 60 ^oC. The DM was used in the investigations of nutrient imbalances. When plants senesced, they were harvested and final yield determined. The yield was compared with the results obtained from dry land farming in the region.

Leaf samples were taken at critical crop growth stages (for example for maize 40-60 cm tall, tasseling and silking) to determine nutritional and possible imbalances. The samples were taken above the ear from three different plants, using hand cuttings. Two to three handfuls of plant leaves replicated three times were collected. No samples were taken within a week after fertilizer has been applied to the crops as fertilizers or herbicides could contaminate the sample and invalidate analytical results. Diseased or dead plant material in a sample was avoided. Sampling plants which have been damaged by insects and stressed extensively by cold, heat, high water content or by waterlogging were also avoided. The frequency of sampling was aimed at monitoring the nutrient status during the growing season.

3.6.3 Soil water balance

Irrigation and rainfall

Amounts of irrigation and rainfall were recorded with tipping bucket raingauges connected to CR10X (Camp bell Scientific Inc, Utah, USA) dataloggers in order to calculate the salt loads on the soil. Manual raingauges were also used as a backup at every site for each pivot and also used to separate the rain from irrigation. There were two electronic and two manual raingauges for each site. Irrigation water samples were collected in 100 mℓ containers over the course of each irrigation season in order to determine the water quality. Water analysis was conducted using established laboratory procedures at the Soil Science Laboratory, Department of Plant Production and Soil Science, University of Pretoria.

In the Waterberg CBM irrigation trial, irrigation amounts were recorded using water meters installed with the irrigation systems. Six water meters were used to measure the flow (m^3) of water to each treatment in the drip system, whereas only one was needed for the sprinkler system. Water was applied based on the envisaged irrigation treatments. The three irrigation amounts envisaged were :

- irrigation to FC **(FC)**;

- a leaching fraction of 23% that applied 30% more water than that needed to return the profile to FC **(LF-23%);** and
- a leaching fraction of 46% that applied 85% more water than that needed to return the profile to FC **(LF-46%)**

Soil water content

Volumetric soil water content at each site was monitored with a neutron water meter (NWM) Model 503DR CPN Hydroprobe (Campbell Pacific Nuclear, California, USA). Two NWM access tubes to a depth of 1.2 m were installed in Major and Pivot Four, and at a depth of 1.0 m in TWF due to the shallower depth of this soil. Two NWM access tubes to depth of 1.4 m were installed at New Vaal. Soil water contents were measured at six depth increments of 0.2 m at Pivot Major and Pivot Four, and at five depth increments of 0.2 m at Pivot TWF. Measurements were made every 10-14 days. Two NWM access tubes to a depth of 0.80 m were installed in Syferfontein, due the shallow depth of the soil. There were five plots and a total of 12 NWM access tubes. Soil water contents were measured at two depth increments of 0.2 m every 10-14 days. The NWM was calibrated for the soils on each site. The calibration equation developed for the site was used to calculate the soil water content in the profile.

Surface runoff

Contour and waterways were designed so that the runoff could leave the pivot over a weir (Figure 3.21a). The weirs were built at the lowest points of fields Major and TWF in 1998 (Kleinkopjé Colliery). A weir was also built at Syferfontein during the winter of 2003.

A pressure transducer measured the water level above the weir, and an **EC sensor** (CS 247 conductivity and temperature probe) determined water quality. The instruments were connected to a CR-510 data logger (Campbell Scientific Inc., Logan, Utah, USA).

a)

b) c)

Figure 3.21 a) Runoff weir layout and b) ISCO sampler at Pivot Major and c) Top view of ISCO sampler with 24 sample bottles

At Pivot Four (Kleinkopjé Colliery), New Vaal Colliery and Waterberg CBM irrigation trial, runoff weirs were not built as no runoff was expected to occur from these fairly flat fields on well-drained, high infiltration capacity soils.

3.6.4 Salt balance

Soil sampling and analysis

At planting, and at the end of the season soils were sampled for each field trial. The sampling was done at 20 cm depth intervals to the bottom of the profile and determinations were made of bulk density, pH, soil saturated electrical conductivity (EC_e), and ion concentrations (Ca, Mg, K, Na, CO_3, HCO_3, Cl, SO_4). The analyses were conducted by the Soil Science Laboratory of the University of Pretoria.

Soil water sampling and analyses

Ceramic cup water samplers at depths of 0.30, 0.60 and 90 m, and an electronic wetting front detector at a depth of 0.40 m were installed in each field at Kleinkopjé and New Vaal. Manual wetting front detectors (WFDs) were also installed at a later stage on depths of 0.30, 0.60 and 0.90 m to get more soil water samples. Due to the shallow depth of the Syferfontein soil, ceramic cups were placed at depths of 0.30 and 0.60 m, and an electronic WFD at a depth of 0.40 m.

Water redistributing in the irrigated profiles after rain or irrigation, was collected about every two weeks from the soil water samplers. The water samples from each field trial were analysed for concentrations of Ca, Mg, K, Na, CO_3, HCO_3, Cl, SO_4 and EC of the soil solution. Sodium Adsorption Ratio (SAR) of the soil solution was calculated for Syferfontein, as Na_2SO_4 dominates the water. SAR for the other fields was not calculated, as the waters were gypsiferous, with negligible amounts of Na. During the trial period, no water could be collected from ceramic cups at Syferfontein. This could be due to high suction or low matric potential of the soil and cracking or swelling of the soil, which resulted in poor contact between soil and ceramic cups.

In the CBM irrigation trial, water infiltrated after rain or irrigation was sampled using wetting front detectors (WFDs) installed at 0.3 m and 0.6 m soil depth, which acted as passive lysimeters (Stirzaker, 2003). Water samples collected from each treatment were analysed for electrical conductivity (EC) of the soil solution. The aim was to see if the EC of the soil solution was above the EC tolerance levels of the crops

Surface runoff water quality

In the winter season (2003) an ISCO 3700 portable water sampler (ISCO, Inc., Lincoln, NE, USA) was installed at the weirs of TWF (Kleinkopjé Colliery) (Figure 3.21b&c) and Syferfontein to sample runoff for detailed analyses. In September 2004 the field trial at Syferfontein was concluded and the sampler was moved to pivot Major. CR10X Campbell loggers, (Campbell Scientific Inc., Logan, Utah, USA) (at TWF and Major), were used to trigger the ISCO sampler for measurement. The dataloggers determined the height of water above the weir every second and converted it to flow using the following equation:

$$Q = 1.585 \text{ x } 5\text{x } h^{2.5}$$

where Q is the flow in m^3s^{-1}, h is the water level above the weir in m and 1.585, 5 and 2.5 are coefficients dependent on the shape and size of the weir. This weir was designed by Prof Simon Lorentz, University of Kwa-Zulu Natal, South Africa, who also determined the values of the coefficients for the equation.

The bottle number, date and time of sampling were stored by the data logger. The ISCO was programmed to stop sampling when water samples had been deposited in all the 24 available bottles. The download of data from the datalogger and collection of water samples from the ISCO sampler were usually carried out fortnightly. Runoff samples were then analyzed for pH, cations, anions, TDS and EC by the University of Pretoria, Soil Science Laboratory. Runoff from rain or irrigation events was measured during the entire period of the study.

3.7 Modelling

3.7.1 Soil Water Balance modelling

The data collected with the intensive monitoring systems were used to determine the components of the soil water and salt balance for each field. For the soil water balance, irrigation and rainfall were measured with automatic raingauges, evapotranspiration was estimated from soil water measurements with a neutron water meter (NWM) and runoff was measured at weirs built at the lowest points of the irrigated fields. Water intercepted by the crop canopy and drainage were estimated with the SWB model. The SWB model was also used to split evapotranspiration into soil evaporation and crop transpiration. For the salt balance, the mass of salts added was determined from irrigation amounts and chemical analyses, salt runoff was measured at the weirs with salinity sensors and laboratory analyses of soil samples were carried out to measure salts in the soil solution. The SWB model was used to estimate the mass of salts precipitated in the soil profile in the form of gypsum and salt leaching.

3.7.2 Modelling, data processing and validations

The data collected in the experimental sites from 1997/98-2006 were used for improvement, development, calibration and validation of the SWB model. Daily weather data such as minimum and maximum temperatures, relative humidity, radiation, wind speed and directions collected with the automatic weather station were used as inputs into the model.

SWB needs initial soil solution chemical properties, irrigation and rainwater chemical characteristics as inputs to determine the quantity of salts in the soil solution of a given layer in a soil profile. The model has eleven soil layers and is set by the user. The actual dates of irrigation and amounts, and water qualities were, therefore, used as inputs into the model. The water quality analyses were done at the University of Pretoria, Soil Science Lab.

SWB calculates the mass of incoming ions diluted in irrigation water, assuming complete mixing of water present in the topsoil layer with the incoming irrigation water. The new concentration of ions in this soil layer is assumed to be the concentration of water penetrating the deep soil layer. The quantity of water penetrating the deeper soil layer is the amount of water that remains after filling the top layer up to field capacity. The same procedure is repeated for each layer. The ionic concentration in each soil layer is updated on a daily basis after crop water uptake is calculated. The salt concentration in the soil solution is controlled by the solubility product of gypsum. A salt will be precipitated from solution once the solubility product is exceeded. The crop growth reduction due to salinity is also related to the osmotic potential of the soil solution in the root zone.

The soil analysis of 1997/98 was used as initial soil chemical property for site TWF and Major. Site Pivot Four and New Vaal started off irrigation in the winter season of 1999 and summer season of 2002, and the chemical properties analysed at this time were used as an initial input to the model. Each of the experimental sites showed large variation in soil properties within the pivots and it was decided to use mean values per depth. The field capacity and permanent wilting point for these sites were also taken mean values per depth.

Specific crop growth parameters already included in the database of SWB (Annandale *et al.*, 1999), were refined in order to account for the specific conditions and cultivars used in these field trials. Improvements of SWB were made to simulate multiple crop rotations. The crop rotation cycle and other pertinent dates required were used as inputs to the model. The maximum rooting depth required by each crop was also compared to the measurements made in the experimental site.

The variables used to evaluate the model were crop growth (top dry matter (TDM), harvestable dry matter (HDM) and leaf area index (LAI)), soil water deficit, soil solution concentrations. Soil water deficit to field capacity determined from NWM measurements, soil solution taken from the ceramic cups and wetting front detectors, and results of crop growth analyses were also entered in the SWB database and compared to simulations.

Simulated graphs of leaf area index (LAI), top dry matter (TDM) and harvestable dry matter (HDM), as well as the soil water deficit to field capacity are presented in Chapter 6. All data used for calibration and validation is available in the SWB database.

Conclusions

The study considered different cropping systems, soils, weather and water qualities to assess the environmental impact and sustainability of irrigation with mine water. Intensive monitoring stations in representative sites of all fields were installed to monitor the soil water and salt balances during the cropping seasons. Crops, soils, weather, irrigation water qualities and surface runoff were monitored for several seasons and the measurements taken were used to validate the SWB model.

CHAPTER 4

CROP PRODUCTION AND PLANT NUTRITION

4.1 Introduction

In this chapter, *crop production* and *plant nutrition* aspects of the study are discussed. The *crop production* section presents the yields and biomass production obtained and discusses possible reasons for suboptimal performance in certain seasons. Yields were also compared to dry land crop production in the region. The *plant nutrition* section discusses results of plant analyses and the imbalances that could occur as a result of unfavourable nutrient interactions. The plant analysis results were interpreted by the Sufficiency Range (SR) approach; this is defined as the range in concentration that can result in 95 to 100% of maximum yield. Diagnosis Recommendation Integrated System (DRIS) was used to rank the most limiting nutrient in the gypsiferous water irrigated crops. In Syferfontein, the effect of the Na_2SO_4 rich irrigation water on forage quality was considered.

4.2 Crop production

The results of the measurements taken for each site are presented in the following discussions.

4.2.1 Kleinkopjé

The yield of maize obtained from fields irrigated with gypsiferous water (average 4 t ha^{-1}) was lower than the average yield usually obtained from fields irrigated with normal water (8 t ha^{-1}) (Du Plessis, 2003), but is higher than the yield of dry land farming (3 t ha^{-1}) (FAO, 2005) (Figure 4.1). According to Maas & Hoffman (1977), maize can still attain potential yield of 100% up to an EC_e (soil saturated paste extract) level of 200 mS m^{-1}. The yield obtained from Pivot TWF and Major, however, was lower than could be predicted from the Maas & Hoffman (1977) yield reduction function. Soil compaction at TWF and the existence of a plinthic layer, which causes limited drainage, at Major could be the possible reasons for the observed yield reduction. The yield reduction in Pivot Four can also be related to the low pH in the soil that could have restricted the availability of nutrients to the plants. Wheat is more tolerant to soil salinity than maize (Maas & Hoffman, 1977), so wheat yield produced on site Major, Pivot four and TWF were not affected by the EC of the irrigation water. According to Maas & Hoffman (1977), wheat can attain a yield of 100% as long as the EC_e threshold does not exceed 600 mS m^{-1}. There was a difference in yields obtained between seasons which could be related to pests and diseases, rainfall or amount of irrigation water applied. Maize crops were damaged in the 2000/01 season, when an excess of herbicide (up to 3 times the planned rate) was wrongly applied to all three pivots.

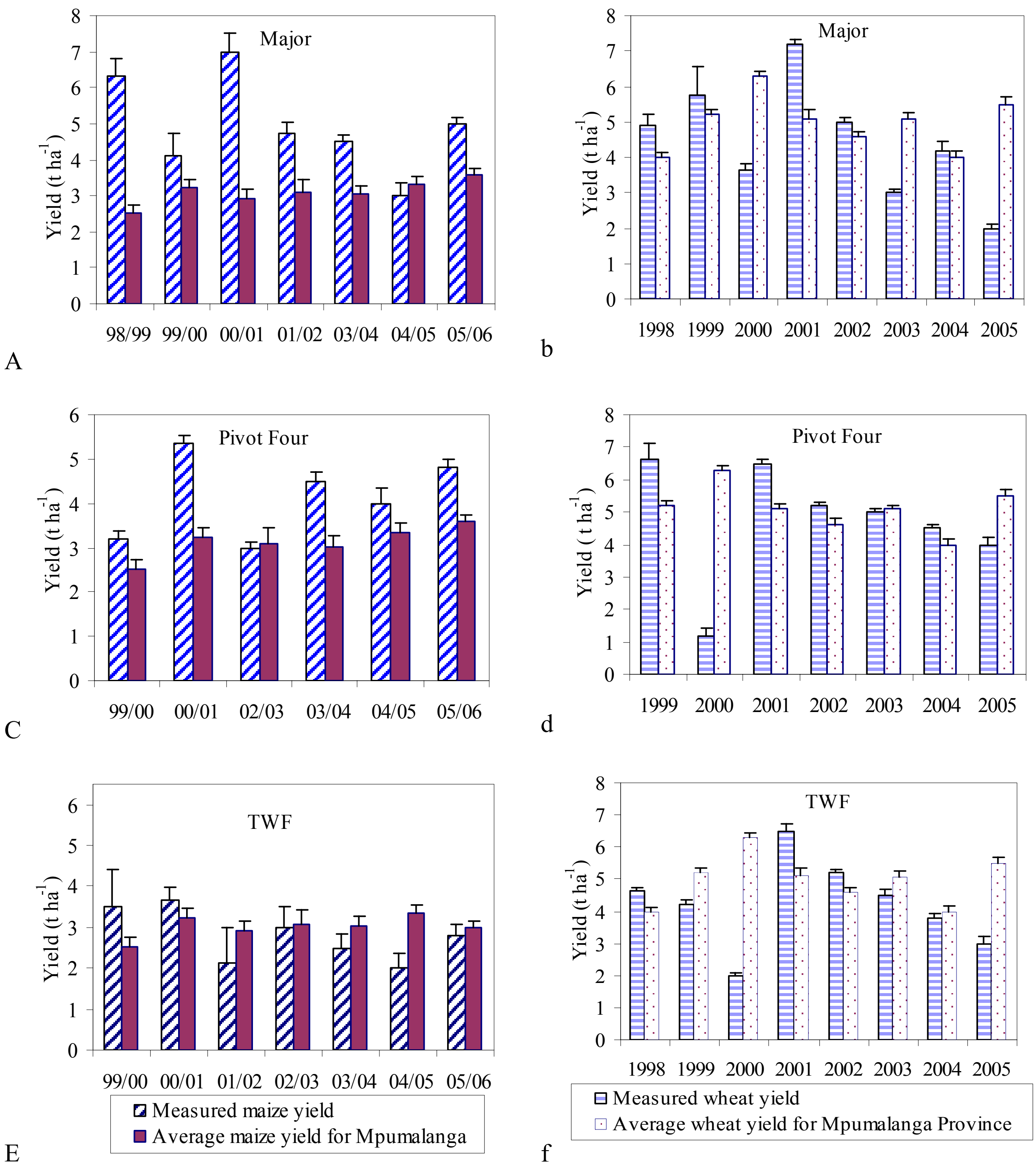


Figure 4.1 Mine water irrigated and dry land yield of maize (a,c and e) and wheat (b,d and f) grown at three pivots at Kleinkopjiè

The yield of maize obtained from Pivot Four was compared with average dry land yield in the region (personal communications, Department of Agriculture, South Africa). The yield obtained from the mine water irrigated soils was higher than the dry land yield (Figure 4.1c). In 2002/03 the yield obtained was lower than the dry land yield. In the same period of time high soluble [K]/[Ca] ratio was observed. The low yield of mine water irrigated maize was apparently related to low potassium for the growing period. K deficiency in these same soils has also been reported in Chapter 4, as Ca excluded K from exchange site. The yield of wheat obtained from Pivot Four was also compared with average yield of irrigated wheat in the Mpumalanga Province (personal communications, Department of Agriculture, South Africa). The yield was comparable to those irrigated with good quality water (Figure 4.1d). In winter 2000, crop failure occurred due to hail.

The yield of maize and wheat obtained from Pivot Major were also compared with average dry land yield of maize and irrigated yield of wheat in the region. The yield obtained from mine water irrigated soils were higher than the average dry land yield for the region (Figure 4.1a), but lower than one could expect from good quality water irrigated crops (FAO, 2005). This is most likely due to the accumulation of salts in the soil above the threshold tolerance of maize especially in the last few years of monitoring, as EC of the irrigation water has climbed from 250 mS m^{-1} to 320 mS m^{-1} (Chapter 3). The plinthic layer at one-metre depth also caused poor drainage and waterlogging problems whenever high rainfall occurred during summer (on the positive side, these wet periods also assisted in leaching salts out of the root zone).

Pivot Major, a poorly drained site, has been irrigated for a longer period of time than Pivot Four, which is a well drained site. Nevertheless, the yield obtained from Pivot Major was comparable to that of Pivot Four. This is related to the high EC of the irrigation water Pivot Four received. The EC of the irrigation water used at Major was around 250 mS m^{-1} in 1997, but increased to a value of 320 mS m^{-1} by the end of 2005. The EC of the irrigation water in pivot Four, started at around 300 mS m^{-1} in 1998 and was fairly stable for several years until 2001, when a rapid increase in EC to a level of 500 mS m^{-1} was observed by the end of 2005. This had a significant effect on the yield of maize over the growing period (Figure 4.2c).

Wheat yield from Pivot Major was also compared to average yield of irrigated wheat in the region. Yield of wheat from mine water irrigated soils was low in the winters of 2000, 2003 and 2005 (Figure 4.1b). In winter 2000, crop failure occurred due to hail whilst in 2003 and 2005; the low yield is related to low amount of irrigation water applied. For example, only an average of 250 mm was applied in the winter seasons, while more water could have been applied (500 mm) to get better yield.

Pivot TWF is a rehabilitated site, and after heavy rain, waterlogging and ponding frequently occurred. A similar condition also arose in the lower lying regions of Pivot Major. The main cause of this is the low hydraulic conductivities of the spoil layer at TWF, and a natural limiting plinthic layer at Major. These are therefore not ideal irrigation sites. Maize yield from mine water irrigated soils in TWF, were often lower than the average dry land yield for the region (Figure 4.1e). This low yield is related to the accumulation of salts above the threshold tolerance for maize (Figure 4.2e) and the waterlogged conditions caused by the low hydraulic conductivities of the spoil layer. The EC of the irrigation water also showed a rapid increase from around 300 mS m^{-1} to a level of 500 mS m^{-1} from 2001-2005 (Chapter 2). In summer, 2004/05 extensive rust disease was also identified on the maize in the late maturity stage and yield was very low. The wheat yield obtained from Pivot TWF was also compared to the average irrigated yield for the region (Figure 4.1f). The yield obtained was usually closer to optimum yield than for the summer crops, as we have much better control over the water balance in winter than in summer.

In winter 2005, wheat was doing very well initially for all pivots and was expected to yield 7 t ha^{-1}. Unfortunately, the electricity supply by the mines to run the pivots was interrupted for six weeks, and as a result, the yield was less than half of what was expected. The yield of wheat obtained from Pivot TWF was observed to decrease from 2001-2005 with the increase in EC of the irrigation water (Figure 4.1f). In the same period of time, Mg in the irrigation water increased and the [K]/[Mg] ratio in the soil solution decreased, indicating the likelihood of potassium deficiency developing (Chapter 5).

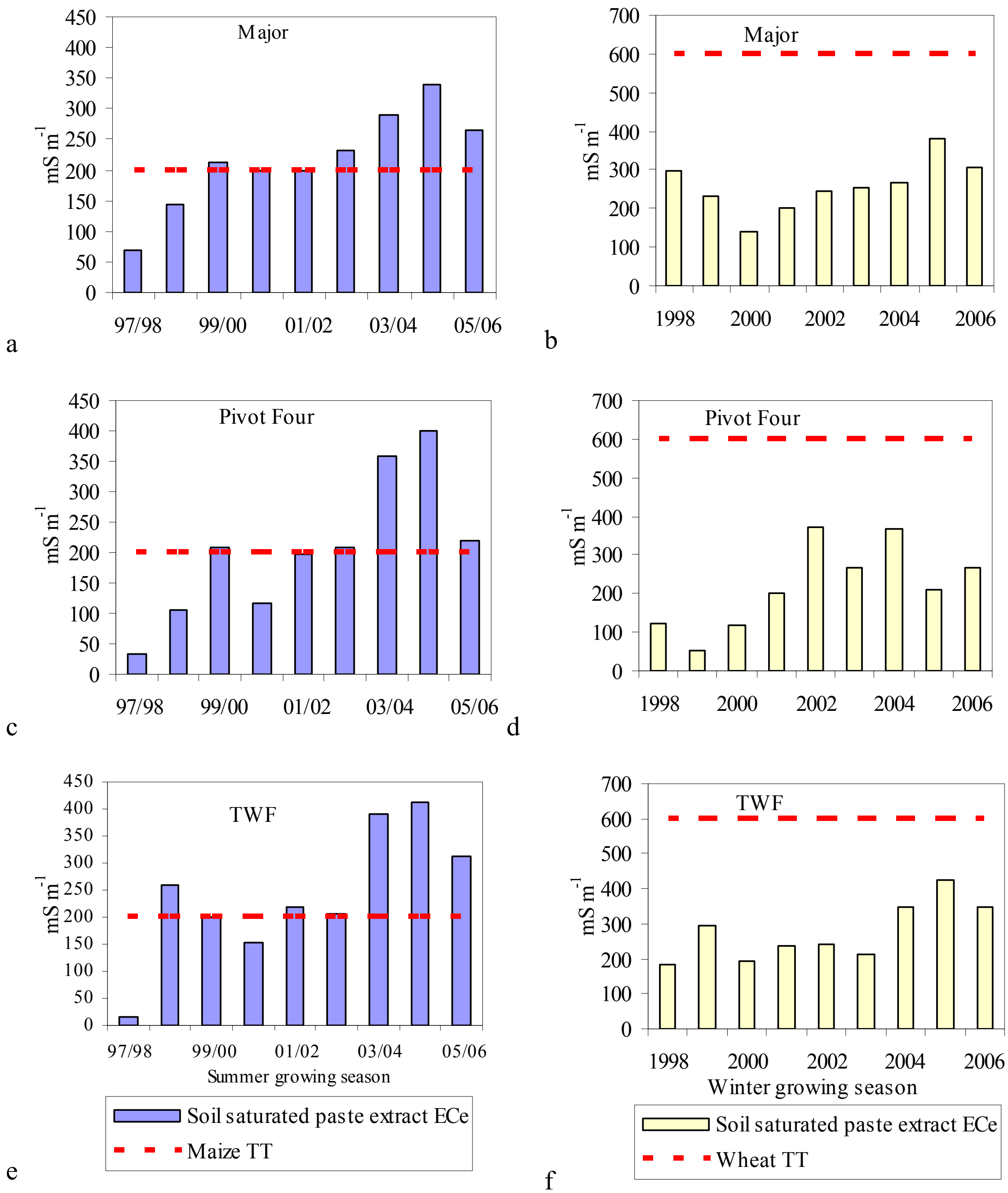


Figure 4.2 Average root zone soil saturated paste extract (EC_e) of soils irrigated with mine water during the growing period and salinity threshold tolerance (TT) for maize and wheat on three pivots at Kleinkopjiè

Potato seed pieces (*Solanum tuberosum* cv. Up-to-date) were planted in Pivot Four at the end of August 2001 and the crop was harvested in January 2002. The marketable potato yields attained was 52 t ha^{-1} in 2001/02 and for 2002/03 at Pivot Major, yields of 62 t ha^{-1} were produced. These can be regarded as good yields for the Mpumalanga Province. Unfortunately no control fields (irrigated with normal water) were available for comparison of crop yield but the yield obtained from mine water irrigation was expected to be better as a result of the dominance of Ca in the irrigation water.

Certainly, crops can be produced with gypsiferous mine waters, but site selection is critical. Pivot Four was always the best site as there were no drainage problems. It is important, therefore, to note that poor crop performance must not automatically be attributed to the quality of the irrigation water.

4.2.2 New Vaal

At New Vaal field crops of maize, wheat and soybean, and vegetables like peas, sweetcorn and pumpkin were planted. The yields obtained were not satisfactory for the trial period, which is related to poor irrigation site selection. The yields from the pea and pumpkin harvests were also low because of very high rainfall late in the season, causing high volumes of water in the dam. The dam is located near to the irrigation site and water was moving laterally in the very sandy soil from the dam, as the dam was unlined and porous. Waterlogging was evident over large areas of the pivot and this influenced the growth of the peas and pumpkins negatively, which caused yield losses (Figure 3.16). To alleviate this problem, a cut-off trench between the dam and the pivot area was excavated in August 2004, and the pivot was planted to soybean in summer 2004/05. The total yields obtained from the crops from 2001 to 2005 are summarized in Table 4.1.

Table 4.1 Crops, cultivars and yields irrigated with gypsiferous mine water (at New Vaal)

Season	Crops and cultivars	Yield ($Mg\ ha^{-1}$)	Comments
2001/02	Maize(cv. PHI 32P75)	7.8	Wet areas
2002	Wheat(cv. SST 825)	3.3	Pollination problems due to hot period
2002/03	Maize(cv. PHI 32P75)	5	Low stand
2003	Peas	1.1	Temperature, low stand
2004	Sweet corn	6.9	Waterlogging
2004	Pumpkin	2.5	Waterlogging
2004/2005	Soya bean	3	Waterlogging

In summer 2001/2002, the maize yield was satisfactory, however crop growth was not uniform throughout the field, as the water table rise resulted in periodic saturation of the soil.

In winter 2002, yield loss occurred as wheat was planted late, which caused late maturity and exposure to hot dry weather during the pollination and grain filling periods. The poor pollination therefore, reduced the silk and resulted in lower yields, even though plant population, fertility, and water availability were optimal.

In summer 2002/2003, a very poor stand was observed for the maize as the rising water table kept the sandy soil continuously wet, resulting in anaerobic conditions. In addition, chemical weed control by the farmer was not satisfactory.

Starting from winter 2003, the farmer decided to attempt to produce higher value vegetable crops like peas, pumpkins and sweetcorn. Unfortunately, after a little irrigation, the water table started to rise and the drainage became limited, even though it is a very sandy soil. As a result, the anaerobic conditions in the root zone resulted in poor germination.

In summer 2004/05, a drainage canal that was meant to cut the field off from the dam was trenched. This was an attempt to limit the lateral water flow from the dam to the field but the improvement seems to have been minimal. Thus, a poor stand and yield of soybean was obtained and the farmer in conjunction with the research team and mine decided to cease operations. Clearly, site selection for irrigation is crucial, and we are confident that it was not the water quality that resulted in these failure, but rather the long periods of waterlogging (Figure 3.16).

4.2.3 Syferfontein

In Syferfontein annual and perennial pasture crops were grown and the yields obtained were satisfactory for the trial period. The pastures grown and the yields obtained throughout the trial period are indicated in Table 3.1 and Figures 4.3.

There were nine harvests during the 2001-2004 growing period. As the planted pastures emerged from seed, they were observed to grow slowly at first and then their growth accelerated until they reached the flowering stage, after which growth slowed. A plateau was also observed during their growing periods, particularly in Lucerne. This was not related to the irrigation water quality. The growth of grasses usually follows a sigmoidal curve from the time of establishment until death in annuals and until a steady condition is reached in perennials (Tainton, 2000).

The regrowth of pastures after mowing should follow the same sigmoidal growth pattern as in the previous cycle (Dovrat, 1993). However, after mechanical harvest and an extended cutting interval, the recovery of Fescue (cv. Iewag), Fescue (cv. Demeter), Eragrostis and Kikuyu was slow. Cutting the grasses extremely short, and dry periods after mowing caused this slow growth. According to Dovrat (1993), small numbers of tillers may have remained after cutting that enabled the regrowth. It could also be due to the decrease in capacity to capture solar radiation. Accordingly, the plants depleted the stored carbohydrate reserves and slow regrowth was observed. Maintaining adequate irrigation and water levels in the soil is also effective in maintaining humidity in the green leafy canopy, so that the grass can continue to transpire and photosynthesise.

Since the pastures were harvested to a height of 3-7 cm above the ground, the apical meristem might have been removed, which could be another reason for the slow recovery of the grasses. Lucerne, a perennial legume, unlike the grasses has a lignified stem, and has the capacity to develop secondary stems from the axillary buds of the lower leaves on the original primary stem (Tainton, 2000). Lateral tillering or branching becomes necessary before continuation of leaf production in grasses. Thus, the height of cutting changes the location of shoots that support regrowth (Dovrat, 1993).

The remaining TDM and leaf area after cutting are the most important factors in determining regrowth (Dovrat, 1993). The regrowth of Lucerne was observed to be faster than the grasses. This might be due to the apex of grasses being higher from the ground while in legumes apical meristem (terminal growing point) remains low to the ground during their vegetative growth (Tainton, 2000).

In this study, the idea was to grow a mixture of grasses and legumes but the tall growing pastures such as Eragrostis and Lucerne formed a canopy that covered the slow growing species. As a result, after the first cut the taller plants crowded out the shorter plants, resulting in pure stands of Lucerne and Eragrostis. This could be due to the capturing of most of the solar radiation by the tall growing grasses, while the slow growing grasses remained shaded (Tainton, 2000).

The average yield and above ground dry matter of Fescue (cv. Iewag) was greater than that of Lucerne, Fescue (cv. Demeter) and Eragrostis. This could be due to the tolerance of Fescue (cv. Iewag) to salinity. According to Tanji (1990), the EC_e threshold of Fescue is 390 mS m^{-1}, while for Kikuyu it is 300 mS m^{-1}. In addition, Tanji (1990) also reported a salinity threshold of 200 mS m^{-1} for Lucerne and Eragrostis. The difference in yield between the two Fescue cultivars could be due to cultivar differences. However, the yields of all the planted pastures were lower than those that could normally be expected (Taiton, 2000) Figure 4.3.

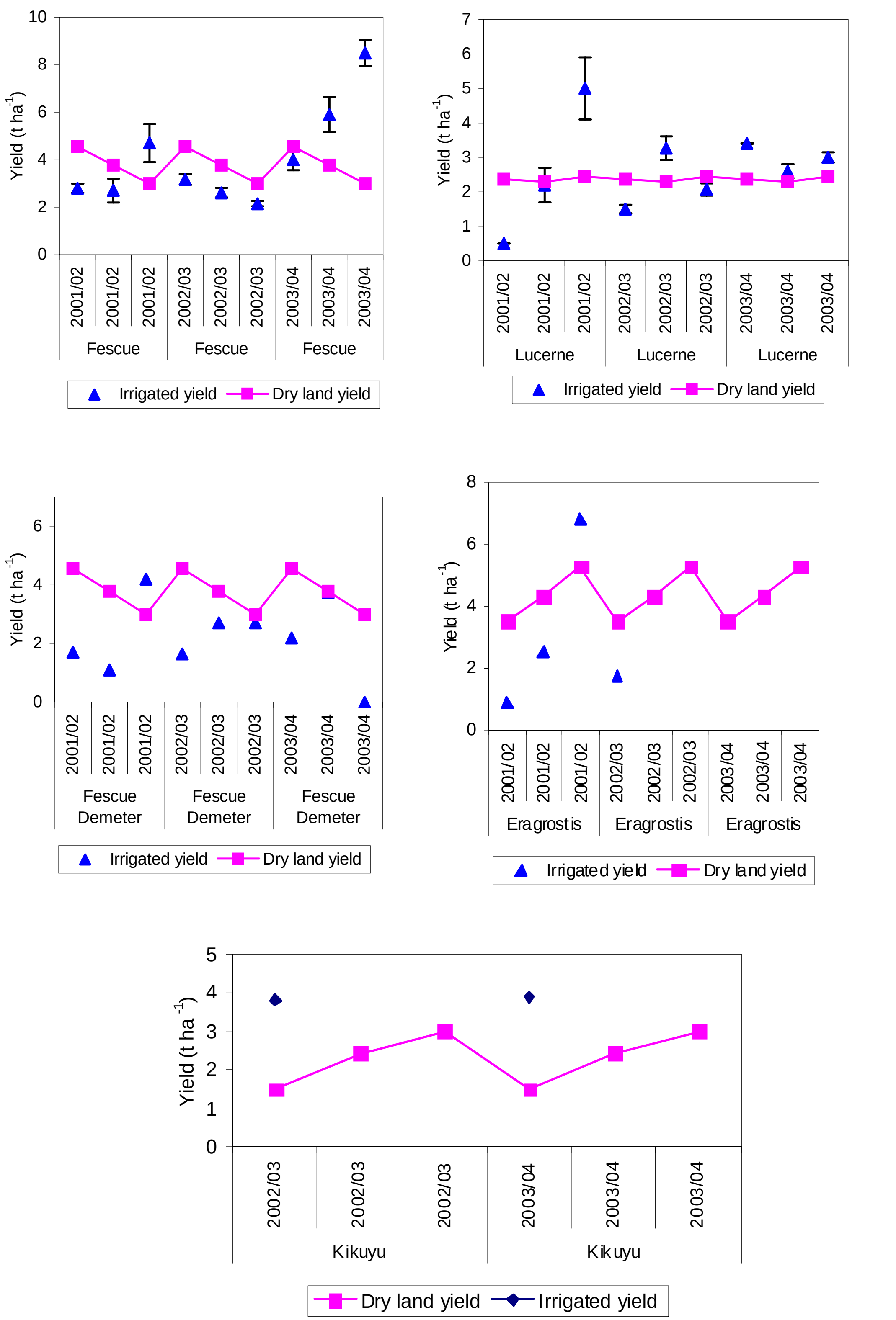


Figure 4.3 Yields of pastures irrigated with Na_2SO_4 rich mine effluent and typical dry land

Although the pastures were all harvested at the same time, the regrowth of Lucerne was observed to be much faster. The basal cover of Fescue (cv. Iewag), Fescue (cv. Demeter) and Kikuyu was outstanding. In the growth cycles, there was no sign of leaf burn due to the mine effluent. The leaves of Lucerne were, however small, which could be due to the high EC of the irrigation water and periodic water logging, as Lucerne is adapted to well drained soils.

4.2.4 Waterberg

Effect of $NaHCO_3$ water on biomass production of barley and ryegrass seemed negligible for the first six weeks of irrigation in the winter 2005 experiment. Although comparable data with good quality water were not available, barley irrigated at a leaching fraction of 23% showed a higher LAI and biomass production than the LF46% and FC treatments (Figure 4.4).

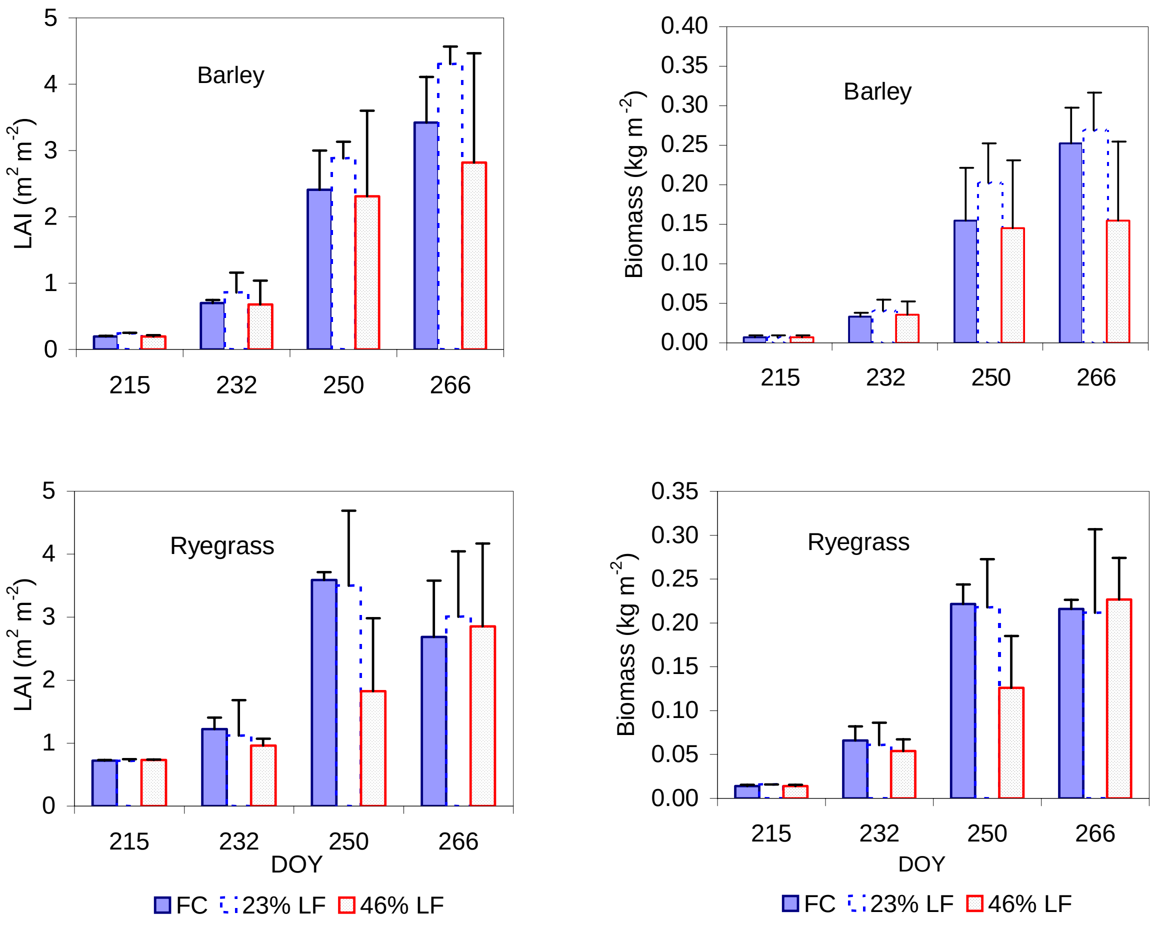


Figure 4.4 Leaf area index and biomass production of the salt tolerant winter crops under different irrigation management strategies

Barley irrigated at a 46%LF showed the lowest performance in terms of biomass production, as the high leaching fraction reached high ESP more rapidly, which caused waterlogging and leaching of nutrients. Low LAI and biomass production in the FC treatment could be due to the accumulation of salts in the root zone (Figure 4.4). Stooling rye did not establish well, which could be due to the late planting date, as it is actually an autumn crop. Italian rye grass, on the other hand, established well with a full ground cover. No difference in biomass and LAI was observed for the Italian ryegrass irrigated to FC and that with a 23%LF. Barley and Italian ryegrass died after six weeks of irrigation as a result of waterlogging, related to the decrease in infiltration rate with the increase in exchangeable sodium in the soil. This is a common effect on certain soils when irrigating with sodium-rich waters (Shainberg & Letey, 1984; Oster *et al*., 1996). Sprinkler irrigated barley and Italian ryegrass did not exhibit foliage scorching symptoms, but senesced early due to ponding.

The biomass yields and above ground dry matter of cotton and Bermuda grass were satisfactory. Cotton irrigated at an LF of 23%, as in the case for the winter season crops, showed higher LAI and biomass production than the 46% leaching fraction and FC treatments (Figure 4.5). A similar tendency was observed for the second sampling of Bermuda grass, although differences were minor (Figure 4.6).

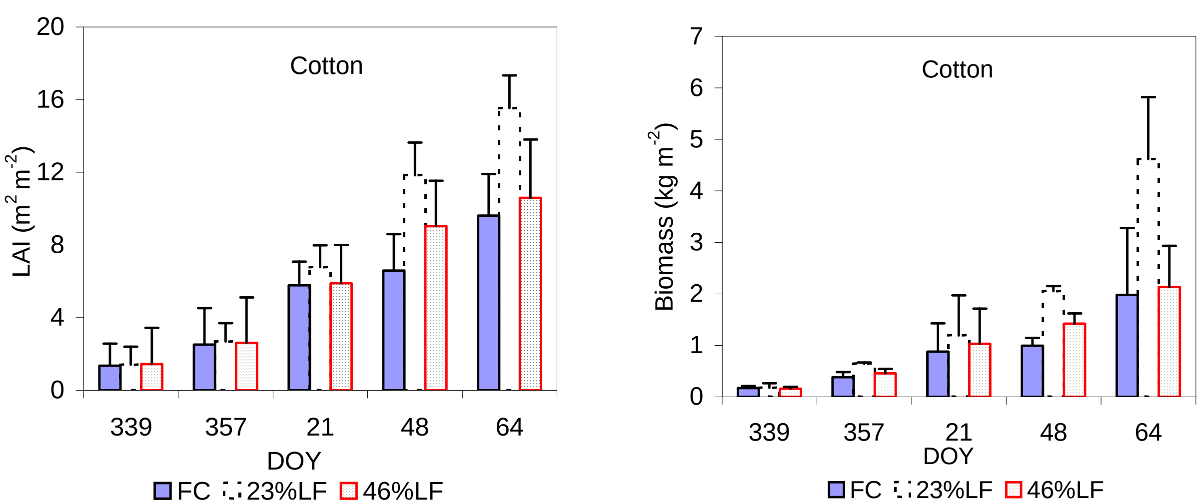


Figure 4.5 Leaf area index and biomass production of cotton under different irrigation management strategies

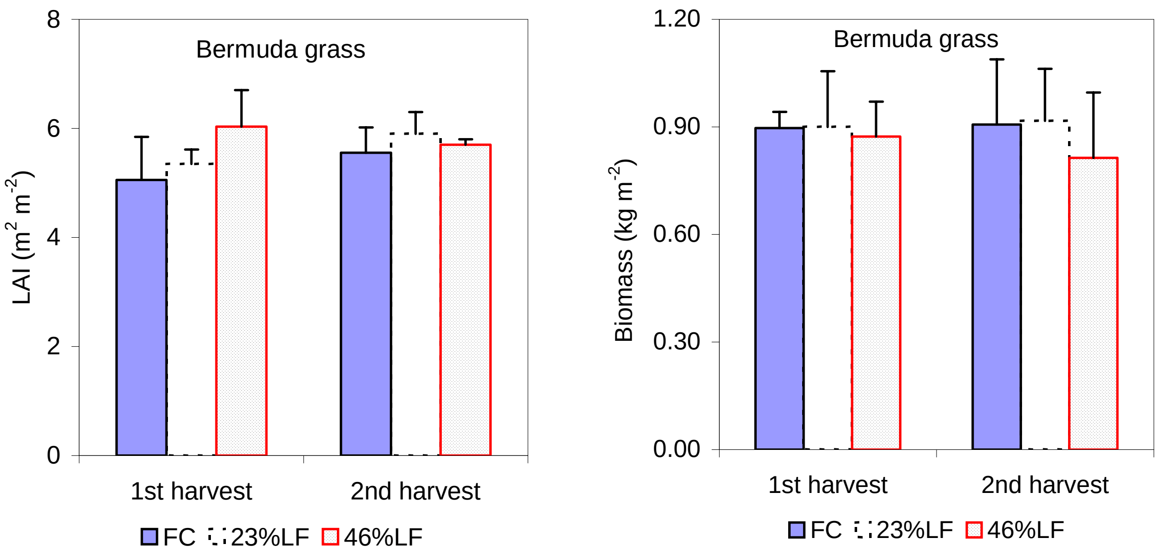


Figure 4.6 LAI and biomass production of Bermuda grass under different irrigation management strategies. First harvest received less saline water, whilst the second harvest was irrigated with 800 mS m^{-1} $NaHCO_3$ water

Table 4.2 Cotton yield and fibre quality obtained from the CBM deep aquifer water irrigated fields

	Cotton				
Irrigation treatment	Yield (t ha^{-1})	Lint uniformity (%)	seed mass (g)	Length (cm)	Micronair (micro g cm^{-2})
FC	5.3(±2.3)	83.3%	390	1.13	4.0
LF-23%	7.0 (±2.4)	84.0%	400	1.17	3.9
LF-46%	5.5 (±2.3)	83.0%	250	1.15	3.2

The cotton yield obtained with this saline water was higher than the average dry land crop production in the area, which is only 0.5-2 t ha^{-1} (Cotton SA, 2006). In this trial periods, the 23%LF seem to have struck a good balance between sufficient salt leaching without excessive nutrient leaching, as several small N top dressings were applied to minimize such losses.

Conclusions

Maize and wheat were irrigated with Ca, Mg and SO_4 rich mine water for several seasons at Kleinkopjé Colliery. Yields of maize obtained at all the sites were depressed below the optimum as salt accumulated in the root zone above the threshold tolerance of the crop. These yields, however, were higher than average dryland yields for the region. Wheat reportedly is more tolerant to salinity than maize and optimal yield was obtained as can be seen by comparing yields with that of irrigated wheat for the region as a whole.

At New Vaal, field crops of maize, wheat and soybean, and vegetables like peas, sweetcorn and pumpkin were planted. The yields obtained were not satisfactory for the trial period, which could be related to poor irrigation site selection. No symptoms of foliar injury due to centre pivot sprinkler irrigation with gypsiferous mine water were observed for all crops. The major problem experienced was waterlogging due to poor site selection, especially during the summer months, when control over the soil water regime is difficult due to rainfall. The problem was not related to the chemistry of the water used for irrigation, as it was observed that crop performance was good in well-drained areas of the fields. Crop production under irrigation with mine water rich in Ca, Mg and SO_4 is, therefore, feasible and sustainable if properly managed.

Pasture production with Na_2SO_4 rich mine effluent was also feasible, at least in the short term (three years), but would need a well-drained profile and a large leaching fraction to prevent unsustainable salt build up in the soil. Unfortunately, the waters did not present much of an opportunity for gypsum precipitation, which is able to drastically reduce the salt load of the receiving waters in the case of Ca and SO_4 rich mine waters. The application of $Ca(NO_3)_2$ as a source of Ca to the soil could remove some SO_4 from the water system and enhance gypsum precipitation.

The highly concentrated $NaHCO_3$ Coal Bed Methane deep aquifer water is of very poor quality for irrigation. Salt tolerant crops of barley, Italian ryegrass, cotton and Bermuda grass, however, can be grown with very skilful irrigation and crop management. Crop production under sprinkler irrigation clearly showed that barley, Italian ryegrass and Bermuda grass were able to grow without leaf burn and toxicity problems. However, cotton foliage was scorched due to the high levels of Na in the irrigation water. It is recommended that with water of this quality, irrigation systems that apply water directly to the soil surface would be preferable. This is especially prudent if one also considers the likely mechanical impact of sprinkler irrigation on surface crusting and on salt accumulation.

4.3 Plant nutrition

Two methods, sufficiency range (SR) and DRIS system were used in the interpretation of the nutrient concentration in the leaves. The sufficiency range (norms) compares the nutrient levels found in plant tissue, while the DRIS system indicates the most limiting nutrient during crop production. The results of the two interpretations are discussed as follows.

4.3.1 Kleinkopjé

Sufficiency range

The interesting observation in this study was that the N content was below the normal range throughout the study period (Figure 4.7). This could be due to poor fertilization management. EC of the irrigation water could have also played a role as similar results were obtained by Feigin (1985). Most salinity and N interaction studies in the field were conducted on soils deficient in N, thus additions of N improved growth and/or yield (Grattan & Grieve, 1998). However, the form in which N supplied to salt-stressed plants can influence salinity-N relations as well as affect salinity's relation with other nutrients (Lewis *et al*., 1989; Martinez & Cerdá, 1989).

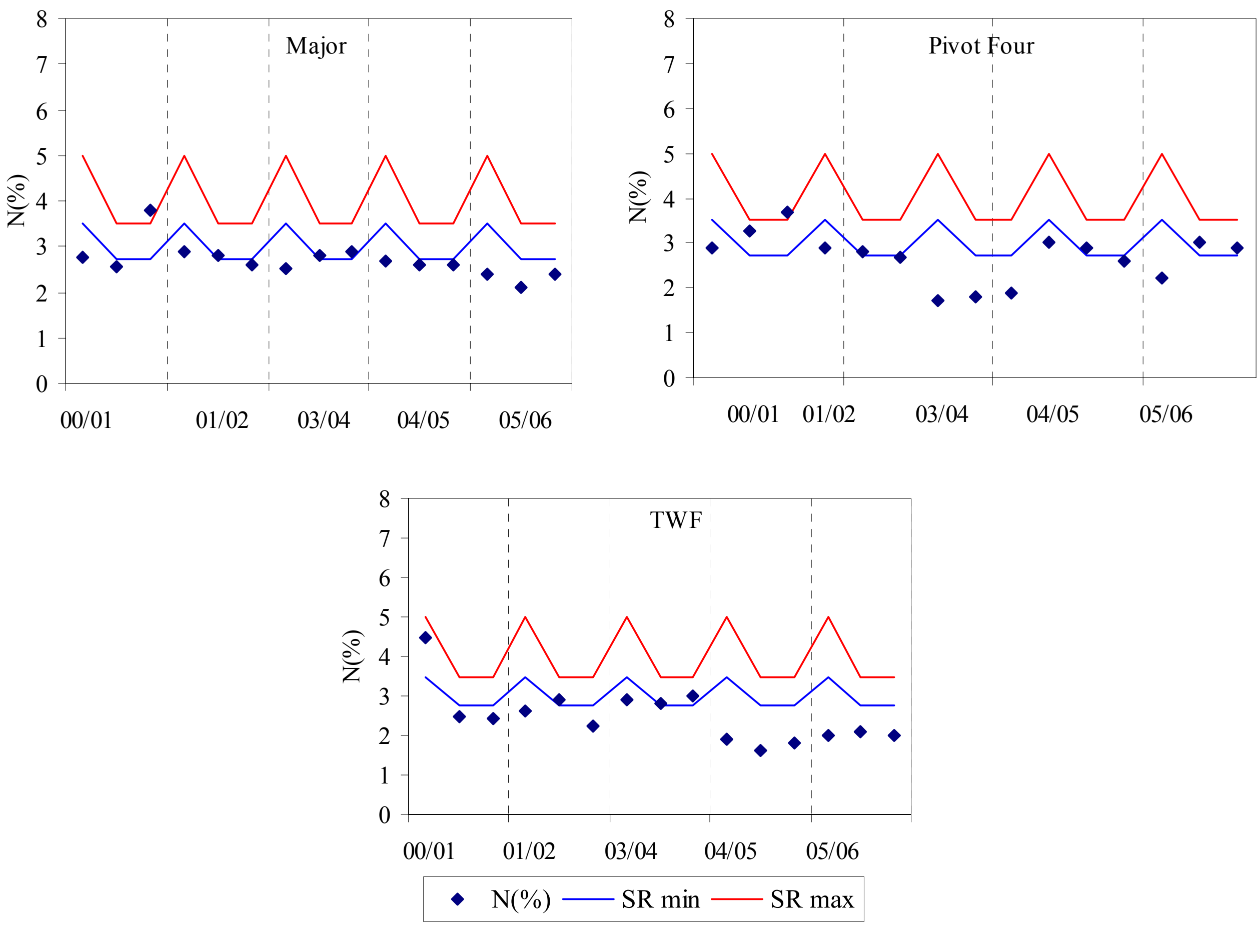


Figure 4.7 N content of maize leaf irrigated with coal mine-water for sites Major, Pivot Four and TWF, and sufficiency range of maize leave irrigated with fresh water

K contents on most samples were higher in the early stages and decreased 67 to 69 days after planting, as it was translocated from old leaves to new growth. In the summer seasons of 2003/04, 2004/05 and 2005/06, K was below the normal range and marginal leaf burn was also observed (Figure 4.8). Other research also has demonstrated that the presence of adequate Ca in the soil influences the uptake of K by favouring the selectivity of K (Grattan & Grieve, 1998). The beneficial effects of Ca on the K status of saline water irrigated crops could be more evident in root tissue rather than the shoots e.g. maize (Izzo *et al*., 1993).

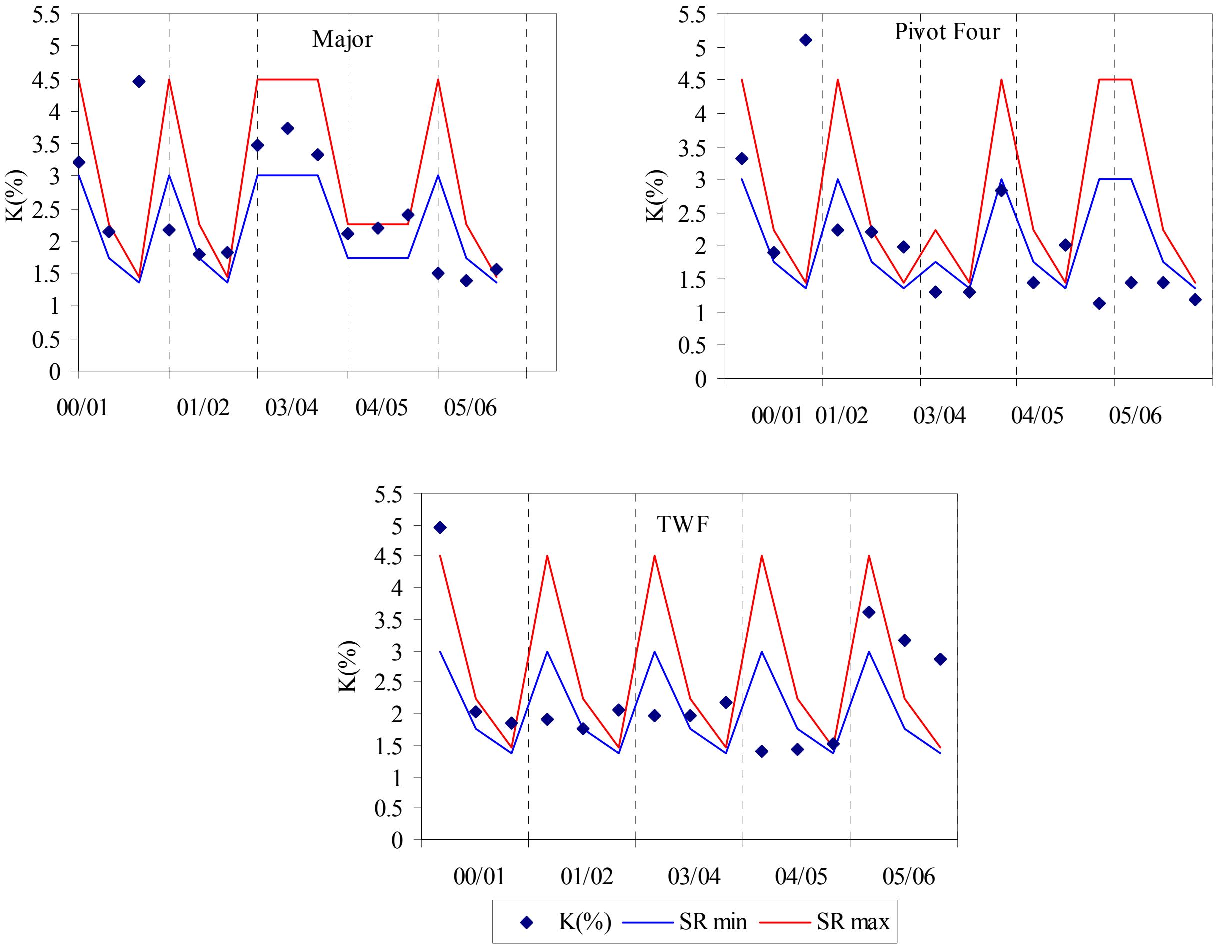


Figure 4.8 Maize leaf K content for sites Major, Pivot Four and TWF

Magnesium content in the plant tissue was with in the normal range in most of observations (Figure 4.9). Pivots Four, TWF, and Major received irrigation water with Mg content that ranged between 150 and 300 mg ℓ^{-1} (Chapter 3). This confirms that no Mg fertilization is required. According to Marschner (1995), Ca is a strong competitor with Mg and the binding sites on the root plasma membrane appear to have less affinity for the highly hydrated Mg than for Ca.

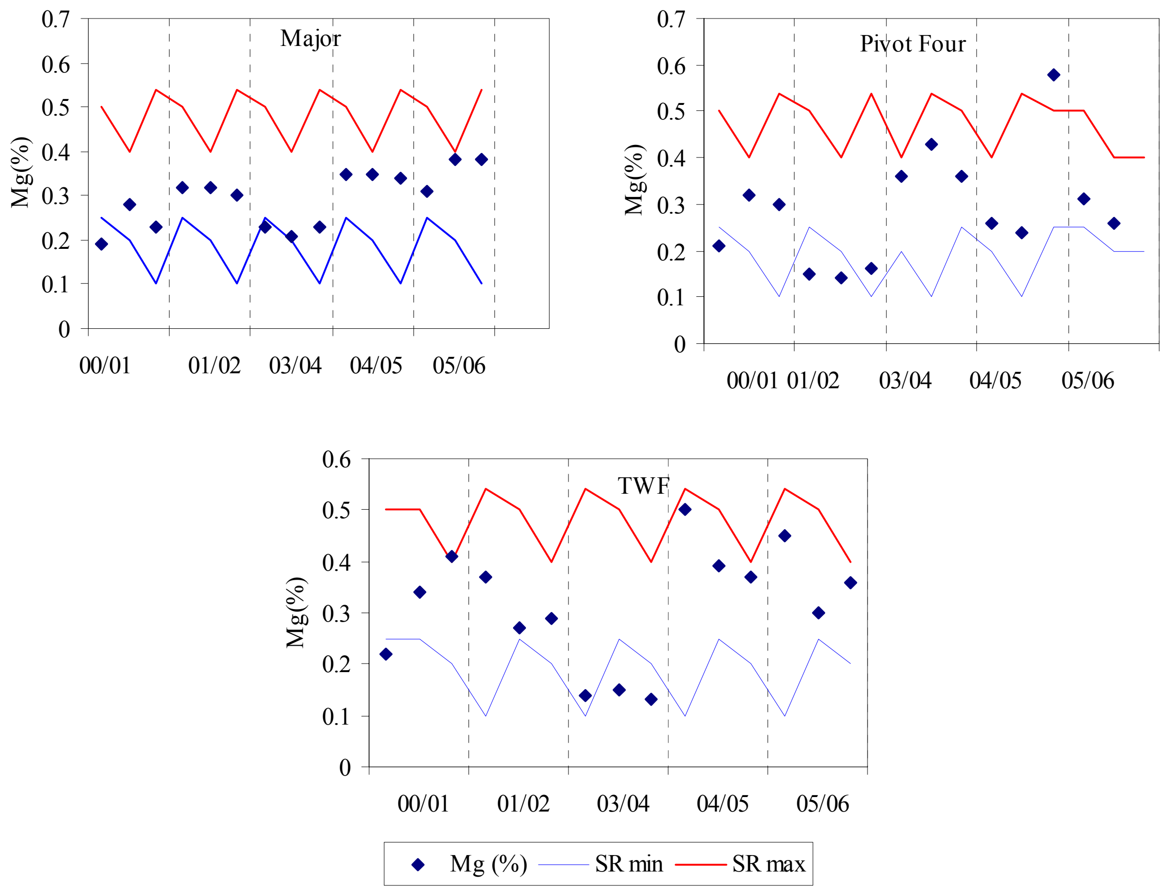


Figure 4.9 Maize leaf Mg content for sites Major, Pivot Four and TWF

The Ca content in the plant leaves was observed in the normal range, except for Pivot Four (Figure 4.10). This could be related to the ion interactions, precipitation of gypsum, and increase in ionic strength that depress the uptake of Ca from the soil solution. According to Suarez & Grieve (1988), these factors reduce the activity of Ca in solution, thereby decreasing Ca availability to the plant. The results obtained in this study agrees to the concept of Gerard (1971) and Bernstein (1975), that says with the increase in salt concentration in a root zone, plant requirement for Ca also increases.

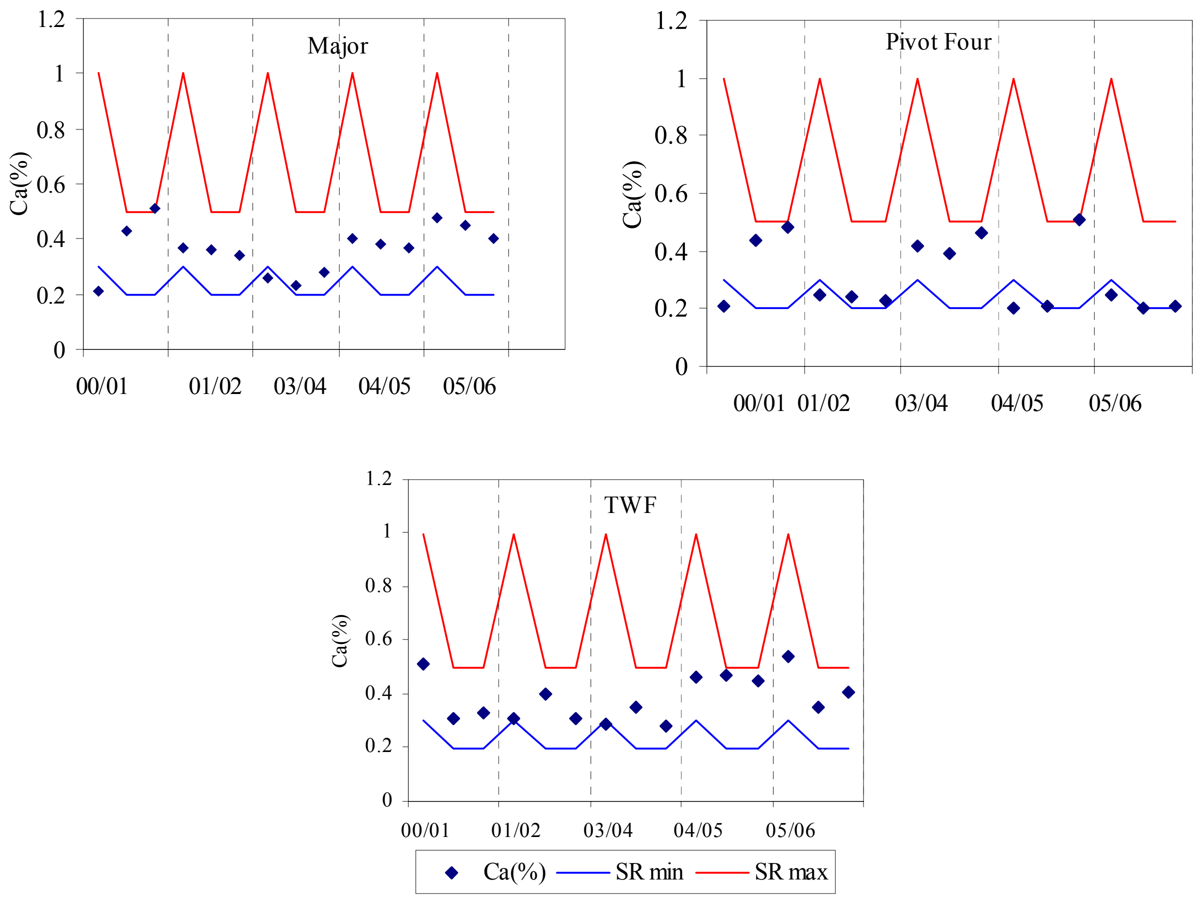


Figure 4.10 Maize leaf Ca content for sites Major, Pivot Four and TWF

SO_4 levels were often above the sufficiency range at Pivot Four and TWF (Figure 4.11). The high SO_4 in the plant tissue was likely due to the high SO_4 levels in the soil solution coming from the irrigation water. The presence of high SO_4 did not bring any problem to crop production throughout the trial period. According to Grattan & Grieve, (1998), many crops are generally more tolerant to sulphate-salinity than chloride-salinity. Other sulphate-salinity studies have also shown that SO_4 have the advantage of reducing the accumulation of potentially toxic oxyanion, molybdate (Läuchli & Grattan, 1993) on plant tissues.

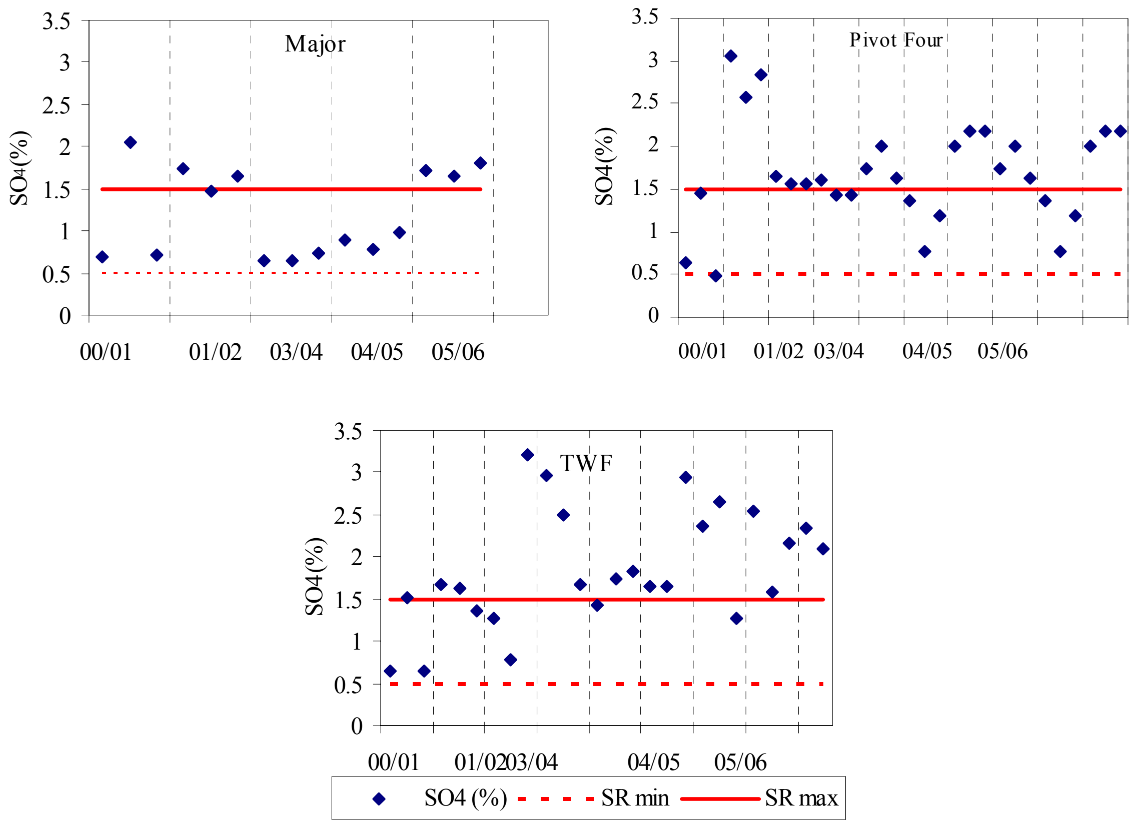


Figure 4.11 Maize leaf SO_4 content for sites Major, Pivot Four and TWF

Diagnosis Recommendation Integrated System (DRIS)

The sufficiency range considered enabled us to see whether the nutrients were within, above or below the normal range but unable to rank which nutrient is most limiting in the crops irrigated with gypsiferous water. Thus, the Diagnosis Recommendation Integrated System (DRIS) was used to rank the most limiting nutrients. Examples of the results of the DRIS indices are shown in Tables 4.3 and 4.4. N, Mg, K and SO_4 were among the most negative, which indicated the most deficient nutrients in the maize leaf. N, K and Ca appeared to be the most deficient nutrients in wheat. Similar results were also obtained for maize and wheat grown in Pivot Four and TWF.

Table 4.3 DRIS indices of maize on site Major

Nutrients	00/01	01/02	03/04	04/05	05/06
	Seasons				
N	**-16**[c]	**-27**[c]	**-25**[a]	-3	**-57**[b]
P	-3	-11	-2	-4	6
K	29	26	**-17**[c]	**-27**[b]	**-61**[a]
Ca	-4	**-31**[b]	-4	-17	5
Mg	**-31**[a]	-16	-11	**-32**[a]	-2
SO_4	**-20**[b]	**-34**[a]	-10	16	5
Cu	-14	7	11	7	**-15**[c]
Fe	-3	3	-11	**-19**[c]	-10
Mn	0	-16	**-18**	7	58
Zn	3	51	15	-8	25

a, b and c indicate most limiting nutrients ranked a - as top limiting nutrient

Table 4.4 DRIS indices for wheat on site Major

Nutrients	2001	2002	2003	2004	2005
	Seasons				
N	**-10**[c]	0	**-37**[a]	**-34**[b]	**-23**[a]
P	7	2	**-18**[c]	4	**-7**[b]
K	6	**-18**[a]	**-29**[b]	**-53**[a]	-3
Ca	**-30**[a]	**-9**[c]	-7	-10	-1
Mg	**-15**[b]	1	13	15	6
SO_4	17	9	24	22	**-7**[b]
Cu	-9	**-12**[b]	5	**-11**[c]	7
Fe	-7	3	-6	8	-4
Mn	**-15**[b]	-3	23	39	4
Zn	8	**-9**[c]	4	6	11

a, b and c indicate most limiting nutrients ranked a - as top limiting nutrient

In the interpretation of the nutrient concentration ratios, more focus was given to K, N and S, because of their major physiological role in the plant. Potassium is known to have a key role in N uptake and translocation (Cushnahan *et al*., 1995), whereas S and N are vital co-constituents of proteins (Marschner, 1995). In all the crops irrigated with gypsiferous mine water, N, K and Mg were required in relatively higher quantities than the other nutrients. Hence, maintaining the correct ratios of these nutrients in crop production using gypsiferous mine water is obviously important. In the maize and wheat leaves, N and K were the most deficient nutrients, compared to the others, and would probably be the most limiting nutrients. Ca and Mg are unlikely to be yield limiting even though their indices are negative. Ca and Mg uptake by plants is a passive process driven by transpiration and mass flow (Marschner, 1995). Therefore, the negative indices could be related to the water uptake of the plants or osmotic potential of the soil that could lower the concentrations in the plant tissues than the other nutrients ratio. Zn, Mn, Cu and Fe showed irregular pattern during the growth period and were not identified as a limiting nutrient by DRIS or SR system.

No nutrient deficiencies on the leaves of potatoes were also observed at any stage during the growing season. All nutrient levels were within acceptable ranges for potatoes (Bennet, 1993) at both sampling times for both seasons. Generally, leaf nutrient levels declined from the first to the second sampling. This drop in nutrient content as the season progresses is a normal phenomenon, known for various annual crops (Lorenz & Tyler, 1983). The high calcium levels in irrigation water did not seem to suppress uptake of other essential nutrients. Good processing tuber quality was realized for both seasons, as reflected by high specific gravity and chip colour values. It can, therefore, be concluded that irrigating potatoes with gypsiferous mine water resulted in high tuber yields of good quality.

In general, the dominant ions in the irrigation water like Ca, Mg and SO_4 were found to be higher than normal in the crops at Kleinkopjé. Less K uptake was traced at Major, Pivot For and TWF, this could be as a result of low [K]/[Ca] ratio in the soil. The nutrient concentrations within plants were also not uniform and varied with time through the growing period. However, there was no any apparent nutrient disorder in the plants.

Micronutrients

The solubility of micronutrients (e.g. Cu, Fe, Mn, Mo and Zn) is usually low (Grattan & Grieve, 1998) however, plants grown in the mine water irrigated soils did not experience deficiencies. Cu was higher at 69 to 74 days after planting for all pivots. Rahman *et al*., (1993) found that maize leaf Cu concentrations decreased when it is salt-stressed, which contrasts these results.

Mn, Fe and Zn were higher than the normal range throughout the growing period for maize in sites Major, TWF and Pivot Four. Similarly, Rahman *et al*. (1993) showed that salinity increased Zn concentration in maize tissues, whilst Hassan *et al*. (1970) point out that salinity decreased Fe concentration in the leaves of wheat and maize which is contrary to our results. High Fe test results normally indicate soil or dust contamination of the plant. The remaining analyses of maize plant material were normal.

4.3.2 New Vaal

At pivot New Vaal, plant samples were only taken from parts of the field that were not waterlogged, as analysis of plant tissue from drowning crops would be meaningless. In the plant analysis results of maize at pivot New Vaal, N was initially lower than the normal range, as the plant samples were taken before fertilizer application. K and Ca were higher than the normal ranges, but decreased at 81 DAP, and increased again 96 DAP. SO_4 was in the normal range throughout the growing period. Cu was high at 41 DAP, but decreased to 81 DAP and then increased again by 96 DAP. Fe also was high at 96 DAP. There were no observations of nutrient disorders during the trial period (Figure 4.12). Plant analyses results from soybeans at different stages during the growing period showed that nutrients were within the sufficiency range (Reuter, 1986). K in Maize leaves was found below the minimum range. Except for peas, no deficiency of macro or micronutrients was noted. Similarly, the plant analyses results of peas showed no nutritional imbalances for the growing period.

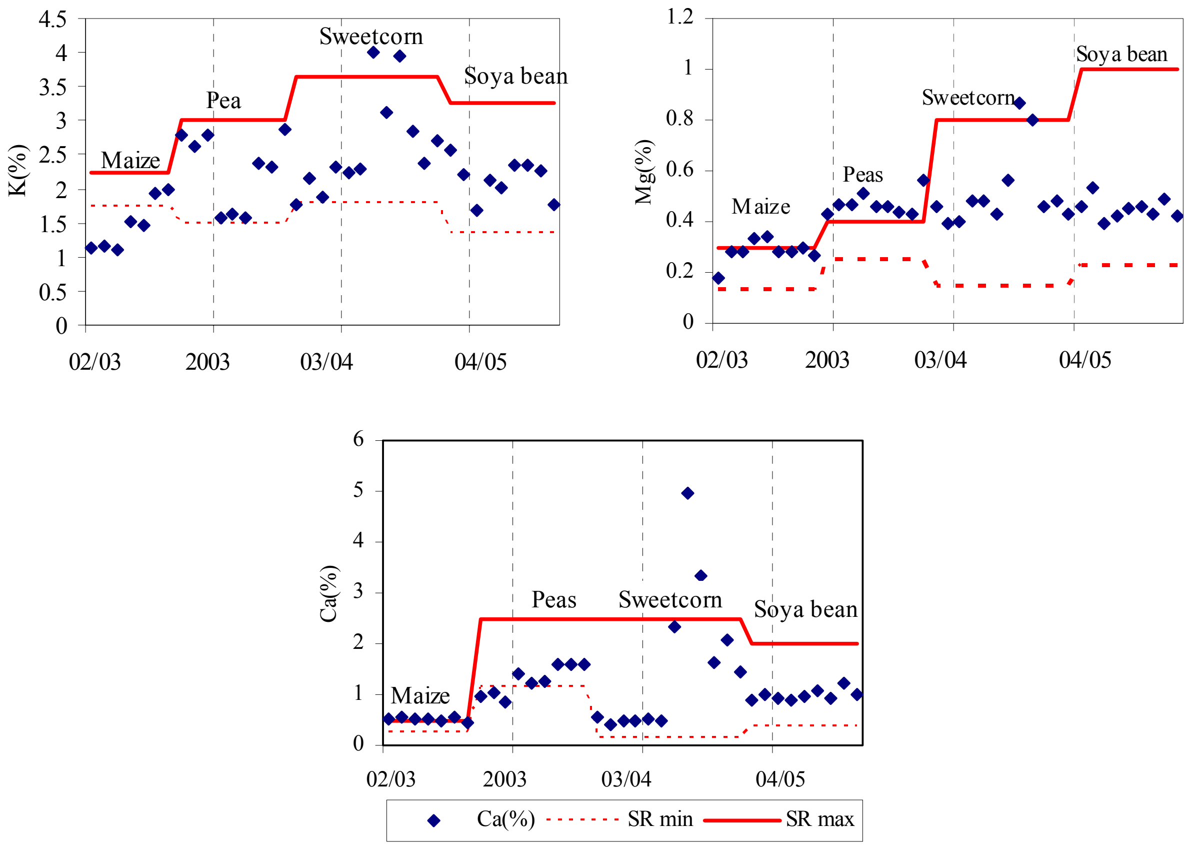


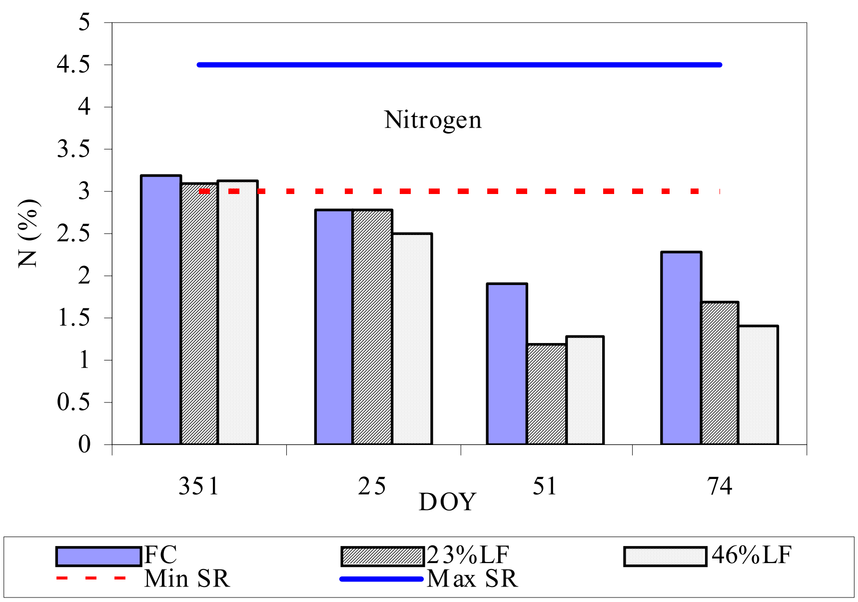
Figure 4.12 Leaf K(%), Mg(%) and Ca(%) content for site New Vaal

4.3.3 Syferfontein

The effect of the Na_2SO_4 rich irrigation water on forage quality (Nitrogen (N) and Crude Protein (CP) contents) of the planted pastures (Fescue and Lucerne) was negligible for the growing period. The N and CP contents of the pastures were also compared with typical values for these pastures found in literature (Appendix A). The N and CP for Fescue (N=19 g kg^{-1} and CP=12 %) and Lucerne (N= 27 g kg^{-1} and CP=17 %) were in the range that can be expected from dry land pasture production, but Eragrostis (N=17 g kg^{-1} and CP=10 %) and Kikuyu (N =12 g kg^{-1} and CP=5 %) showed lower quality than expected. This could possibly be due to natural behavior of Eragrostis to accumulate Na in the root that caused nutritional imbalances. Uptake of considerable Na by Kikuyu from the soil solution also disturbed enzymatic process of the plant and affected forage quality (Tainton, 2000).

4.3.4 Waterberg

Plants were not analysed in the winter experiment, as plants died due to waterlogging. In the summer experiment, plant samples were taken four times for Cotton and Bermuda grass. The sufficiency ranges for normal growth of cotton and the measured results are shown in Figures 4.13 and 4.14. In this study, deficiencies of N, Ca and Mg were observed throughout the growth period, probably due to the leaching of fertilizer and the presence of high Na in the soil. Only leaf K was sufficient in the latter part of the season.



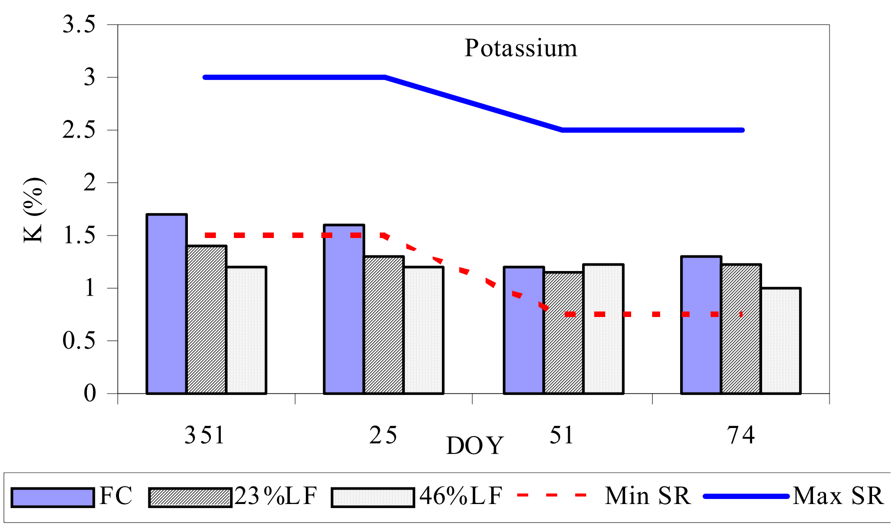


Figure 4.13 N and K concentrations in the leaves of cotton drip irrigated with CBM water, following different irrigation management strategies

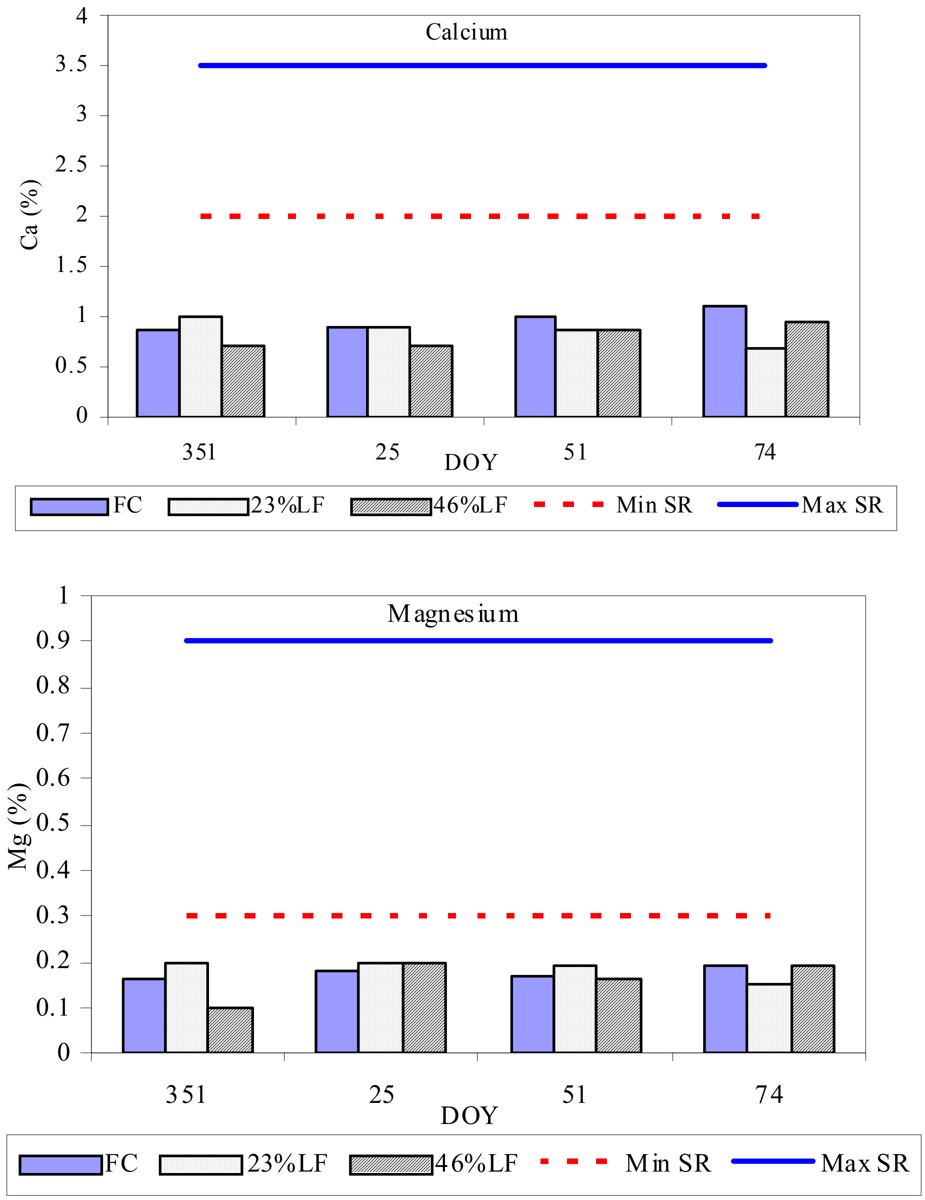
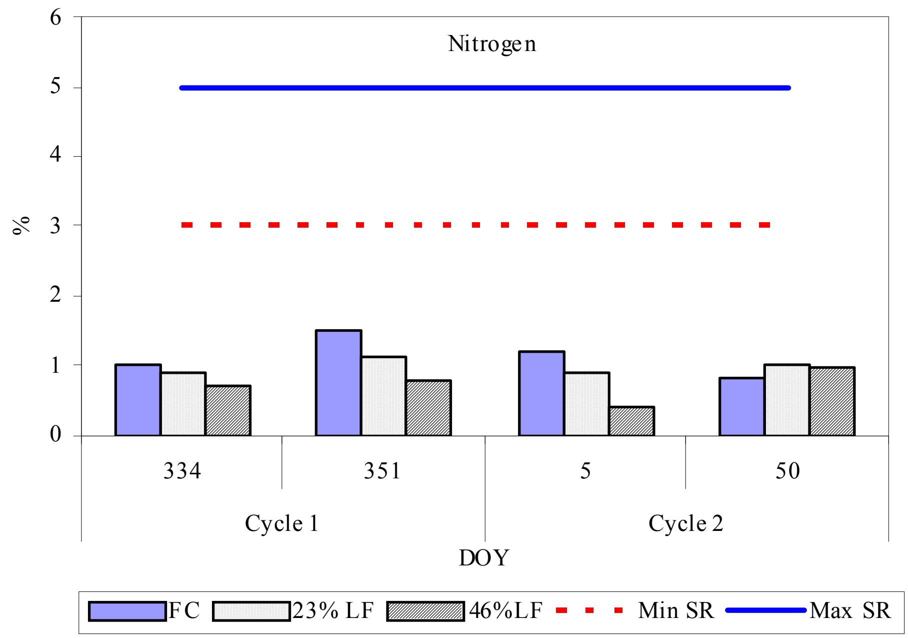


Figure 4.14 Ca and Mg concentration in the leaves of cotton drip irrigated with CBM water following different irrigation management strategies

The sufficiency range of N, K, Ca and Mg for the normal growth and leaf analysis of Bermuda grass of two cycles is shown in Figures 4.15 and 4.16. Sufficient levels of nitrogen in Bermuda grass are considered to be between 3.0 to 5.0% (Jones *et al*., 1991), signifying that the grass in this irrigation trial was not adequately supplied with nitrogen. Potassium levels in the 46%LF were also lower than the FC and 23%LF treatments. This could be due to the high leaching fraction applied. In the grasses irrigated with 23%LF, relatively higher in nutrient level than the other treatment was observed, nevertheless, they were below the sufficiency range for the rest of the growing period.



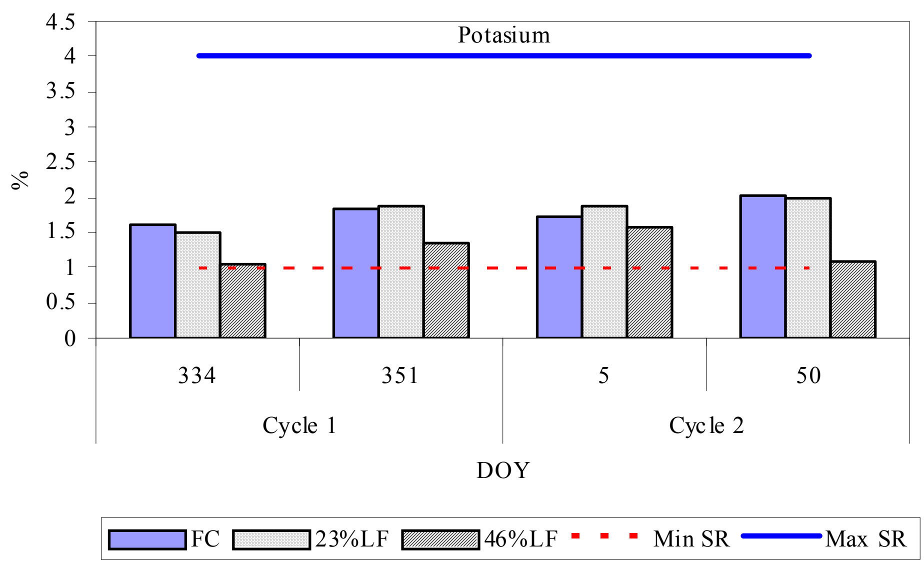
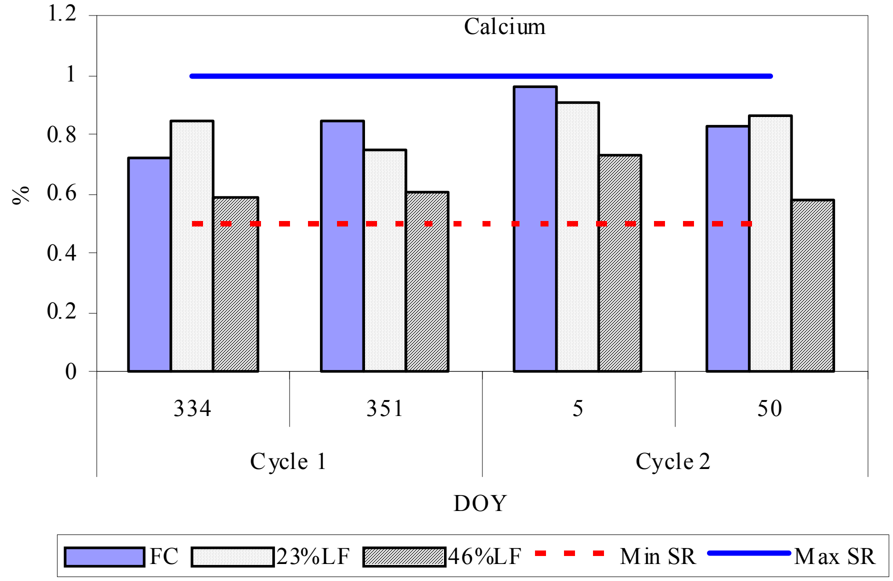


Figure 4.15 Concentrations of N and K of two growth cycles of Bermuda grass drip irrigated with CBM water following different irrigation management strategies



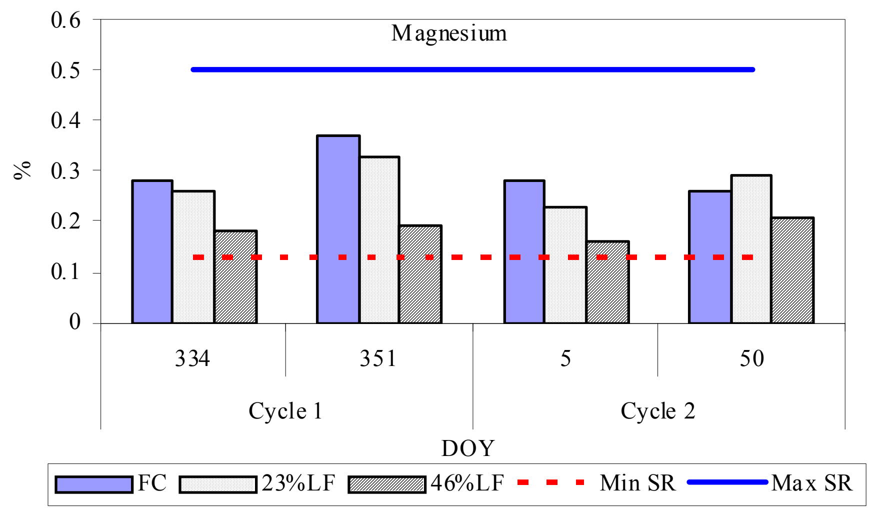


Figure 4.16 Concentration of Ca and Mg of two growth cycles of Bermuda grass drip irrigated with CBM water following different irrigation management strategies

Conclusions

In conclusion, results of plant analysis were useful to diagnose nutrient deficiencies and to reveal imbalances between nutrients that can cause unfavourable nutrient interactions. Visual symptoms are also an important part of diagnosing nutrient deficiencies and toxicities in the field. We attempted to distinguish symptoms from non-nutritional causes like disease or pesticide toxicity. Clearly recognizable leaf symptoms associated with specific nutritional disorders were not observed. It, therefore, seems that one can produce crops using gypsiferous mine water without experiencing major plant nutritional problems, but it is essential to take into account what ions are being added to the soil in the irrigation water. Particular attention should be given to K fertilization as it may become unavailable due to high Ca and Mg in the soil.

In general, the dominant ionic species in the irrigation water like Ca, Mg and SO_4 were found to be higher than normal in the crops at Kleinkopjé. Less K uptake in particular was also observed under all the pivots and, this could be as a result of the low [K]/([Ca] + [Mg]) ratio that had developed over time. At New Vaal, the results indicated that the nutrient concentrations were found to be within the SR norms. The possibility of incurring deficiency and toxicity symptoms with the New Vaal Colliery water is unlikely. However, the ability to identify deficiencies and toxicities of plant nutrients before they limit crop yield is of major importance for successful gypsiferous mine water irrigation of crops.

At Syferfontein, the effect of the Na_2SO_4 rich irrigation water on forage quality of the planted pastures (Fescue and Lucerne) was negligible for the growing period. Eragrostis and Kikuyu showed low quality as compared to typical fresh water irrigated pastures. This could possibly be due to the uptake of considerable amounts of Na from the soil solution that may have inhibited the enzymatic processes of the plant.

In the CBM irrigation trial, crops irrigated with a high leaching fraction needed higher K and N amounts, as the high leaching fraction leached the nutrients from the soil. Special attention should be given to K and NO_3 fertilization management, as the high irrigation frequency and leaching fraction can leach the nutrients below the root zone.

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CHAPTER 5

SOIL PROPERTIES

5.1 Introduction

In this Chapter, the impact of irrigation with coal-mine water on soil chemical properties is assessed. The impact was determined by taking soil samples in different locations in the irrigated sites at the end of each season. The aim is to understand the impact of irrigation with different qualities of coal-mine water on soil chemistry, as cations and anions added through irrigation are critical for determining the sustainability of crop production.

5.2 Kleinkopjé and New Vaal

5.2.1 Soil salinity

Soil chemical analyses indicated that soil saturated paste extract (EC_e) fluctuated in the growing period. It increased in the winter and subsequently decreased in the summer because of leaching by the summer rainfall. At pivot Major the mean EC_e was higher in the uppermost (0-20 cm) layers and decreased down the profile (Table 5.1) while maximum EC_e (419 mS m^{-1}) was observed at 40-60 cm depth. In soils of Pivot Four and TWF, mean EC_e was low in the uppermost (20 cm) layer compared to the 40-60 cm layer (Table 5.1), this indicates a deeper movement of salts in the soils of Pivot Four than in Pivot Major. According to Chadwick & Graham (1999), salts move readily with saturated and unsaturated water flow in soil and gypsum precipitates when their solubility is exceeded. Maximum EC_e of 494 mS m^{-1} and 411 mS m^{-1} were also observed for Pivot Four and Tweefontein. This could be due to the deterioration of the water quality that pivots Four and TWF received (Figure 3.17a).

According to Maas & Hoffman (1977), at these levels of EC_e no yield reduction is expected for wheat, but a yield reduction of >15% is estimated for maize. EC_e at Pivot TWF was observed to increase in the region of 40 cm depth in all the seasons, this trend suggests that a salt front was moving downward and accumulated in the root zone. Such accumulation can be detrimental to crop production if the amount of water applied is not increased to leach the salts deeper into the profile.

The mean EC_e at New Vaal was < 100 mS m^{-1} (Table 5.1). The sandy nature of New Vaal soil allowed water to leach the salts down the profile. EC_e was observed to fluctuate in the range of 25 - 131 mS m^{-1}. Maximum EC_e was observed in the 20-40 cm layer. According to Maas & Hoffman (1977), all sensitive crops can be grown at this range of salinity.

Table 5.1 Soil saturated paste extract (EC_e) of four sites irrigated with gypsiferous mine water for different cropping sequences ¥

	EC_e (mS m^{-1})											
Soil depth	Pivot Major			Pivot Four			Pivot TWF			New Vaal		
(m)	Mean±SD	Max	Min	Mean±SD	Max	Min	Mean±SD	Max	Min	Mean±SD	Max	Min
0.20	315±40	362	200	303±95	494	178	343±70	413	222	86±26	121	60
0.40	281±53	380	109	329±100	444	190	411±72	479	256	70±31	116	48
0.60	265±99	419	127	321±74	415	216	371±69	471	234	74±14	93	62
0.80	245±84	368	115	316±71	401	214	328±100	483	150	57±18	82	42
1.00	254±88	373	162	315±78	419	181	376±76	478	292	51±30	85	22
1.20	224±111	344	88	334±78	472	217	370±68	437	310	72±42	105	25
1.40	163±81	260	74	289±55	357	212	-	-	-	37±17	49	25
1.60	143±46	200	103	249±4	252	246	-	-	-	-	-	-

¥ From winter 2001 to summer 2006/07 for pivots Major, Pivot Four and TWF. For New Vaal from winter 2001 to summer 2004/05. Total samples 897.

In all the irrigated sites, the EC_e values after the summer rainfall were lower than the winter season. This shows that the salinity level can be managed acceptably for sustained crop production. However, the extent of salt leaching and crop establishment depend on total amount of summer rainfall and adequate drainage.

5.2.2 Soil pH and gypsum

The tolerance limit of pH for irrigation water ranges from 6.0 to 9.0 (Grattan & Grieve, 1994). The pH of the saline mine water was within this permissible limit (Figure 3.17b) and also did not influence pH of the irrigated soils (Table 5.2). HCO_3 that entered the soil system was probably neutralised through the bonding with H from the exchange complex displaced by Ca and Mg. Acidity generated by fertilizers and other acidifying processes, e.g. oxidation of reduced S compounds from dry deposition, may also have neutralized some of the alkalinity. It could also be related to the organic matter content in the soil, which provided much pH buffering (Van Breemen *et al*., 1983).

Mean pH values measured at Major, Pivot Four and TWF was around pH 5 (Table 5.2). A dolomitic lime application of 3 t ha^{-1} in winter 2004 in these irrigated sites, however, increased pH of the topsoil slightly in the subsequent summer season. This increase in pH was not substantial but high pH (above 9) generally causes nutrient deficiencies or toxicities as a result of the sorption behaviour of micro nutrients (Van Breemen *et al*., 1983). On the other hand, low pH may affect plant growth indirectly e.g. by increasing aluminium or manganese solubility and by limiting availability of molybdenum, phosphorus, calcium, or magnesium (Adams, 1981).

Greater variability of pH in the upper most layers (0-40 cm) was observed than for the subsoil (60-80 cm) (Table 5.2). This shows that organic matter content of the soil, fertilizer and lime input to the topsoil was not uniformly distributed. Nevertheless, pH will not be a threat from the point of agricultural productivity if dolomitic lime is applied properly to raise the pH into the desired level (pH 6 to pH 7).

In New Vaal the pH of the soil was in the range between 4.2 and 7.5 (Table 5.2). In summer 2003/04, it drastically increased due to the application of lime. Similarly Gupta *et al*., 1989 also noted that pH increases with the application of lime. In this season, interveinal chlorosis, distortions of new growth and short internodes were observed. These symptoms are indications of unavailability of micronutrients that were affected by the increase in pH of the soil.

The soil solution saturation with respect to gypsum increased since the start of the irrigation trial. Gypsum precipitation was observed throughout the profile with the highest precipitation in the 20-60 cm where roots continuously dry out the soil solution through transpiration. Less gypsum was recorded in the soils sampled after summer rainfall due to dissolutions. Higher gypsum levels were observed in the winter season, as the soil was irrigated with a larger quantity of saline mine water in winter than in summer.

The amount of gypsum precipitated up to 2006 at Pivot Major was equivalent to 63.04 t ha^{-1}, at Pivot Four 47.03 t $ha^{-1}$and for the rehabilitated irrigation site of TWF, it was 64.73 t ha^{-1}. Apparently less gypsum precipitation in Pivot Four was recorded as the site was irrigated for a shorter period of time than the other two sites. The presence of gypsum in the soil did not result in any physical and/or chemical property changes which could adversely affect crop production and soil management.

Table 5.2 Soil pH (H_2O) of four sites irrigated with gypsiferous mine water at different cropping sequences ¥

	Soil pH(H_2O)											
Soil depth	Pivot Major			Pivot Four			Pivot TWF			New Vaal		
(m)	Mean±SD	Max	Min	Mean±SD	Max	Min	Mean±SD	Max	Min	Mean±SD	Max	Min
0.20	5.2±0.4	5.7	4.6	5.4±0.5	6.1	4.8	5.6±0.4	6.2	5.2	5.8±1.2	7.6	4.2
0.40	5.1±0.3	5.4	4.6	5.0±0.4	5.8	4.6	5.5±0.4	6.0	4.9	6.4±0.6	7.4	5.8
0.60	4.6±0.2	4.8	4.3	4.9±0.3	5.6	4.6	5.1±0.3	5.4	4.6	5.7±1.3	7.5	4.1
0.80	4.6±0.3	5.0	4.3	5.0±0.3	5.4	4.5	4.9±0.3	5.1	4.4	6.4±0.7	7.6	5.7
1.00	5.0±0.3	5.3	4.5	5.2±0.3	5.8	4.8	5.1±0.4	5.9	4.8	6.3±0.8	7.2	5.5
1.20	5.2±0.6	5.9	4.8	5.3±0.4	5.9	4.8	5.1±0.8	5.9	4.4	6.3±0.6	7.1	5.9
1.40	5.2±0.6	5.9	4.7	5.4±0.3	5.7	5.0	-	-	-	6.5±0.5	6.8	6.1
1.60	5.3±0.2	5.8	4.6	5.4±0.1	5.5	5.3	-	-	-	-	-	-

¥ From winter 2001 to summer 2006/07 for pivots Major, Pivot Four and TWF. For New Vaal from winter 2001 to summer 2004/05. Total samples 897.
SD- Standard devation Max - Maximum Min- Minimum

5.2.3 Soil nutrients and fertilization

Ca and Mg increased in the irrigated soils of site Major, Pivot Four and TWF as compared to samples collected outside these sites (Tables 5.3, 5.4, 5.5 and 5.6). The distribution pattern of Mg in the profile, however, shows an increase in concentration down the profile (Table 5.5). This indicated that Mg is the most mobile ion at Major, Pivot Four and TWF of the three dominant ions (Ca, Mg and SO_4) in the irrigation water. The higher mobility of Mg in the soil is also attributed to preferential adsorption of Ca by negatively charged surfaces, resulting in the exclusion of Mg from the exchange complex in the topsoil. According to Hunsaker & Pratt (1971), soils with exchange complex arising from organic matter, peat, kaolinite, and oxides of Fe and Al have a higher affinity for Ca than for Mg. Subbian *et al.* (2000), also reported that Mg deficiencies are intensified by high levels of Ca in a soil.

The mass transfer of Ca down the soil profile is the lowest of the three dominant ions in the irrigation water and accumulation of Ca in the top 60 cm resulted (Table 5.3). This is attributed to gypsum precipitation and Ca adsorption. There was not any observation of soil structure deterioration due to this accumulation of Ca in the soil. According to Moutier *et al.*, 1998, saturated hydraulic conductivity of Mg-saturated soils was much lower than that of Ca-saturated soil. The exchangeable Ca present in the irrigated soil was also found adequate for optimum crop growth. Kamprath (1984), recorded that exchangeable Ca levels of 2.0 cmol $_{(c)}$ kg^{-1} is adequate for supplying the Ca requirement of most plants. Exchangeable Na was not expected in the soils of Major, Pivot Four and TWF as the irrigation water and the soil had negligible amounts of Na. However, the summer rainfall could have also favoured adsorption of Ca rather than Na by diluting the soil solution, as demonstrated by Reeve & Bower (1960).

Table 5.3 Mean, SD, Max and Min Ca ($cmol_{(c)}\ kg^{-1}$) levels in gypsiferous mine water irrigated soils ¥

Ca ($cmol_{(c)}\ kg^{-1}$)												
Soil depth	Pivot Major			Pivot Four			Pivot TWF			New Vaal		
(m)	Mean±SD	Max	Min	Mean±SD	Max	Min	Mean±SD	Max	Min	Mean±SD	Max	Min
0.20	7.1±2.9	10.1	1.9	5.2±2.2	8.0	2.0	6.2±2.6	8.9	2.4	1.4±0.4	2.0	1.0
0.40	5.1±1.1	6.6	4.3	2.4±0.7	3.3	1.2	4.6±1.8	6.9	2.4	0.9±0.7	2.3	0.5
0.60	2.3±0.9	3.3	1.1	1.6±0.5	2.3	1.1	2.0±0.6	3.2	1.5	0.7±0.5	1.8	0.3
0.80	2.3±0.9	3.4	0.9	1.6±1.0	3.9	0.8	1.4±0.6	2.5	0.8	0.8±0.5	1.9	0.4
1.00	2.1±0.6	3.1	1.4	1.3±0.4	1.8	0.8	2.0±0.8	2.9	1.3	0.8±0.5	1.9	0.5
1.20	1.3±0.4	1.7	1.1	1.5±0.4	2.1	0.9	1.2±0.1	1.3	1.1	0.9±0.5	1.9	0.5
1.40	1.0±0.6	1.6	0.5	1.7±0.4	2.1	1.0	-	-	-	-	-	-
1.60	0.8±0.2	1.3	0.3	1.4±0.2	1.8	0.6	-	-	-	-	-	-

¥ From winter 2001 to summer 2006/07 for pivots Major, Pivot Four and TWF. For New Vaal from winter 2001 to summer 2004/05. Total samples 897.
SD- Standard devation Max - Maximum Min- Minimum

Table 5.4 Mean, SD, Max and Min Ca ($cmol_{(c)}\ kg^{-1}$) of the experimental soils at initial condition

Ca ($cmol_{(c)}\ kg^{-1}$)				
Soil depth	Pivot Major	Pivot Four	Pivot TWF	New Vaal
(m)	Mean±SD	Mean±SD	Mean±SD	Mean±SD
0.20	1.9±2.9	5.2±2.2	2.4±2.6	1.2±0.3
0.40	4.5±1.1	2.4±0.7	3.1±1.8	3.6±0.1
0.60	1.6±0.9	1.6±0.5	1.4±0.6	1.2±0.2
0.80	1.5±0.9	1.6±1.0	2.9±0.6	1.9±0.3
1.00	2.1±0.6	1.3±0.4	2.0±0.8	1.6±0.02
1.20	1.3±0.4	1.5±0.4	1.1±0.1	1.7±0.01
1.40	1.0±0.6	1.7±0.4	-	-
1.60	0.8±0.2	1.4±0.2	-	-

Table 5.5 Mean, SD, Max and Min- Mg ($cmol_{(c)}\ kg^{-1}$) of gypsiferous mine water irrigated soils ¥

Soil depth (m)	Pivot Major Mean±SD	Pivot Major Max	Pivot Major Min	Pivot Four Mean±SD	Pivot Four Max	Pivot Four Min	Pivot TWF Mean±SD	Pivot TWF Max	Pivot TWF Min	New Vaal Mean±SD	New Vaal Max	New Vaal Min
0.20	0.9±0.9	1.8	0.2	0.8±0.4	1.5	0.1	0.9±0.4	1.2	0.1	0.4±0.05	0.5	0.4
0.40	0.7±0.4	1.2	0.2	1.1±0.7	2.0	0.2	1.6±0.8	2.6	0.2	1.1±1.2	2.9	0.3
0.60	0.6±0.2	0.9	0.2	1.2±0.6	1.9	0.5	1.4±0.8	2.3	0.2	0.3±0.2	0.6	0.2
0.80	0.9±0.3	1.2	0.4	1.2±0.6	1.8	0.1	1.3±0.7	2.1	0.4	0.6±0.1	0.7	0.4
1.00	1.2±0.5	1.6	0.3	1.5±0.4	1.9	1.0	1.0±0.7	1.8	0.5	0.5±0.3	1.0	0.2
1.20	1.2±0.2	1.4	1.1	1.4±0.2	1.6	1.2	1.0±0.8	1.5	0.4	0.6±0.4	1.1	0.4
1.40	1.2±0.3	1.4	0.8	1.4±0.1	1.6	1.4	-	-	-	0.5±0.3	1.0	0.2
1.60	1.2±0.2	1.4	0.8	1.3±0.2	1.5	1.2	-	-	-	-	-	-

Mg ($cmol_{(c)}\ kg^{-1}$)

¥ From winter 2001 to summer 2006/07 for pivots Major, Pivot Four and TWF. For New Vaal from winter 2001 to summer 2004/05. Total samples 897.
SD- Standard devation Max - Maximum Min- Minimum

Table 5.6 Mean, SD, Max and Min- Mg ($cmol_{(c)}\ kg^{-1}$) of the experimental soils at initial condition

Soil depth (m)	Pivot Major Mean±SD	Pivot Four Mean±SD	Pivot TWF Mean±SD	New Vaal Mean±SD
0.20	0.09±0.01	0.77±0.09	0.31±0.00	0.64±0.04
0.40	0.09±0.02	0.60±0.19	0.36±0.01	0.20±0.03
0.60	0.08±0.01	0.32±0.14	0.30±0.03	0.41±0.02
0.80	0.07±0.05	0.24±0.06	0.35±0.05	0.37±0.00
1.00	0.10±0.03	0.22±0.05	0.70±0.04	0.28±0.06
1.20	0.12±0.03	-	1.30±0.03	0.32±0.03

Mg ($cmol_{(c)}\ kg^{-1}$)

The level of K in the irrigated soils was very low for all the sites. This could be due to the Ca concentration in the irrigation water that replaced the potassium in the exchange site by a cation exchange process. Exchangeable [K]/[Ca] ratios decreased with time and higher ratios were observed in the 60-120 cm layer at TWF and 0-60 cm at New Vaal (Figure 5.1). At Major the [K]/[Ca] ratios were higher in the 60-120 cm. In the same depth the Ca concentration was observed to be high. According to Johnston & Goulding (1992), about one kg of K ha^{-1} soil could be leached for each 100 mm of rain water draining through a profile but this value is larger if K is displaced with irrigation water containing a higher concentration of Ca ions. Meiri *et al*., 1984, also found similar findings that large amounts of potassium was leached in soils irrigated with poor quality water containing significant concentrations of Na, Mg and Ca. Feigenbaum (1986) also reported K losses equivalent to 90-300 kg ha^{-1} when 430 mm of solution containing 5 and 50 $cmol_{(c)}$ l^{-1} of mixed NaCl/$CaCl_2$ were applied to soil columns in the laboratory. This could lead to a drop in potassium uptake by plants.

The extra irrigation water, leaching requirement, that were applied to maintain low EC_e levels probably have also caused further K losses from the irrigated sites. On average of 75 kg ha^{-1} $year^{-1}$ K was applied using fertilizers such as 4:1:1 (22), 2:3:4 (30), 6:3:2 (22) and 2:3:2 (22) to counteract the leaching of K, but most of this K was available for leaching as there was no space for it on the Ca and Mg dominated exchange site.

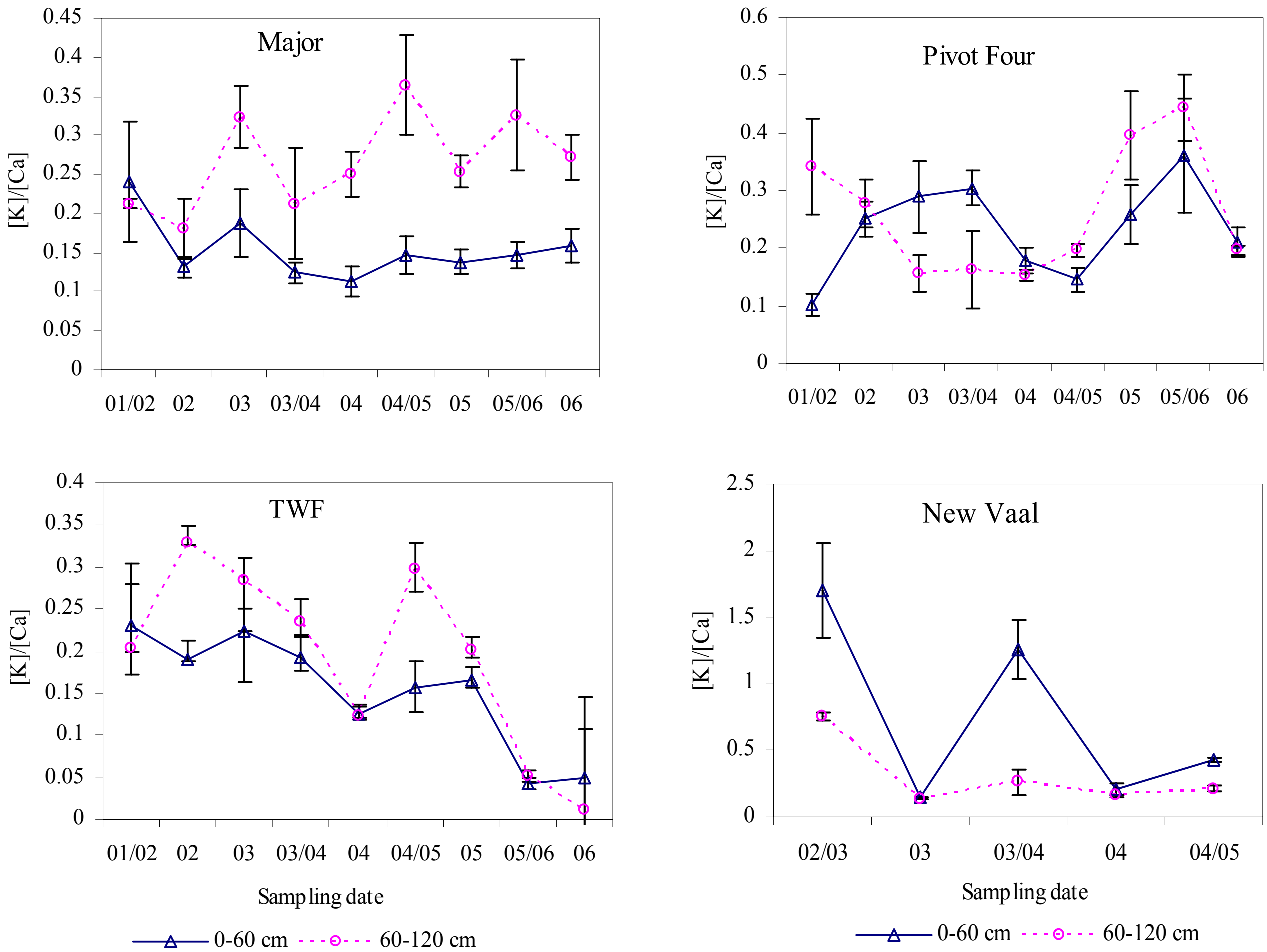

Figure 5.1 Temporal changes of exchangeable [K]/[Ca] for the irrigation sites

Phosphorus was generally high in the 0-20 cm depth at Major, Pivot Four and TWF with a decreasing trend down the profile (Table 5.7). The higher P content in the top layer could be due to sorption of the added phosphorus, biological activity and accumulation of organic material in the surface layers. It could also because of the low solubilities of calcium phosphate compounds in soils in the presence of gypsum. According Harmsen 1984, the activity of phosphates in soil solution at equilibrium with solids depends upon the activities of Ca, Al, Fe and on the pH of the soil system. The variation of the available P content between the sites could be attributed to the chemical and physical properties of the soils. However, high variation of the P was observed for New Vaal. This is because the soil samples taken in the summer 2001/02 and winter 2003 were immediately after fertilizer application.

The seasonal application of phosphorus fertilizer also contributed to the high accumulation of P in the upper layer. On average 72 kg ha^{-1} $year^{-1}$ P from different forms of fertilizers such as 4:1:1 (22), 2:3:4 (30), 6:3:2 (22), 5:3:4 (22) and 2:3:2 (22) were applied. This continual application of fertilizer could exceed the optimum requirement of the crop. Once P become excessive in the soil, the environmental impact through potential loss in runoff and drainage water could be greater than any agronomic benefits of further P applications. On the other hand, once the level of P reached such high levels, considerable time will be required for significant depletion. According to McCollum (1991), without further P addition, 16-18 years of cropping maize or soybean would be needed to deplete the P content from 100 mg P kg^{-1} to the threshold agronomic level of 20 mg P kg^{-1}. In soils irrigated with gypsiferous mine water, management practices that maximize the build up of organic matter during the growth period may be required to reduce the external phosphorus requirements as fertilizers.

Table 5.7 Mean, SD, Max and Min- P (mg kg^{-1}) of the soils irrigated using gypsiferous mine water¥

	P (mg kg^{-1})											
Soil depth	Pivot Major			Pivot Four			Pivot TWF			New Vaal		
(m)	Mean±SD	Max	Min	Mean±SD	Max	Min	Mean±SD	Max	Min	Mean±SD	Max	Min
0.20	23.1±6.5	39.6	14.1	36.4±16.9	67.9	20.1	34.5±21.4	69.3	11.8	35.5±49.4	112.8	7.6
0.40	5.3±2.9	9.9	1.5	11.7±8.7	24.8	2.6	6.4±2.4	10.7	3.6	58±71	170	8.8
0.60	2.5±1.0	3.6	0.7	3.5±2.8	9.0	0.8	3.6±1.5	5.4	1.4	235±354	776	2.9
0.80	2.5±0.6	3.0	1.3	2.7±1.1	4.5	0.9	4.5±1.4	6.6	2.6	9.9±10	26	2.3
1.00	2.3±0.8	3.2	1.4	2.1±0.6	3.2	1.7	7.3±4.0	13.2	4.4	3.5±2.4	7.1	1.9
1.20	2.2±0.8	3.1	1.5	1.8±0.4	2.3	1.4	4.9±1.2	6.1	3.6	2.4±0.7	3.1	1.7
1.40	1.7±0.5	2.2	1.3	1.4±0.2	1.6	1.2	-	-	-	3.1±0.5	3.4	2.8
1.60	1.2±0.1	1.2	1.9	1.6±0.6	2.0	1.1	-	-	-	-	-	-

¥ From winter 2001 to summer 2006/07 for pivots Major, Pivot Four and TWF. For New Vaal from winter 2001 to summer 2004/05. Total samples 897.

S did not show a definite increasing or decreasing trend as a function of depth in all the irrigated sites, and was more evenly distributed in the soil profile compared to Ca, Mg and P. More SO_4 was added through irrigation than Ca and Mg, which could explain the higher S concentrations in the soil profile. Taking an average SO_4 concentration in the irrigation water of 2145 mg ℓ^{-1}, and assuming a cumulative seasonal irrigation of 500 mm of gypsiferous mine water, 10.7 t ha^{-1} a^{-1} is added to the soil through irrigation. A 500 mm a^{-1} gypsiferous mine water with a Ca concentration of 507 mg ℓ^{-1} (for Pivot Major) will result in a Ca load of 2.5 t ha^{-1} a^{-1}. Mg added would be 0.97 t ha^{-1} a^{-1}, based on a solution concentration of 193 mg ℓ^{-1}. Low nitrogen and organic matter content (0.3-0.4%) of the irrigated soil could be related to the high concentration of Ca and SO_4 in the irrigation water that stimulated the soil micro-organisms responsible for mineralization. Gupta & Salaran (1971) also found that the addition of gypsum stimulated the fungus population that are responsible for mineralization in a given soil.

At New Vaal, the soluble and exchangeable ions in the saturated soil extract also fluctuated due to seasonal rainfall as well as irrigation and rainfall events. Soluble SO_4 was also fluctuating during the seasons; there was high SO_4 in the soil solution in winter than in summer as there was less rainfall to dilute the soil solution. In summer 2002/03, the rainfall amount was low and the SO_4 was observed to increase as the irrigation amount was increased to satisfy the atmospheric demand. The average Na in the irrigation water is 135 mg ℓ^{-1} during the trial period. In summer 2003/04 high mass of sodium was added to the profile, as the water quality was getting poorer in quality compared to the previous seasons. However, the clay content of this soil is less than 5%, thus dispersion did not occur and is also unlikely to occur.

In this study, the concentration of Ca and SO_4 ions increased in the irrigation water during the trial period, while K and Mg decreased in the soil exchange site. Accordingly, it becomes obvious that K and Mg fertilization is of major importance to the coal-mine water irrigated soils. The application rates, however, will depend on soil type, irrigation water quality, cropping system, the soil management practices used, and the degree of crop intensification.

Fertilizing soils by considering the exchangeable cation ratio is a common practice. The nutrients targeted in the management of mine water irrigated soils were the ratios of exchangeable Ca, Mg and K, as these sources of nutrients are often assumed predominantly to be in the exchangeable form. However, mine water irrigated soils are not normal agricultural systems as the soil contains considerable amounts of soluble salts due to the continuous input of salts through irrigation.

The existing routine laboratory soil test was used to differentiate between the exchangeable and soluble Ca in the gypsiferous mine water irrigated soils. The results indicated that the difference between ammonium acetate extractable Ca and saturated paste Ca concentrations is not only attributable to exchangeable Ca. The ammonium acetate extracted Ca disguised the Ca dissolved from gypsum, and increased the actual exchangeable Ca. Therefore, the existing routine laboratory soil tests overestimated exchangeable Ca and the Ca/Mg ratio on the exchange complex. This is illustrated in Figure 5.2 from a soil sample taken at Pivot Major in June 2004. The reason behind this is that all soluble Ca cannot be removed when preparing a saturated paste from gypsum rich soils. To estimate actual exchangeable Ca, the soil should be successively leached with water, or equilibrated with a large solution to soil ratio to remove all the water soluble Ca. The overestimation was especially high for the depth interval with the highest gypsum content (30-60 cm depth interval). Therefore, the normal routine soil analytical method to differentiate between exchangeable and soluble Ca is not applicable to soils that contain gypsum.

The interference of gypsum on exchangeable Ca determination and over estimation of the exchangeable [Ca]/[Mg] ratio on these samples are indicated in Figures 5.2 and 5.3. The overestimation was especially high for the depth interval with the highest gypsum content (30-60 cm depth interval). The actual exchangeable [Ca]/[Mg] ratio was 4.2 and the artifact [Ca]/[Mg] ratio was 13.04. Fertilization with potassium will also be affected if the ratio of K/Mg or K/Ca is considered for fertilization in such soils.

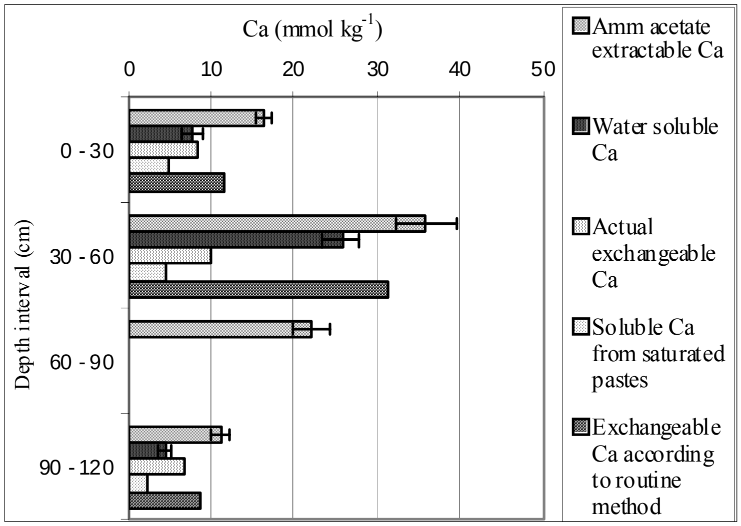

Figure 5.2 Interference of gypsum in the determination of exchangeable Ca using the routine method (Major, 2004)

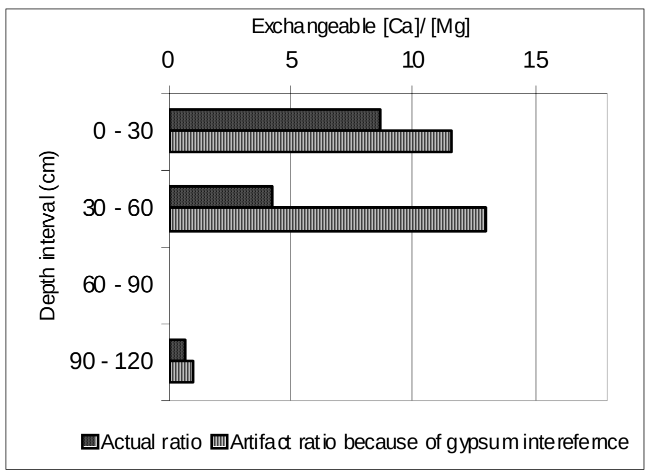

Figure 5.3 Actual [Ca]/[Mg] ratio versus [Ca]/[Mg] artifact ratio because of gypsum interference

5.3 Syferfontein

5.3.1 Soil salinity

The EC_e increased over the trial period (Figure 5.4), as compared to the initial conditions of the soil. As one would expect, EC_e of the soil was lower in summer than in winter, as summer rainfall leached out the salts from the profile. For instance, EC_e measured in May 2003 was lower than October 2002 due to the high summer rainfall in January-March 2003 that diluted the soil solution (Figure 5.4). According to Maas & Hoffman (1977), the EC_e threshold tolerance of Fescue is 390 mS m^{-1} while for Kikuyu it is 300 mS m^{-1} for a 100% yield potential. In addition, Tanji (1990) also reported a salinity threshold of 200 mS m^{-1} for Lucerne and Eragrostis. EC_e in the experiment exceeded the threshold tolerance values of Eragrostis and Lucerne (Figure 5.5) but was below to the threshold tolerances of Fescue and Kikuyu.

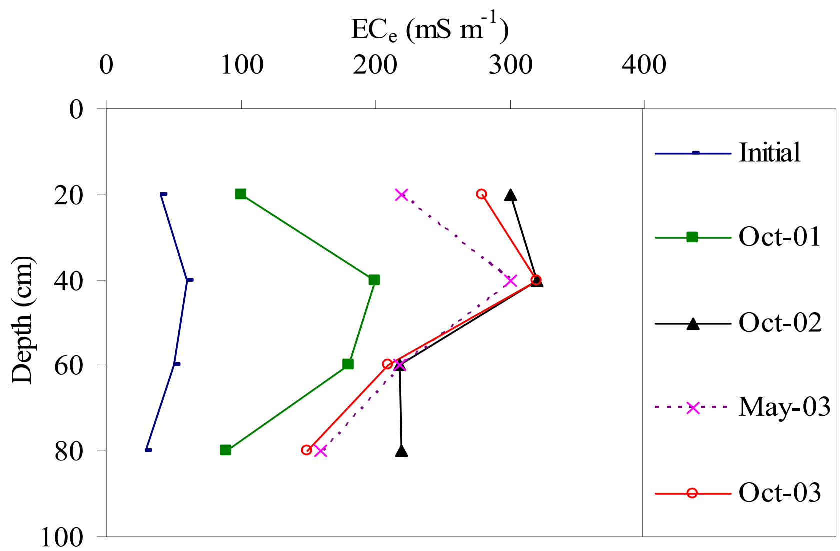

Figure 5.4 Average EC_e (mS m^{-1}) of the soil at initial condition and during the trial period

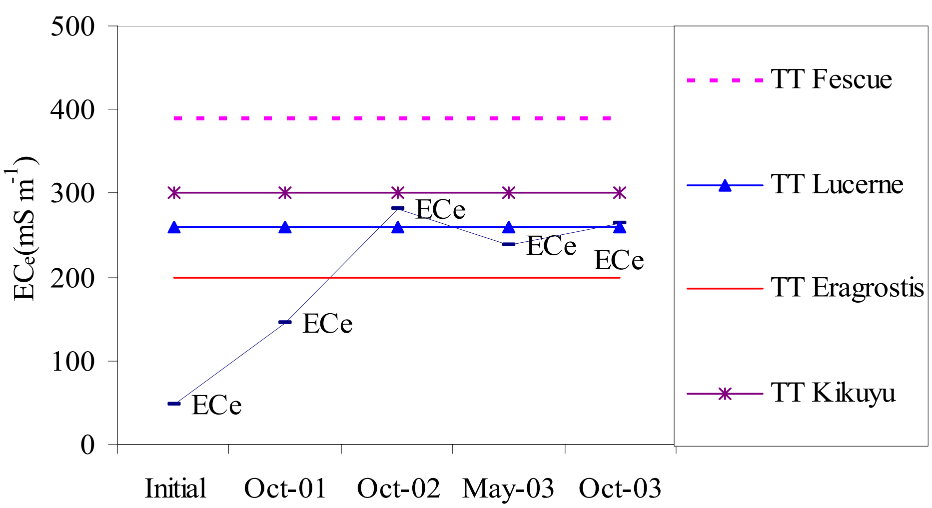

Figure 5.5 EC_e (mS m^{-1}) measured during the trial period and threshold tolerance (TT) of pastures

5.3.2 Soil sodicity

ESP of the soil was observed to fluctuate (Figure 5.6) but with a highest ESP in the upper few centimeters of the soil. ESP increased in May 2003 with irrigations, then dropped again in October 2003 due to the application of $Ca(NO_3)_2$, as Ca source displaces Na (Figure 5.6) in the soil solution. The ESP of the soil did not reach a level that could exhibit infiltration problems, as it was compensated by its high salinity. In the future one has to expect a slow change in the physical property of the soil.

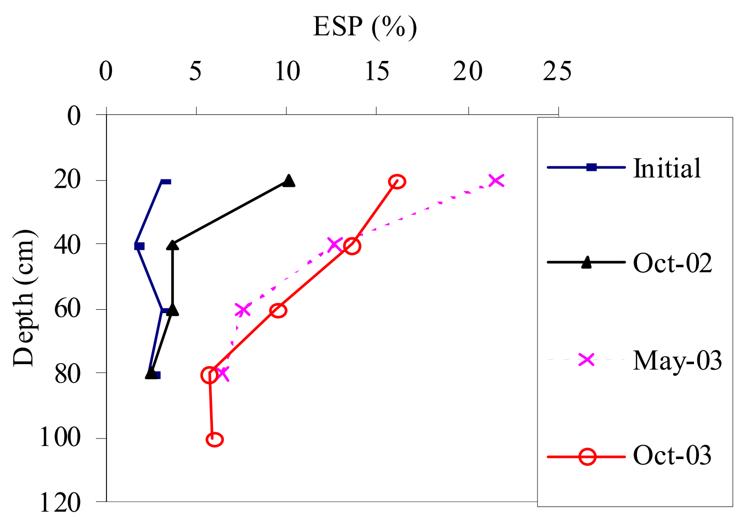

Figure 5.6 Average ESP (%) of the soil at initial condition and during the trial period

No crust formation was observed during the trial period, as the high clay content made the soil not prone to crust formation. Similar findings were also made by Ben-Hur *et al* (1985), who found that soils with 20 to 30% clay were the most susceptible to crust formation; those with clay content >40% had stable aggregates and less sensitivity to crust formation.

The exchangeable Ca and Mg were found to be lower in upper part of the profile than deeper down (0.6 -1.0 m) the profile, whereas they were high at 0.4-0.6 m depths. On the contrary, the exchangeable Na was higher in the top layer than the exchangeable Ca and Mg. This is because Na replaced other cations (Ayers & Westcot, 1985). However, the trend of exchangeable and soluble Na was declining down the profile. K decreased in quantity during the trial period, probably it is replaced by Ca and Mg. Regular application of Ca $(NO_3)_2$ as a fertilizer could be important in leaching out the Na from the exchange site.

5.4 Waterberg

5.4.1 Soil salinity

Soil chemical analyses indicated that the soil saturated paste extract EC (EC_e) increased in the winter season from the initial conditions (Figure 5.7). It did, however, not reach values critical for yield reduction for the leaching fraction treatments. It decreased markedly during the summer irrigation trial after the rainy period and irrigation with clean water, which flushed the salts from the profile. According to Maas & Hoffman (1977), barley can still attain potential yields when EC_e is 800 mS m^{-1}, while potential yield for Italian ryegrass is achieved below a threshold EC_e value of 560 mS m^{-1}. For the LF treatments EC_e of the soil profile at the end of the winter experiment, however, was found to be far lower than the maximum thresholds for yield reduction for barley and Italian ryegrass (Figure 5.7a). Cotton can attain its potential yield with EC_e levels up to 770 mS m^{-1}. The EC_e of the irrigated soil was found to be below this maximum threshold for yield reduction at the end of the summer season. Similarly, the accumulation of salts in this wet summer was not problematic for Bermuda grass, for which the potential yield threshold EC_e is 690 mS m^{-1} (Figure 5.7b). However, in drier years cropping may not be successful as salts could accumulate in the profile, resulting in EC_e values higher than the threshold tolerances.

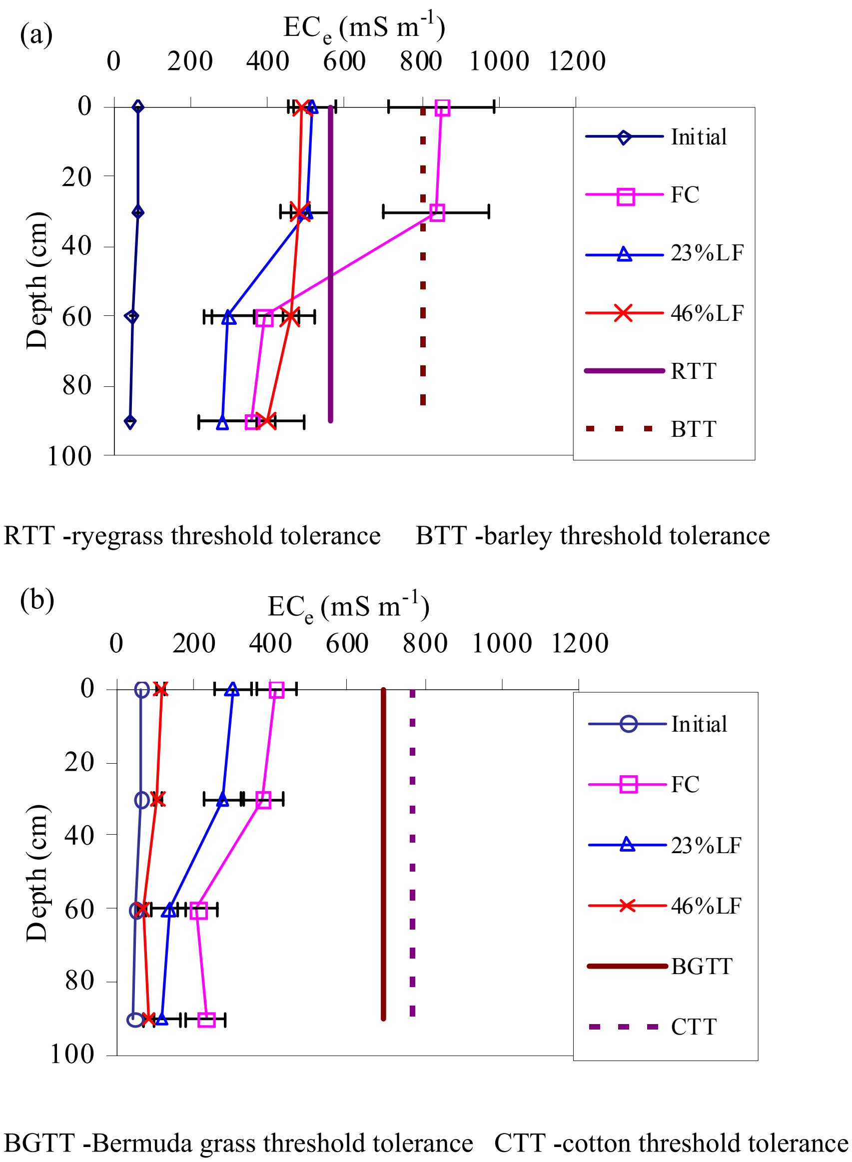

Figure 5.7 Soil saturated paste extracts at the end of (a) the winter 2005 trial and (b) the 2005/06 summer trial

For the FC treatment in the winter season, EC_e increased above the threshold values for ryegrass and barley, and clearly would need leaching for sustainability. In the summer season, however, for all treatments, salinity was reduced due to leaching and it should, therefore, be easy to reclaim this light soil if irrigated for an extended period, as long as structural problems which limit water flow through the profile can be managed. The environmental issue then, will of course be the impact of salty leachate on groundwater.

5.4.2 Sodicity and infiltration

The presence of high sodium levels in the irrigation water caused the soil to develop a high ESP. ESPs in the leaching fraction treatments were higher than for the FC treatment, as more Na is added and other cations are washed out of the soil, causing sodium enrichment, which resulted in lower soil salinity than the FC treatment, but a high soil sodicity (Figure 5.8).

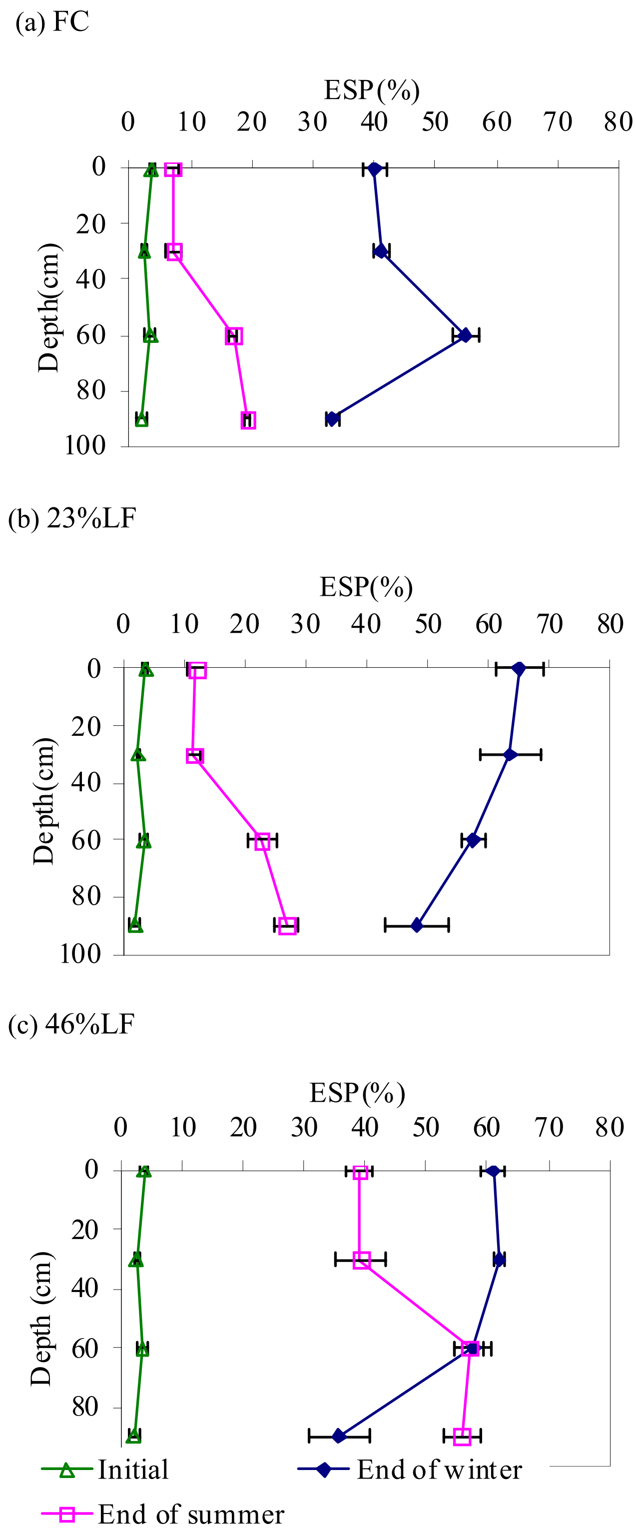

Figure 5.8 Exchangeable sodium percentage of the soil irrigated at (a) FC, (b) 23%LF and (c) 46%LF

The extremely high ESP values in the winter irrigation trial caused waterlogging problems. Irrigations were scheduled every day to have a high irrigation frequency and to keep the osmotic potential as high as possible. Waterlogging was also in part due to the irrigation system design criteria, as high delivery rate drippers were chosen to minimize the risk of emitter clogging, and a high density of drippers was selected to create a one dimensional wetting pattern. This resulted in an extremely high irrigation application rate (44 mm h^{-1}), which caused runoff and ponding, as the infiltrability of the soil diminished due to the high level of sodium in the soil. In the summer irrigation trial, ESP decreased due to the application of 25 t ha^{-1} gypsum, as the Ca source was able to displace Na on the exchange sites. Furthermore, the 40 t ha^{-1} sheep manure-crops residue mix and the summer rainfall contributed to alleviating the infiltration problem experienced in the winter season. The sheep manure was useful in the slow release of nutrients, while the crop residues kept the soil porous, and the rainfall washed the salts out of the root zone. In the 46%LF treatment, ESP was high throughout the profile (Figure 5.8), while EC_e was quite low (Figures 5.7a and 5.7b). According to Shainberg & Letey (1984) and Bauder & Brock (1992) a high leaching fraction reduces soil EC_e without affecting soil ESP. ESP only dropped with the application of gypsum to less than 15% at the 0-30 cm depth in the 23%LF and FC plots in the summer irrigation trial (Figure 5.8).

5.4.4 Soil solution EC

In the winter experiment, EC of the soil solution collected with passive lysimeters at 30 cm for the LF46% treatment stabilized at around 800-1000 mS m^{-1}, which was lower than for the FC and LF23% treatments (Figure 5.9). Therefore, if one was to irrigate with this water to FC, without purposeful leaching, an enormous accumulation of salts is expected to occur in the long run.

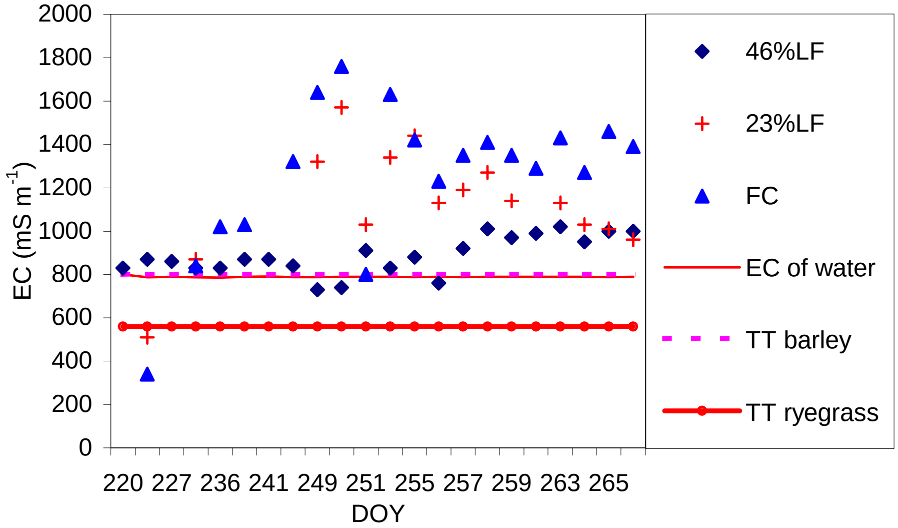

Figure 5.9 EC of the soil solution captured from WFDs installed at 30 cm depth in the FC, 23%LF and 46%LF treatments and threshold tolerance (TT) to salinity (EC_e) of the crops grown in winter 2005

In the summer irrigation trial, crops were irrigated with less saline water (100 mS m^{-1}) for about 8 weeks, and the EC of the soil solution was observed to drop to between 220 and 400 mS m^{-1} for FC and 23%LF, whereas for the 46%LF, it took on a value close to the incoming irrigation water salinity of 100 mS m^{-1} (Figure 5.10). However, once irrigation with the bicarbonate rich water commenced, EC of the soil solution jumped to about 800 mS m^{-1} and then declined after rain to about 400 mS m^{-1} for all the treatments. The EC of the soil solution measured in the FC plots was observed to be higher than that of the other treatments. The 46%LF treatment had less salt in the soil solution than did the other two treatments, as the high leaching fraction was clearly effective at diluting the soil solution to a value close to that of the irrigation water (Figure 5.10). The passive lysimeters in the 46%LF treatment collected soil solution very rapidly, which indicated that the high LF leached salts deep into the soil. The successful leaching of the salts could also be related to the low CEC of the soil (20 $cmol_c$ kg^{-1}), which allowed free movement of the soil solution in the soil. In the FC treatment, the EC of the soil solution overshot the threshold of crop tolerances, which indicates clearly that a large LF is required.

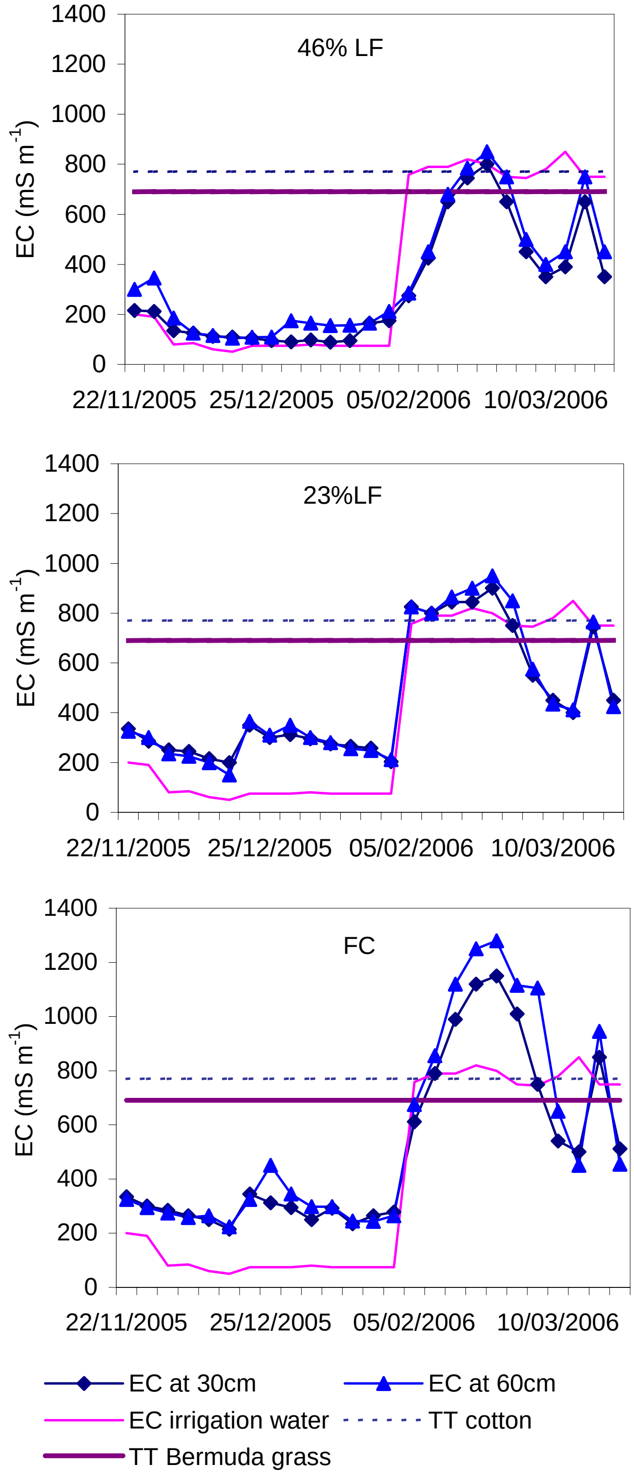

Figure 5.10 EC of the soil solution, EC of irrigation water and crop threshold tolerance (TT) during the summer 2005/06 growing period

Conclusions

A seasonal fluctuation in soil salinity was observed due to rainfall in the summer season with dry winters. In the summer, low soil salinities were maintained because the salt load was low (less irrigation) and the opportunity for flushing salts out of the root zone was higher than in winter. Average EC_e at both Pivot Major and Pivot Four increased to around to 400 mS m^{-1} in winters. Pivot Four was more saline than Pivot Major, TWF and New Vaal. This was caused by the increase in salinity of the water of Tweefontein Pan. There was also an increased in salinity at New Vaal as a result of deteriorating water quality. The soil salinity shot up from a low base and oscillated around 250 mS m^{-1}, as was predicted by Annandale *et al*. (1998).

Gypsum precipitation was shown to be taking place in the soil. Gypsum accumulated in the soils over the irrigation period. The amount of gypsum precipitated at Pivot Major was equivalent to 63 t ha^{-1}, at Pivot Four 47 t $ha^{-1}$and in the rehabilitated irrigation site of TWF was 65 t ha^{-1} (on average 5 t ha^{-1} $year^{-1}$). The lower gypsum precipitation levels at Pivot Four, compared to the other sites at Kleinkopjé, resulted from this site being irrigated for a shorter period of time than the other two sites. The presence of gypsum in the soil did not result in any physical and/or chemical property changes, which could adversely affect crop production and soil management.

Soils irrigated with such gypsiferous mine water might suffer from K or Mg deficiencies, as Ca dominate the exchange complex. Thus, K and Mg levels on the adsorption complex of the soil should be monitored to prevent its deficiency and the application of potassium containing fertilizers is necessary on gypsiferous mine water irrigated soils. Thus, soils irrigated with gypsiferous mine water need to be managed and fertilized differently to crops produced under normal farming conditions.

The effect of Na_2SO_4 rich mine effluent water on the soil chemical properties was evaluated at Syferfontein. The salts accumulated at 0.4-0.6 m depths, which indicates that salts are leached from the soil surface. An increase in salts was generally observed during the growing period, while it fluctuated with rainfall and dry spells. The EC_e of the soil decreased after heavy rainfall, and average EC_e was not above the threshold level that could restrict crop growth for Fescue. A high ESP was observed in the upper few centimetres of the soil and fluctuated during the growing period. The determination of the hydraulic conductivity of the soil is recommended to monitor the effect of the water on the infiltration rate of the soil, as high Na levels are likely to cause deflocculation or dispersion of clay particles.

The effect of $NaHCO_3$ saline water on soil chemical properties and physics was also evaluated. EC_e reached a maximum value of around 800 mS m^{-1} in the winter season, which could limit yields of salt tolerant crops. In the summer experiment, however, the accumulation of salts in the root zone was far lower than the threshold tolerance level due to the high summer rainfall. The high sodium adsorption ratio of the irrigation water increased ESP values in the soil and led to severe clay dispersion in the winter season. The application of gypsum and organic matter to the soil, however, minimized the negative effects of the irrigation water on infiltration. The high irrigation frequency was also essential to keep the salinity stress as low as possible by keeping the soil wet (high matric potential) and the soil solution as dilute as possible (high osmotic potential).

It was concluded that irrigation with gypsiferous mine water could provide a promising option to the mining industry for the strategy of water management by irrigating winter and summer crops throughout the year. This would not only reduce the direct discharge of such waters to rivers, which could cause environmental problems, but also permit crop production in dry areas and take a lot of salts out of water system.

The Na_2SO_4 rich mine effluent could be used sustainably for pasture production in the longer term on better soil. In particular, if summer rainfall is sufficient to dilute salts and if fertilization with $Ca(NO_3)_2$ is applied to reduce the Na/Ca ratio in the soil solution, pastures could grow sustainably. The application of $Ca(NO_3)_2$ as a source of Ca to the soil could also remove some SO_4 from the water system by enhancing gypsum precipitation.

Only salt tolerant crops can grow with the $NaHCO_3$ water, and if a high leaching fraction is used, together with the application of gypsum as a source of Ca to displace adsorbed Na.

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CHAPTER 6

FIELD SCALE MEDIUM-TERM MODELLING OF CROP GROWTH, SOIL WATER AND SALT BALANCES

6.1 Introduction

Chapters 4 and 5 ascertained that crops could be grown successfully when irrigated with gypsiferous mine water, at least in the short to medium-term (nine years), without noticeable negative impacts on soils and crop production. It would be useful, however, to gain insight into likely longer term (several decades) crop performance and expected environmental impacts of large scale irrigation, to determine the sustainability of irrigation with such mine waters. Since long-term field experiments are expensive, time-consuming, limited in extent and therefore produce only site-specific information, computer simulation is a logical option to predict the performance of various crops grown with different irrigation water qualities, on different soils and under different climatic conditions over long periods. The Soil Water Balance (SWB) model is a crop growth-soil salinity model developed and validated during previous studies (Annandale *et al*., 1998), and was found to offer detailed insight into water and salt balances in space and time. The current study has also provided extensive data sets, which SWB can further be tested and calibrated.

In order to adequately address the impact of large-scale irrigation with mine water on ground and surface waters, it is essential that field scale soil water and salt balances be predicted reliably. In this chapter, the ability of the model developed for this purpose (SWB), to predict crop growth, soil water and salt balances, is discussed. In Section 6.1 of this chapter, model validations for crop growth, soil water deficit to field capacity and soil chemistry are discussed for gypsiferous and Na_2SO_4 rich mine waters. Site New Vaal is excluded from validations as water logging was problematic due to site selection. Data collected from the $NaHCO_3$ water was not long enough for model validations and this is therefore not included in this section. In Section 6.2, summaries of the components of the soil water and salt balance for gypsiferous and Na_2SO_4 mine water are presented, and this addresses the *sustainability* of irrigation with these mine waters from the point of view of *crop production and soil chemical properties*. Section 6.3 presents long-term scenario simulations for gypsiferous, Na_2SO_4 and $NaHCO_3$ mine water, and addresses the long-term environmental impact of these waters. The expected long-term effect of irrigation with gypsiferous mine water seems to have been reliably predicted a decade ago already by Annandale *et al*., (1998). The conclusions drawn from their studies are, therefore, briefly discussed.

6.2 Model simulations

In order to accurately estimate the unknown components of the soil water and salt balance with the SWB model (drainage, evaporation from the crop canopy, salts leached and precipitated), it is necessary to be able to accurately simulate growth of the crops. For this purpose, specific crop growth parameters already included in the database of SWB (Annandale *et al*., 1999), were refined in order to account for the specific conditions and cultivars used in these field trials. Furthermore, crop specific growth parameters were determined for each pasture species grown at Syferfontein, according to the procedure developed by Jovanovic & Annandale (1999), using growth analysis, soil monitoring and weather data measurements over the trial period. Improvements to SWB were made to be able to simulate multiple crop rotations, and the growth and harvest cycles of pastures.

6.2.1 Crop growth and soil water deficit

At Kleinkopjé Colliery, crops were rotated for 17 seasons at site Major and 18 seasons at site TWF. Each season's data was used to validate and simulate the soil water and salt balance for pivots Major and TWF. Only 15 seasons for Pivot Four were simulated, as this site was established after the other two. At Syferfontein, 9 pasture harvests were simulated.

Simulated results are indicated in graphical plots of the time variation of the crop growth variables, leaf area index (LAI ($m^2\ m^{-2}$) and top dry matter (TDM (t ha^{-1})), and soil water deficit to field capacity in Figures 6.1-6.5. Figures 6.1 and 6.2 are examples for single season simulations, Figures 6.3-6.5 are examples for crop rotations and (Example for pastures is in Appendix B, Figure B4). The graphs include simulated (solid lines) and measured data points (symbols). The soil water deficit graphs show the predicted profile water content deficit to field capacity over time. Negative values in the figure show that the soil water exceeded field capacity while positive values are deficits to field capacity. For all crops, the simulated values of LAI, TDM and deficit were generally reasonably accurate.

Results were evaluated using the graphs of simulated and measured values, and statistical parameters such as the coefficient of determination (r^2), Wilmot's index of agreement (D), root mean square error (RMSE) and mean absolute error expressed as a percentage of the mean of the measured values (MAE). These parameters were recommended by De Jager (1994) to assess model accuracy. He also recommended, as model prediction reliability criteria, that r^2 and D should be > 0.8, and MAE should be < 20%. The simulated and observed values agreed quite well for the growing period. The statistical parameters r^2, D, RMSE and MAE are indicated in Table 6.1 and Table 6.2 and are for the single season simulations.

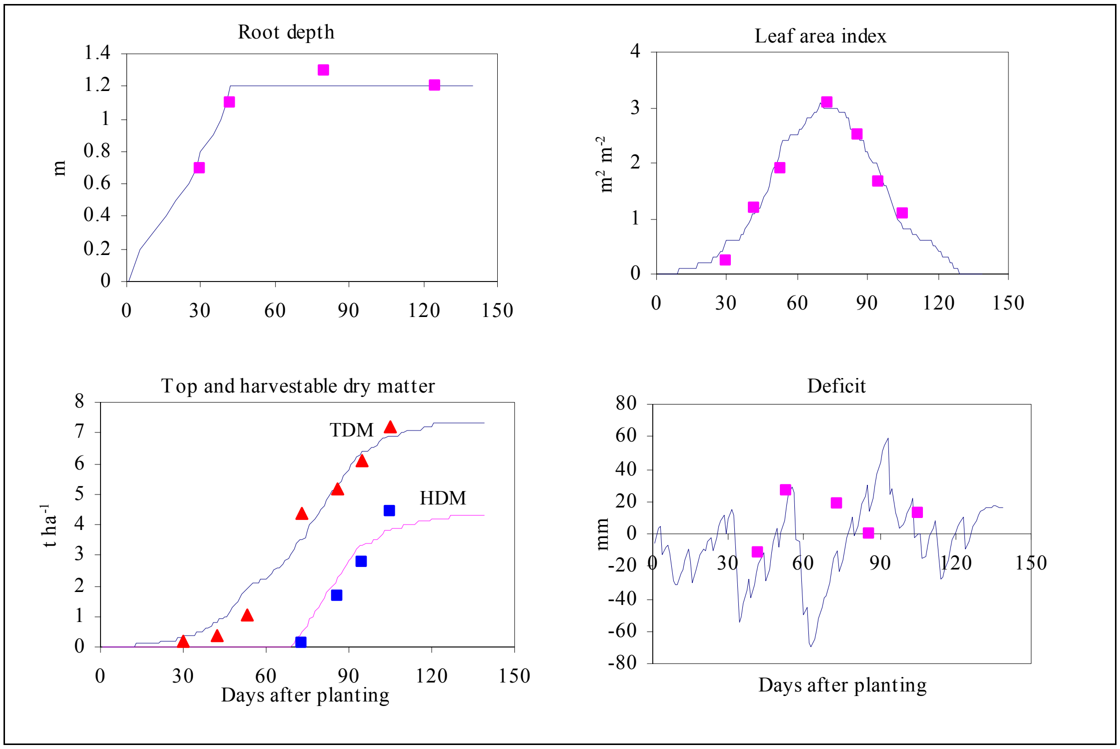


Figure 6.1 Observed (symbols) and simulated (lines) RD, LAI, TDM, HDM and deficit to FC for Maize cultivar cv. PHI 32P75, Pivot Major for the summer season 1999/2000

Table 6.1 Statistical parameters of LAI, TDM, Deficit and RD for Maize cv. PHI 32P75, Pivot Major for summer season 1999/2000

Statistical parameters	LAI	TDM	Deficit	RD
Number of observations	7	7	5	4
r^2	0.94	0.97	0.78	0.94
D	0.98	0.99	0.73	0.96
RMSE	0.30	0.60	17.4	0.10
MAE	11%	13%	105%	6%

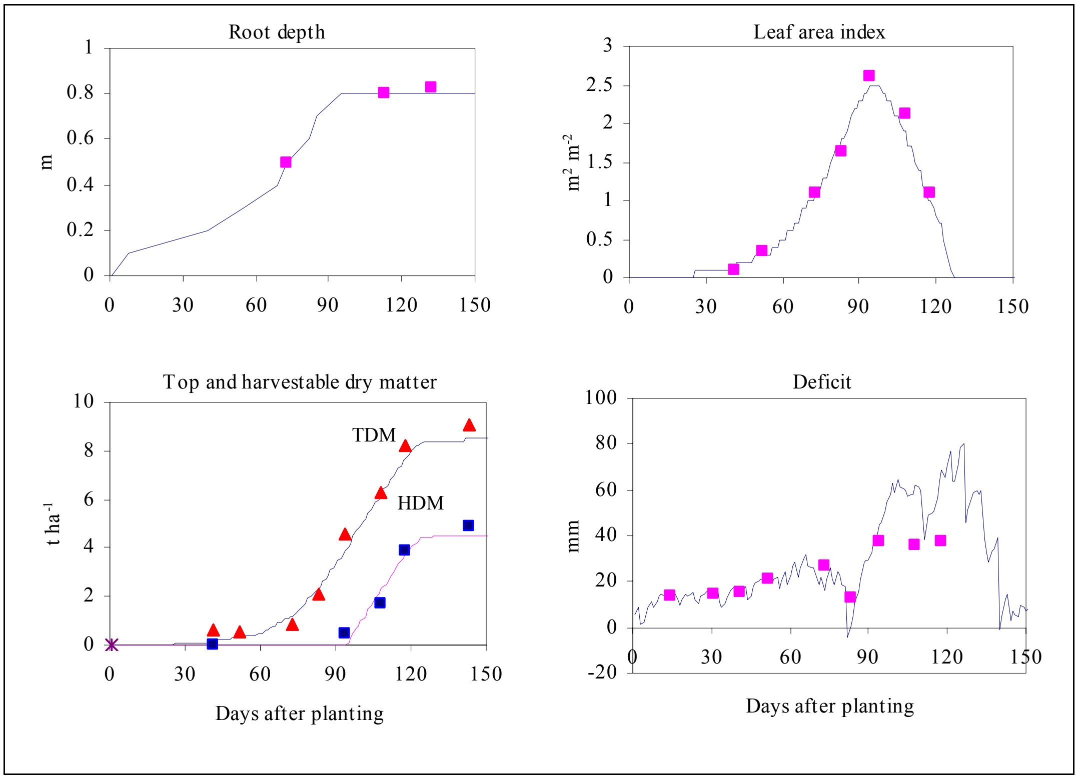


Figure 6.2 Observed (symbols) and simulated (lines) RD, LAI, TDM, HDM and deficit for Wheat cv. SST 825, Pivot Major, winter season 2000

Table 6.2 Statistical parameters of LAI, TDM, Deficit and RD for Wheat cv. SST 825, Pivot Major winter season 2000

Statistical parameters	LAI	TDM	Deficit	RD
Number of observations	7	7	9	3
r^2	0.99	0.99	0.81	0.99
D	1.00	1.00	0.78	0.99
RMSE	0.10	0.40	16.6	0.00
MAE	7%	9%	44%	3%

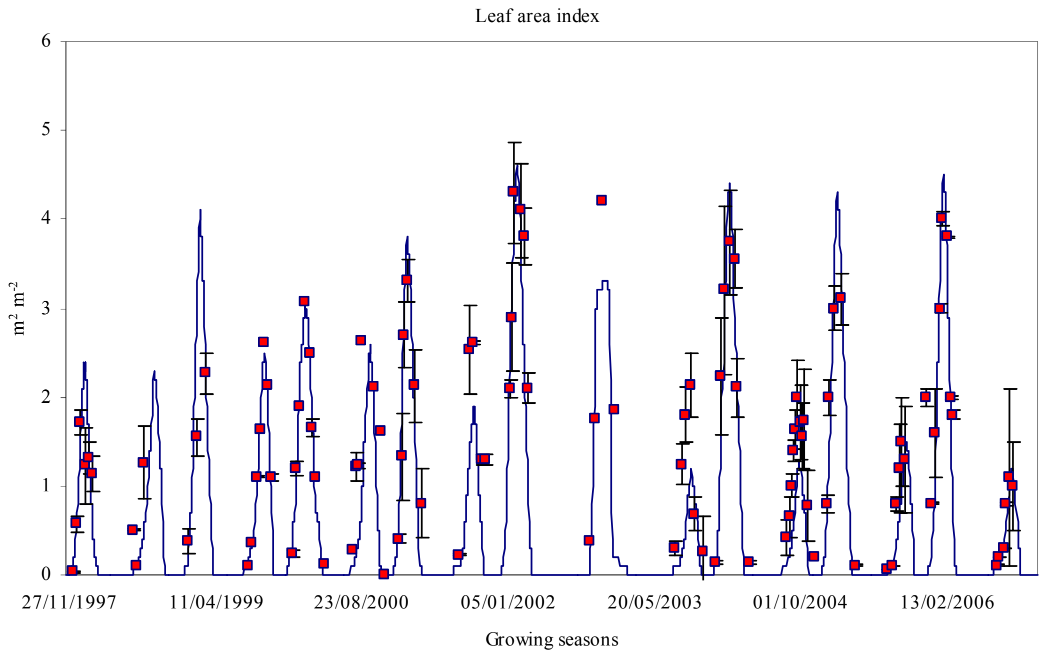


Figure 6.3 Simulated (solid lines) and measured (symbols) LAI of crops rotated between 1997/98 and 2006 for Pivot Major

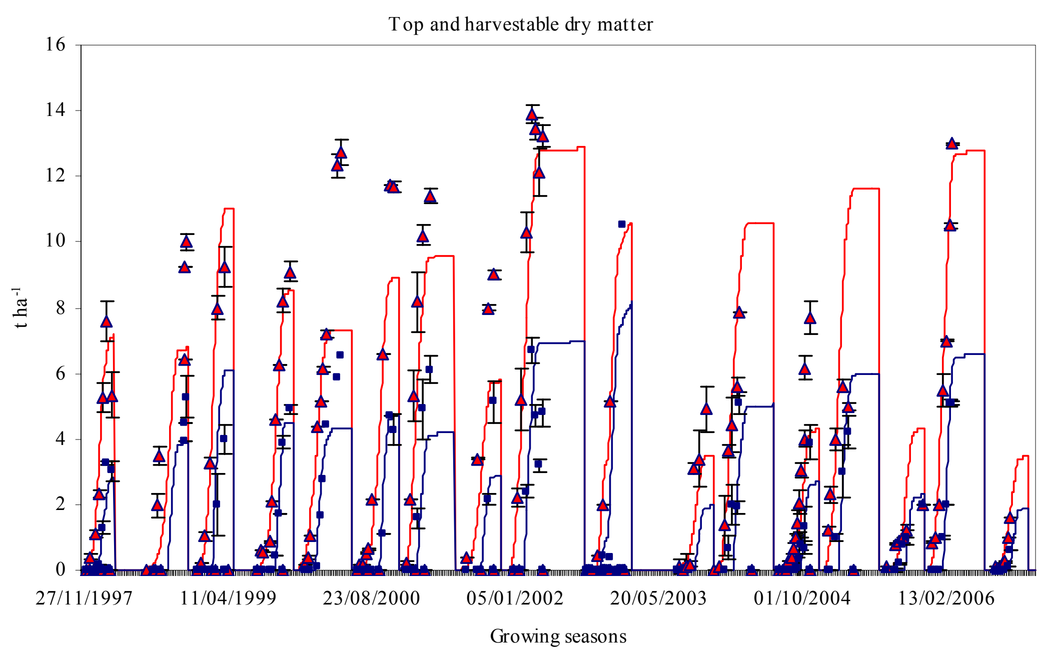


Figure 6.4 Simulated (solid lines) and measured (symbols) TDM and HDM of crops rotated between 1997/98 and 2006 for site Major

Pivot Major was characterized by large soil water deficits when there was no irrigation applied or rainfall, and the crop growth associated with such deficits was observed to be poor. An example of a comparison between measured and modelled profile deficit to field capacity is shown in Figure 6.5. The irrigated field clearly shows good correlation between modelled and simulated deficits during most seasons, with generally quite small biases. The model performed well with errors typically in the range of 10-20 mm. The discrepancies between simulated and measured values could be related to assumptions made in the model, measurements and input errors. These include calibration of neutron probe, installation of access tubes and probably also reliability of rainfall recorded.

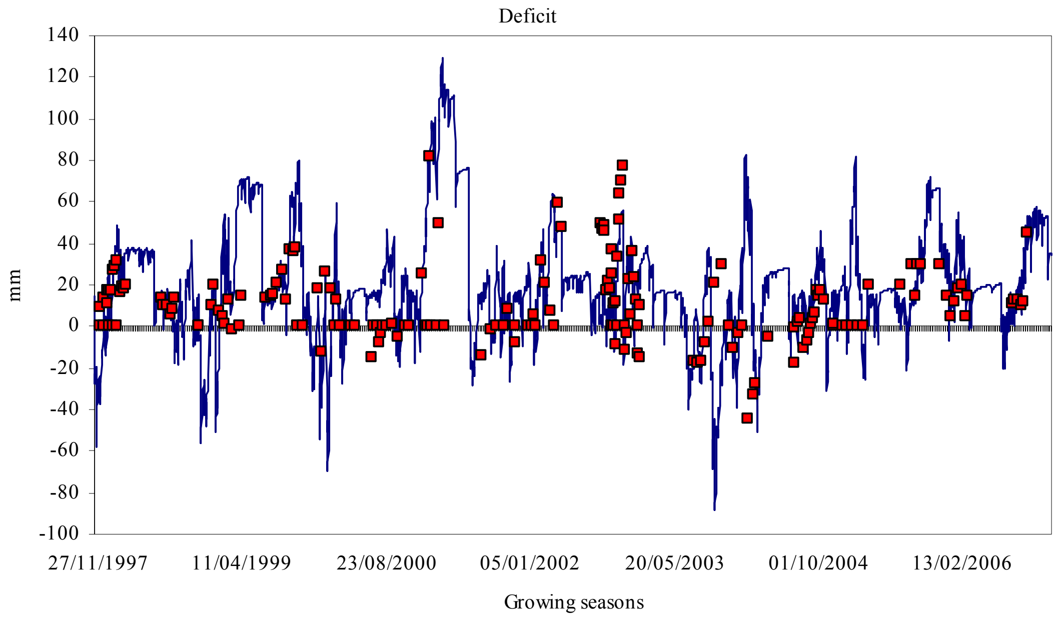


Figure 6.5 Simulated (solid lines) and measured (symbols) soil water deficit to field capacity (Major, 1997/98-2006), positive values are deficits and negative values indicate that the profile is wetter than field capacity

6.2.2 Soil chemistry

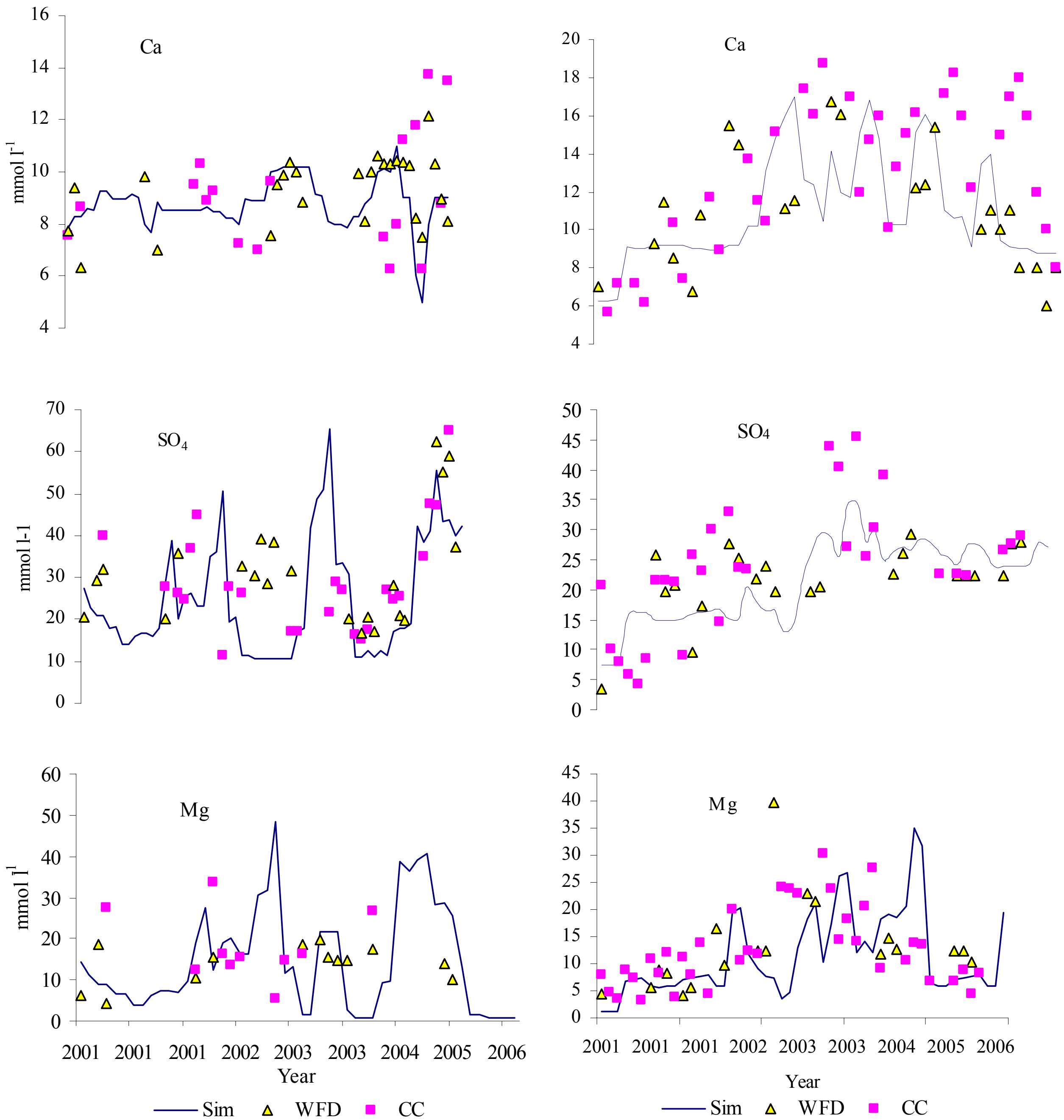
The soil solution concentrations varied considerably during the growing period due to irrigation water quality, variability of soil water chemistry, variability in soil type, and variability in climatic conditions. The major ions considered were Ca, Mg, SO_4, Na, K and Cl.

Soil solution data collected from wetting front detectors (WFD) and suction cups (CC) at Kleinkopjé indicated that the irrigation sites were frequently subjected to relatively high Ca and SO_4 inputs, which may have influenced temporal variation in Ca and SO_4 during the crop rotations. The concentrations of particular ions in the soil solution also varied, depending on fertilization and irrigation water quality fluctuations. The fluctuations of the solution chemistry are also related to soil water content.

SWB needs initial soil solution chemical properties, and irrigation and rainwater chemical characteristics as inputs, to model the quantity of salts in soil solution of each layer in soil profile. SWB calculates the mass of incoming ions diluted in irrigation water, assuming complete mixing of water present in the topsoil layer with the incoming irrigation water. The new concentration of ions in this soil layer is assumed to be the concentration of water penetrating the soil layer below. The amount of water penetrating the following soil layer is the amount of water that remains after filling the top layer up to field capacity. The same procedure is repeated for each layer. The ionic concentration in each soil layer is updated on a daily basis after crop water uptake is calculated. The salt concentration in the soil solution is controlled by the solubility product of gypsum. A salt will be precipitated from solution once the solubility product is exceeded. The crop growth reduction due to salinity is also related to the osmotic potential of the soil solution in the root zone.

SWB results of soil solution concentration of each ion simulated in each soil layer were compared with measured values, captured by suction cups (CC) and wetting front detectors (WFDs), to validate the model. The comparisons were made for six years of data for Pivot Major and simulations showed fairly good agreement with the measured data (Figures 6.6 and 6.7). Additional model validations are presented in Appendix B. Differences between measured and simulated values could be due to: soil heterogeneity and sampling errors, preferential paths of water and salt movement through the soil profile, and fertilizer input and salt removal by the crop, as none of these effects are considered in the model.

The model predicted soil solutions concentrations quite close to measured values. This gives confidence in the predictive capacity of the model for long-term impact assessment of irrigation with gypsiferous mine water.



Major Pivot Four

Figure 6.6 Observed and simulated concentration of Ca, SO_4 and Mg for Major and Pivot Four

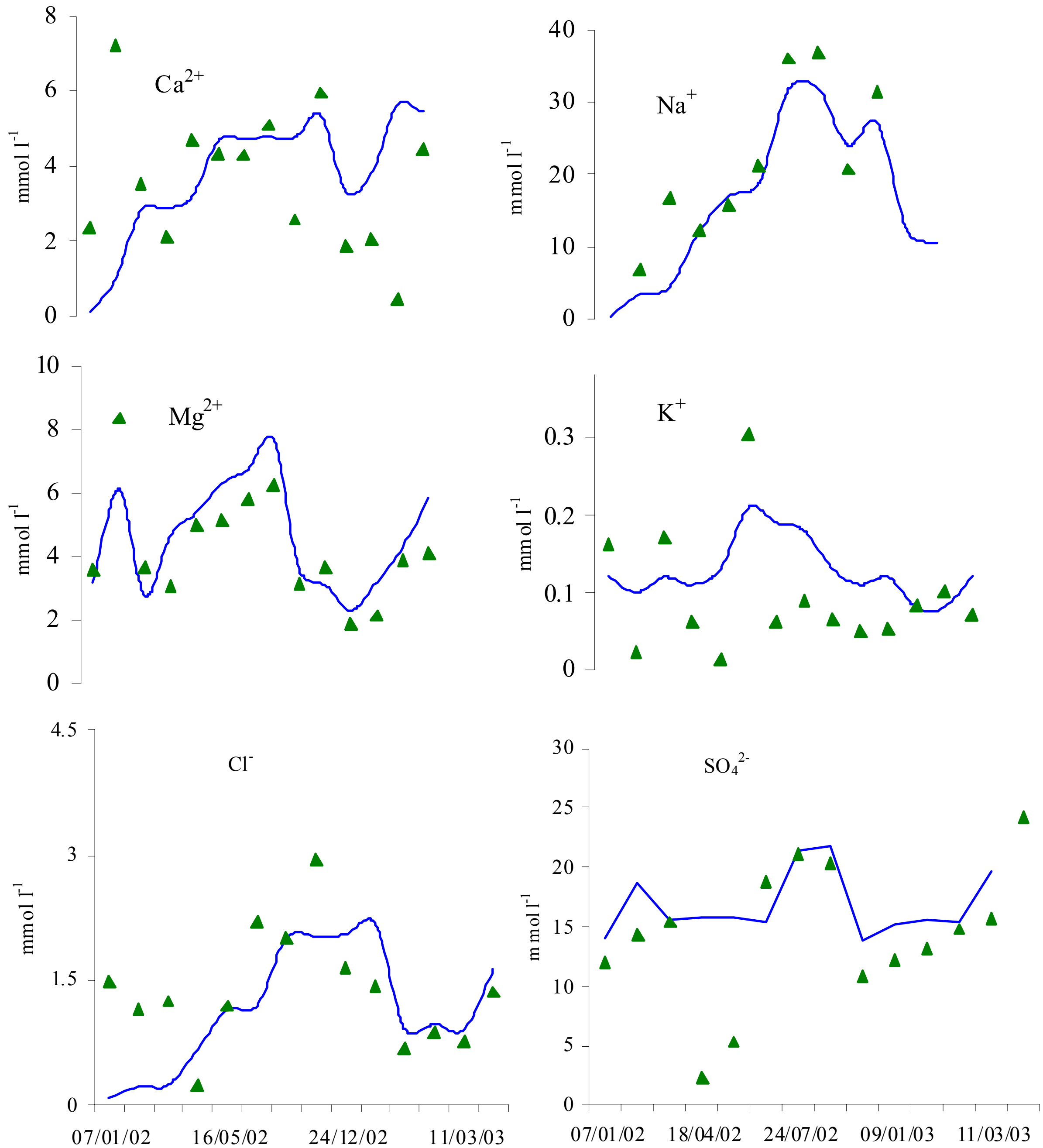


Figure 6.7 Simulated (solid lines) and CC or WFD (symbols) for concentration of Ca, Na, Mg, K, Cl and SO_4 in the soil solution at a depth of 0.4 m in the Eragrostis field (January 2002 - March 2003)

EC_e of the soil profile was also estimated and compared to soil saturated paste extract measured at the end of each summer and winter season. Higher values of EC_e were estimated and measured in the winter season. According to Annandale *et al*. (1998), EC_e was predicted to fluctuate around 250 mS m^{-1}. This is nicely illustrated in Figure 6.8 for Pivot Major; it is heartening to see that such prediction into the future can indeed be reliably made using well constructed models. The figure also indicates that a crop with a better tolerance to salinity (Maas, 1986) is required in the winter than in the summer seasons.

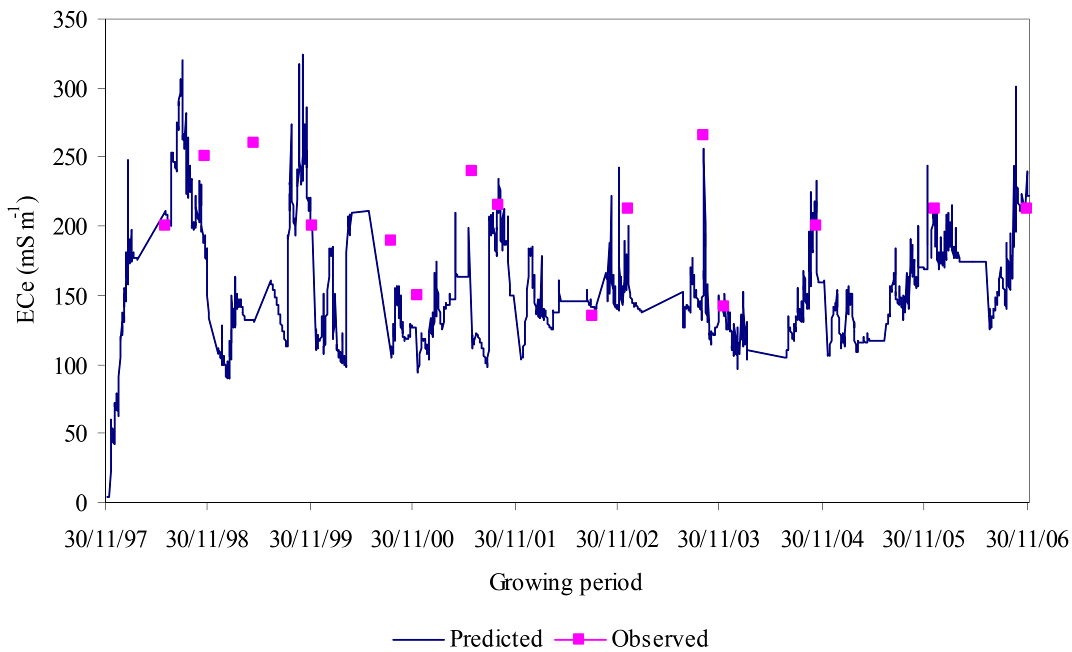


Figure 6.8 Observed and simulated EC_e (mS m^{-1}) for Pivot Major (1997-2006)

6.3 Soil water and salt balances

The SWB model predicted the water balance as well as the salt content of the soil reasonably well. Summaries of the components of the soil water and salt balance for gypsiferous mine water and Na_2SO_4 irrigated fields, and the periods of measurement with intensive monitoring stations are presented below.

6.3.1 Kleinkopjé

The measuring period at Pivot Major included nine summer crops and eight winter crops, of which three summer and three winter crops were measured by Annandale *et al*. (2001). Annual crops required a drying off period at the end of each season. Crops were, therefore, sorted out that they senescence on time. Seasonal irrigation varied depending on rainfall. Irrigation was higher in winter than in summer. The opportunity is, therefore, greater for the mines to use water in winter than in summer. Predicted soil water and salt balances for the 1997-2006 crop rotations at Major are presented in Table 6.3, with salt balances given in Table 6.4.

Table 6.3 Simulated annual values of the soil water balance components for Pivot Major at Kleinkopjé Colliery from the start of irrigation in 1997

Year and Crops	Rainfall (measured) (mm)	Irrigation (measured) (mm)	Soil water evaporation (simulated) (mm)	Crop transpiration (simulated) (mm)	Drainage (simulated) (mm)	Canopy interception (simulated) (mm)	Runoff (simulated) (mm)	Change in soil water storage (simulated) (mm)
Sugarbeans (1997/98)	288	187	131	281	109	14	4	-64
Wheat (1998)	79	427	101	369	42	13	3	-22
Maize (1998/1999)	173	265	85	306	21	10	26	-10
Wheat (1999)	101	306	111	286	0	15	5	-10
Maize (1999/2000)	521	90	147	233	112	14	50	55
Wheat (2000)	84	380	140	324	39	18	2	-59
Maize (2000/01)	302	257	126	306	41	9	19	58
Wheat (2001)	142	399	185	251	141	20	7	-63
Maize (2001/02)	422	217	211	319	0	21	34	54
Potato (2002/03)	278	487	165	360	169	9	57	5
Wheat (2003)	165	502	164	266	237	14	15	-29
Maize (2003/2004)	529	311	163	257	181	7	202	30
Wheat (2004)	101	294	145	228	45	17	2	-42
Maize (2004/2005)	301	335	92	382	146	10	8	-2
Wheat (2005)	76	313	110	213	26	12	6	22
Maize (2005/2006)	427	202	149	321	133	16	15	-15
Wheat (2006)	80	290	129	209	8	9	3	12
Total (1997/98-2006)	4069	5262	2354	4911	1450	228	458	-80

Table 6.4 Simulated annual values of the salt balance components for pivot Major at Kleinkopjé Colliery from the start of irrigation in 1997

Year and Crops	Salts added (measured) (Mg ha^{-1})	Salts runoff (simulated) (Mg ha^{-1})	Salts leached (simulated) (Mg ha^{-1})	Gypsum precipitated in the soil – end of season (simulated) (Mg ha^{-1})	Change in soluble salt content in the soil (simulated) (Mg ha^{-1})
Sugarbeans (1997/1998)	5.58	0.02	0.17	2.28	3.11
Wheat (1998)	12.44	0.03	0.10	6.88	5.43
Maize (1998/1999)	7.34	0.16	0.13	4.43	2.62
Wheat (1999)	8.59	0.05	0	5.13	3.4
Maize (1999/2000)	2.61	0	5.96	-0. 50	-3.35
Wheat (2000)	11.84	0.06	3.53	6.17	2.08
Maize (2000/01)	8.28	0.22	3.34	2.60	2.12
Wheat (2001)	10.20	0.14	11.29	5.11	-6.34
Maize (2001/02)	6.46	0.07	0.00	2.83	3.56
Potato (2002/03)	13.49	0.10	10.68	5.85	-3.14
Wheat (2003)	12.92	0.24	10.14	5.44	-2.9
Maize (2003/2004)	8.03	0.18	6.62	2.26	-1.03
Wheat (2004)	8.23	0.01	0.06	1.7	6.46
Maize (2004/2005)	9.4	0.09	0.75	0.6	7.96
Wheat (2005)	11.21	0.04	2.35	4.16	4.66
Maize (2005/2006)	10.02	0.03	2.42	5.01	2.56
Wheat (2006)	9.37	0.01	0.32	4.78	4.26
Total (1997/98-2006)	156.01	1.45	57.86	65.23	31.46

Evapotranspiration (ET) values for the simulated crops are expressed as the amount of water lost in mm per season. At planting, ET is made up of only evaporation of water from the soil surface. As the crop emerges and begins to develop leaf area, an increasingly larger portion of ET results from transpiration from the crop canopy. Soon leaves shade a large portion of the soil surface, and ET is then largely due to transpiration. During most of the crop's growing season, transpiration is responsible for the largest portion of water loss from the field (Table 6.3). In the 9 years (1997-2006) of irrigation with coal-mine water, clearly the largest seasonal irrigation requirement was to supply transpirational needs, and not evaporation. The average potential ET for the summer season was 550 mm, which is higher than from the winter season value of 370 mm. This is due to the higher evaporative demand and longer growing period in summer. Irrigation supply, however, was greater during winter, due to the lack of winter rainfall (Table 6.3). The average seasonal ET simulated for the wheat-maize rotation was as high as 445 mm for Maize and 413 mm for Wheat. Average transpiration for summer seasons (maize) during the trial period was 300 mm. More than 77% of the irrigation and rainfall was evapotranspired over the study period. Similar results were also obtained for the other pivots. The rainfall contribution to crop evapotranspiration was mainly during summer, and was higher than the irrigation supplied to the fields. The rainfall in the summer growing period was beneficial in leaching salt, but also contributed to more recharge, which increased waterlogging at New Vaal.

Drainage was limited at Pivot Major by a plinthic layer at ~ 1.0 m soil depth. At Pivot TWF, drainage was assumed to be zero as the spoil layer, also at ~ 1.0 m soil depth, has a hydraulic conductivity much lower than the overlying soil. However, the topography of the site results in subsurface hill slope flow, so there is in reality a mechanism to leach excess salts from the profile. In the summer season, on average 18% of the irrigation and rainfall is simulated to have drained below the root zone for Major, while for Pivot Four the average simulated drainage was 23%, this is high due to the free draining character of the site. In the winter season, drainage was less than for the summer season, calculated to be 14% and 18% for Pivot Major and Pivot Four respectively. The summer rainfall had a tremendous effect on irrigation management in terms of waterlogging and salt leaching. The simulations also showed that smaller drainage volumes but of higher salinity occurred in the winter, and higher volumes of drainage but with lower salt concentrations occurring in the summer. This shows that with the unpredictable nature of rain one has more control over the soil water balance in the winter months. Due to the contribution rain makes to ET, crops were irrigated with larger volumes of mine water in the winter than in summer seasons.

Leached salts at Pivot Tweefontein were calculated to be zero because no drainage was simulated, but salts were able to leave the field in the run off water, some of which came from subsurface flow. Considerable masses of salt were predicted to precipitate in the soil profile in the form of gypsum. The negative change in salt content in the soil indicates a decrease in soil salinity through gypsum precipitation during the measuring period.

Simulations over a 9 year (1997-2006) period highlight that a large proportion of the applied mine water is consumptively used as evapotranspiration. Due to the gypsiferous nature of the applied water, this concentrating effect caused a large portion of the salts to precipitate as gypsum in the soil.

In the summer, lower soil salinities were maintained, partly because the salt load was lower than in winter due to the lower irrigation amounts and also because the opportunity for flushing salts out of the root zone is higher. The average annual rainfall (19.2 mg ℓ^{-1} salt) in summer season is 321 mm, and 106 mm falls during the winter season, which ends in early summer. Average (2240 mg ℓ^{-1}) input in summer is 280 mm, with 374 mm in winter. The simulated annual total salt input and salt storage of the study area fluctuated depending on irrigation water quantity and quality. Salt storage increased when the salinity of water inputs exceeded those outputs. As an example for site Major, the simulated cumulative change in salt storage over the 9-year simulation period, shows a total increase of 31.46 t ha^{-1}. The salt-balance results indicate that crop productivity can be sustainable, as the dissolved salts stabilized at a level still acceptable for crop production, which could be due to gypsum precipitation in the soil and leaching.

6.3.2 Syferfontein

The measurement period was from 01/10/2001, when the pastures were fully established (Appendix C (Table C1)). Almost full canopy cover of pastures ensured high transpiration and low soil evaporation. Low canopy coverage was predicted for lucerne during the early growth stages. The model predicted, therefore, large volumes of irrigation and rainfall to evaporate after mowing.

Drainage was limited by the heavy soil texture. The change in soil water storage was relatively small as the field was irrigated throughout the season. Variability in the components of the soil water balance was observed due of variability in irrigations and water use of the different species measured. The components of the salt balance varied accordingly (Appendix C, Table C2). The positive change in salt content in the soil indicated an increase in soil salinity due to irrigation with water rich in highly soluble Na_2SO_4.

6.4 Long-term scenarios

In the previous two sections, 6.1 and 6.2, the SWB model was validated and used successfully to simulate medium term field scale and soil water and salt balances. This gave us confidence to use the model for long-term scenario simulations. In the following section, long-term scenarios for gypsiferous mine water, Na_2SO_4 and $NaHCO_3$ coal-mine waters are presented.

6.4.1 Irrigation with gypsiferous rich mine water

Annandale *et al*. (1998) used SWB to simulate long-term scenarios for gypsiferous mine water. The model was used to simulate 30 years of irrigation with gypsiferous water, followed by 20 years of dry land summer cropping, to determine if the problem of salt disposal was merely being postponed. According to the long-term simulations for a pearl millet-oats rotation on a sandy soil, substantial volumes of water can be used, and masses of salt disposed of, through irrigation. This can be best achieved through high frequency irrigation of crops year round. Results of this simulations were also used in the assessment of long-term impact of gypsiferous mine water on groundwater systems (Annandale *et al*., 2006). Results of this study suggest that irrigating large areas with gypsum rich mine water could be feasible and sustainable if careful attention is paid to the specificity of each situation. Annandale *et al*. (2006) concluded that irrigation with gypsiferous mine water, if properly managed, could seriously be considered as part of the solution towards the challenge of responsible management of the considerable volumes of mine water available during mining and post closure.

Since long-term simulation scenarios were carried out for gypsiferous mine water, in the following section, attention will be given to the modelling exercise that evaluates the long-term impact and sustainability of irrigation with Na_2SO_4 and $NaHCO_3$ waters from the point of view of crop production and soil chemical properties.

6.4.2 Irrigation with Na_2SO_4 rich mine water

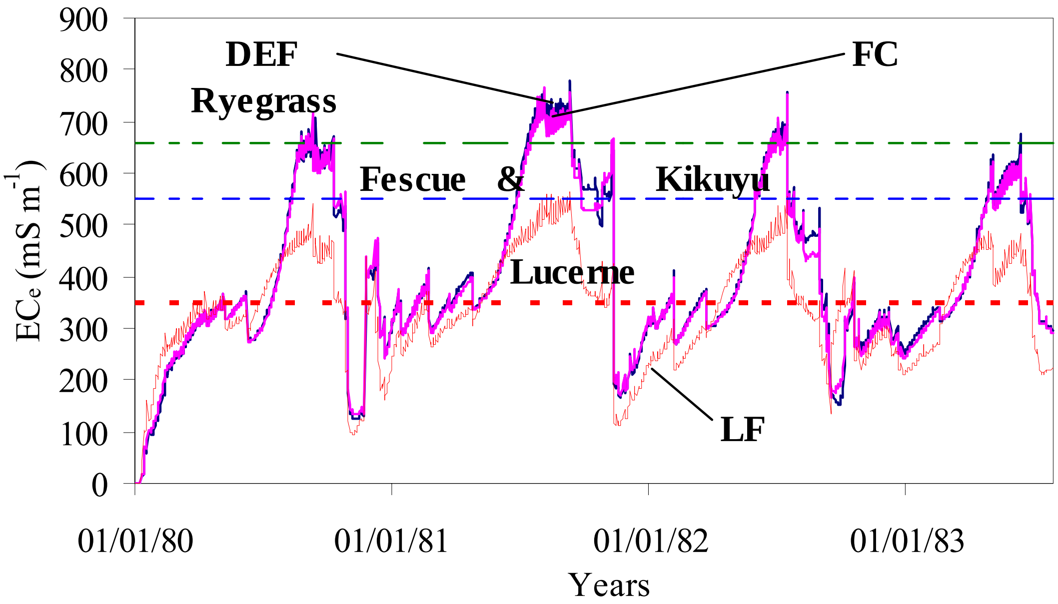
Twenty years of irrigation with Na_2SO_4 rich mine effluent were simulated using historic daily data collected from a meteorological station at Secunda. Three irrigation management strategies were also evaluated in an attempt to identify suitable irrigation management options for sustainable utilization of such waters in the long-term. Three irrigation management scenarios: a room for rain-deficit irrigation scenario applying only 90% of the water needed to bring the profile to FC (DEF); irrigation to FC (FC); and a leaching fraction of 20% that applied 25% more water than that needed to return the profile to FC (LF-20%), were chosen arbitrarily.

Results show that a large quantity of salt was added and leached from the leaching fraction scenario during the 20 year irrigation period (Table 6.5). Smaller quantities of salt were leached from the DEF irrigation strategy and gypsum was predicted to precipitate in the top 0.2-0.6 m soil layers with small quantity. The DEF strategy showed the highest maximum soil saturated EC_e (root density weighted soil saturated EC) during the 20 years irrigation period (Table 6.5). This was compared with the EC_e threshold tolerance published by Maas and Hoffman (1977) for the crops irrigated.

Table 6.5 Predicted average annual salt balance for 20 years of irrigation with Na_2SO_4 rich mine effluent

Salt balance	FC	LF 20%	DEF
Salt added (Mg ha^{-1} yr^{-1})	31	47	30
Salt leached (Mg ha^{-1} yr^{-1})	29.2	44.8	28.5
Salt precipitated (Mg ha^{-1} yr^{-1})	1.9	2.2	1.48
Salt runoff (Mg ha^{-1} yr^{-1})	0	0.01	0
Soluble salt storage (Mg ha^{-1} yr^{-1})	0.005	0.001	0.02
Maximum root density weighted soil saturated EC_e (mS m^{-1})	780	555	800

The maximum root density weighted soil saturated EC_e predicted for Fescue, Kikuyu, Lucerne and Ryegrass was higher than the threshold level indicated by Maas & Hoffman (Figure 6.9). Therefore, both DEF and FC irrigation strategy were found unsustainable for pasture production, as salts could build up in the profile above the threshold tolerance of the pastures.



Dashed horizontal lines- EC_e thresholds for lucerne, fescue and kikuyu, and ryegrass at 90% yield potential (Maas & Hoffman, 1977)

Figure 6.9 Predicted root density weighted soil saturated EC_e of pastures irrigated with Na_2SO_4 rich mine effluent for 20 years using three different irrigation strategies (three arbitrary years at the beginning of the simulated period are shown)

While the EC_e predicted at a 20% leaching fraction irrigation strategy seems favourable for growing pastures at a yield potential of 90% (Figure 6.9), considerable quantities of salts were predicted to leach below the 0.8 m deep soil profile. This obviously has an implication for groundwater pollution. Geo-hydrological and surface water modelling should, therefore, be done to determine the impact of these salts reaching ground and surface water sources.

6.4.3 Irrigation with $NaHCO_3$ rich mine water

Twenty-two full years of historic daily weather data were obtained for the meteorological station located close to the Waterberg CBM project in Lephalale (Ellisras). This is the nearest weather station to the proposed Waterberg CBM project with a reasonably long record of data, and was therefore used as input to the SWB model. SWB was run for several irrigation management strategies for a long-term barley-cotton rotation. This would help to quantify the environmental impacts and predict potential soil water and salt balances. The model assumed irrigation with $NaHCO_3$ water to be applied whenever a threshold deficit to field capacity of 15 mm was exceeded. Three irrigation amounts were selected: a room for rain-deficit irrigation scenario, applying only 90% of the water needed to bring the profile to FC (DEF); irrigation to FC (FC); and a leaching fraction of 23% that applied 30% more water than that needed to return the profile to FC (LF-23%), chosen arbitrarily.

The simulations showed that with well drained soils and a high leaching fraction, root weighted soil saturated paste extract conductivities (root weighted EC_e), did not exhibit an increasing trend beyond the threshold for salt tolerant crops, thereby suggesting that production of specific crops for a limited period may be feasible. Figure 6.10 shows simulated root density weighted electrical conductivity of the saturated soil extract (EC_e) for three irrigation management strategies for three years. In the Figure, three years were arbitrarily chosen for close examination, as results were similar for other years.

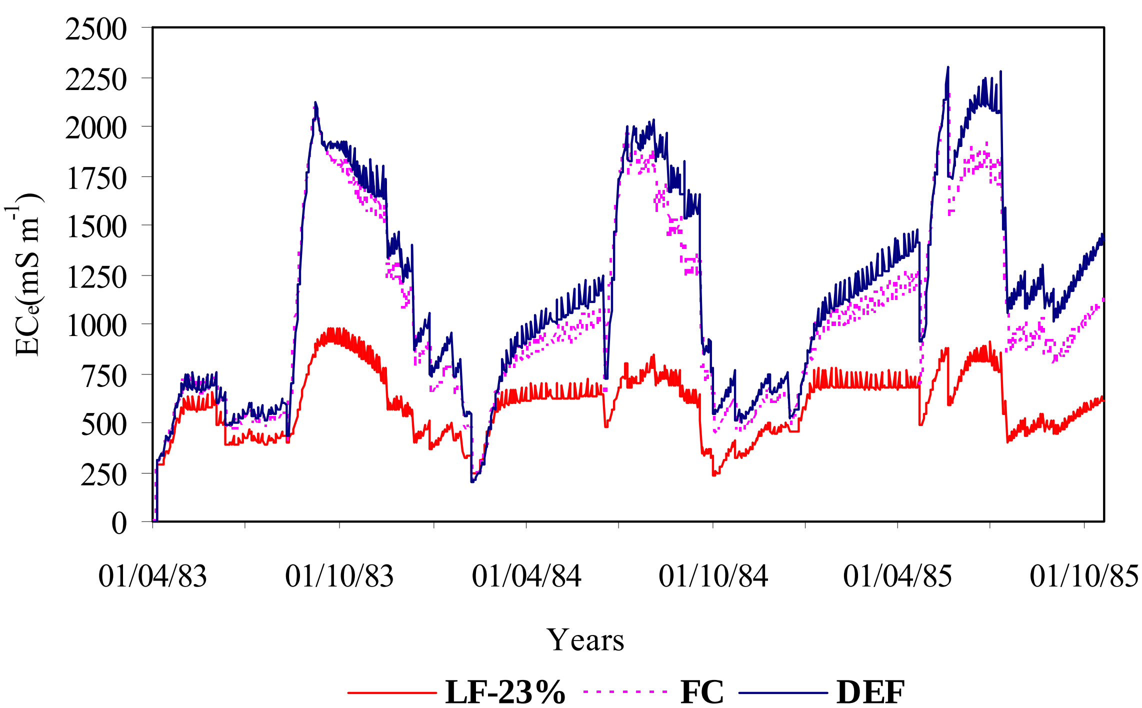


Figure 6.10 Simulated root density weighted soil saturated EC_e of a barley-cotton rotation irrigated at a threshold deficit of 15 mm with $NaHCO_3$ deep aquifer water for three arbitrarily chosen years

The deficit irrigation and field capacity strategies showed high soil saturated EC_e levels during the 22-year irrigation period. For the 23% leaching fraction strategy, soil saturated EC_e was far lower over this period. Salts built up in the soil during winter, and decreased again during summer as rainfall increased the rate of leaching.

The soil saturated EC_e of the 23% LF management option was compared to maximum EC_e for a 90% yield potential reported by Maas & Hoffman (1977) for cotton and barley (Figure 6.11). The EC_e levels predicted for these crops were mostly below the threshold levels indicated by these authors. Predicted soil EC_e rises to a maximum of 857 mS m^{-1} for barley and 981 mS m^{-1} for cotton. It, therefore, seems unlikely that excessive salinity stress will occur with this irrigation management and cropping system option.

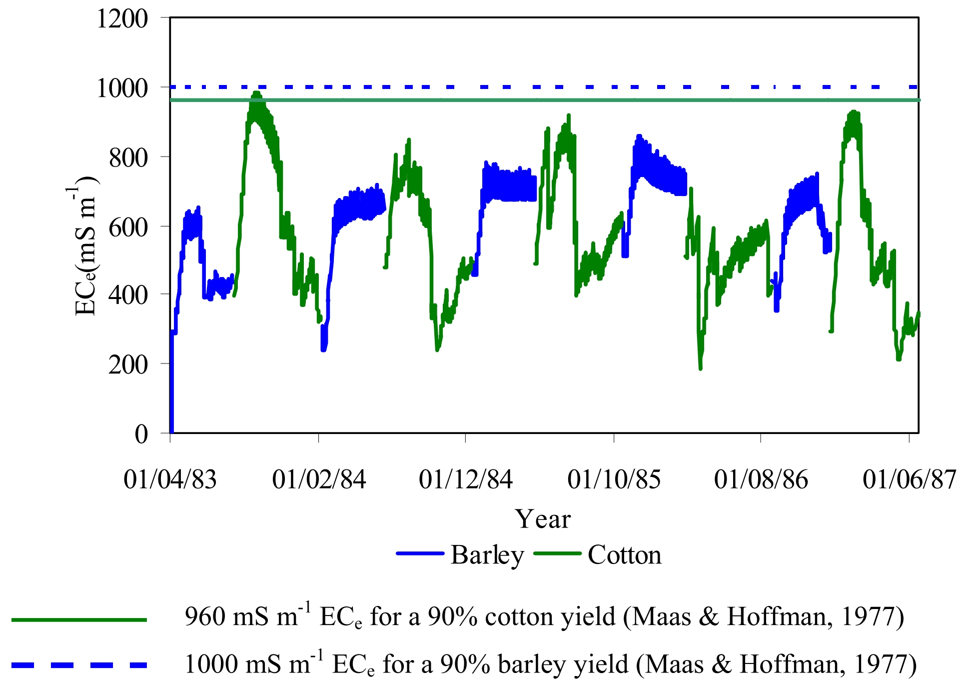


Figure 6.11 Simulated root density weighted soil saturated EC_e of a barley-cotton rotation irrigated at a 23% LF and threshold deficit of 15 mm, compared to Maas & Hoffman (1977) norms for a 90% yield potential

The amount of salt applied to the field is greater for the 23% LF scenario, compared to irrigation to field capacity or the room for rain-deficit irrigation scenarios (Table 6.6).

Table 6.6 Predicted annual components of the salt balance, using $NaHCO_3$ deep aquifer water for a 22 year barley-cotton rotation with a 23% LF and a threshold deficit of 15 mm

Components ($Mg\ ha^{-1}\ yr^{-1}$)	Statistics				
	Average	St. dev.	Max	Min	Median
Salts added	52	3.7	58	39	51
Salts leached	51	8.7	62	21	53
Soil profile storage	1	0.01	1.5	0.5	0.3

The leaching fraction of 23% seems to be a quite reasonable irrigation water management strategy for the barley-cotton rotation, as it provides a balance between crop yield reduction and excessive localized salt leaching. However, these salts must be leached from the profile if cropping is to be sustainable. Therefore quantification of the impact this will have on the shallow aquifer is essential. The output from SWB is recommended to be used by geo-hydrological modellers for simulation of the groundwater impact of irrigation with these waters.

Conclusions

This modelling study evaluated the SWB model for its accuracy in simulating several crop rotations. SWB predicted crop growth, water balance and salt content of the soil reasonably well. This gives some confidence that the SWB model can be used to predict various scenarios to determine the impact of the long-term use of such waters on crop production and soil properties.

The validation of the chemical equilibrium and solute transport subroutines in SWB was done by comparing SWB estimates of soil solution concentration of each ion simulated with measurements of solutions from suction cups and wetting front detectors. The comparisons were made for six years of data. In general, the model predicted soil solution concentrations quite closely to the measured values. This gives us still more confidence in the predictive capacity of the model for longer-term impact assessments of irrigation with such mine waters.

Root zone salinity simulated for gypsiferous mine water did not rise on average above 250 mS m^{-1}. Variation in soil salinity is mostly due to changes in annual rainfall over the modelled period. Excessive salt accumulation can be detrimental to crop production, and therefore, one has to monitor soil salinity regularly to ascertain if the leaching fraction needs to be adjusted or not so as to leach excessive salts below the root zone.

The long-term simulations for the pastures indicated, between 1255 and 2100 mm per year of mine effluent could be applied. EC_e predicted for the DEF and FC irrigation strategies fluctuated, but at a level higher than expected. These strategies are unsuitable for pasture production, as the threshold tolerance of the pastures is far lower than the predicted EC_e. Simulated EC_e at a LF of 20% revealed more favourable conditions. The threshold EC_e for a 90% yield potential is far higher of 20%LF treatment. The selected pastures, therefore, can be irrigated sustainably using Na_2SO_4 rich mine effluent, but the possibility of locking up salts in the profile using gypsiferous rich water is unlikely. Thus, groundwater impact may be a great concern. In the long-term, irrigating with Na_2SO_4 rich mine effluent water could have considerable impact on groundwater, as a net downward flow of water through the root zone is needed to leach the salts to a suitable depth.

The long-term simulations using the $NaHCO_3$ water indicated that on average, using a 23% leaching fraction, 1872 mm per year of $NaHCO_3$ water could be applied through irrigation to a barley-cotton rotation. Almost all (98%) of the salts added through irrigation were predicted to leach from the soil profile for this scenario. The leaching fraction of 23% seems to be a quite reasonable irrigation water management strategy for the barley-cotton rotation, as it provides a balance between crop yield reduction and crop tolerance to salinity. The likely environmental impact of the required high LF probably does not make this the best approach for mining to manage waters of these qualities. A Serial Biological Concentration (SBC) (Blackwell *et al*., 2001) approach could be used to concentrate up the water, so there would be less water to treat, but it would be of a higher salinity.

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CHAPTER 7

SURFACE RUNOFF FROM COAL-MINE WATER IRRIGATED FIELDS

7.1 Introduction

The possibility of irrigating crops using mine water at commercial scale was tested in a sequence of field trials (Chapters 3 to 6), where several field crops and pasture species were successfully grown. The Soil Water Balance (SWB) model was also improved to simulate several crop rotations (Chapter 6) and to predict the long-term effects of various management scenarios on the soil water and salt balance (Annandale *et al*., 2001).

Runoff could be generated from irrigated fields, depending on rainfall amount and intensity, topography, soil type, soil water content, vegetation cover and land use (Mishra & Singh, 2003). Runoff quantity can be measured by erecting V-notch weirs at the lowest end of the irrigated fields, where runoff converges. Runoff quantity and quality measurements are important to determine salt loads from coal-mine water irrigated fields, that may end up in surface waters. Conducting long-term field experiments to quantify runoff from fields is expensive, so models are usually used. In this chapter, modifications made to SWB, with model calibration and validation simulations to estimate runoff, are presented.

7.2 Modelling surface runoff

Reliable estimation of runoff quantity is essential for runoff quality considerations. There are different techniques to estimate amount of runoff. The most commonly used method is the Soil Conservation Services Curve Number (SCS-CN), developed in (1949) in the USA (SCS, 1971). The SCS-CN method is characterized by the equation:

$Q = (P - 0.2S)^2 / (P + 0.8S)$ where Q is the Runoff, P is Precipitation and S Initial abstraction (stored on the surface, intercepted, and infiltrated water), all in mm. S is derived from

$S = (25000/CN)-250$.

CN is known as the curve number, and is determined from antecedent soil water content (AWC), which is an index of soil wetness, for different hydrological soil groups in the USA. A higher curve number indicates the response from a field with a fairly uniform soil with a low infiltration capacity. A low curve number gives the response expected from a field with good infiltration. The curve number could vary from 0 to 100 (Mishra & Singh, 2003). Models such as CropSyst (Stöckle & Nelson, 2000) and GLEAMS (Leonard *et al*., 1987) use this same SCS-CN method to estimate runoff. The SCS-CN approach, however, does not consider the quality of runoff.

The practical application of this procedure to estimate runoff should be simple and direct. It relies on the determination of the curve numbers, which are widely documented in the literature for various land uses and soil types (NEH-4, 1985; Chow *et al*., 1988; Pilgrim & Cordery, 1993). In spite of its apparent simplicity, difficulties come in with the determination of antecedent soil water conditions (AMC) when applying the model outside the USA, as these soils are often not classified into the four hydrological soil groups A, B, C and D, used by the model.

Models in South Africa such as ACRU (Schulze, 1986), also use the SCS-CN method, where S is modified as the soil water deficit to saturation of a thin surface layer, and is calculated as part of the daily soil water balance. The thickness of the surface layer used in this calculation is important. If the whole profile is taken, for instance, runoff may never be simulated.

SWB also estimates surface runoff on the basis of the SCS-CN approach. It is driven by daily rainfall and irrigation, and relates the S value, called the runoff parameter (Rop) in the model, to the irrigated field's characteristics. This approach of SWB to estimate runoff, however, did not consider antecedent water content of the surface layer and the possibility that water flowing over the field could come into contact with salts in the soil surface. The objective of the study was, therefore, to modify initial abstraction (S) in the original SCS-CN model by including the soil water deficit of the top layer, calculated from the daily soil water balance. In addition, a thin soil surface layer parameter to consider salt mixing at the surface was included to improve estimates of salt runoff.

The SWB model

In SWB, when crops are overhead irrigated or if it rains, plant leaves intercept some water. However, if the rain plus irrigation is less than can be intercepted by the canopy, none will reach the soil. However, if rainfall or overhead irrigation is more than can be intercepted by the canopy, some will reach the soil, and if this water is greater than or equal to the antecedent water content deficit to saturation of the upper most soil layer, runoff is assumed to occur. The calculation of Q was modified, therefore, as follows:

If P+I > AWC, then $Q = ((P+I) – AWC)^2 / ((P+I) + 0.8Rop)$ Where

P - precipitation (mm)

I - irrigation (mm)

AWC - antecedent water content AWC = (WCSat[1]-WC[1])dz[1] (mm)

WCSat[1] - saturated water content of layer 1 (m m^{-1})

WC[1] - water content of layer 1 (m m^{-1})

dz[1] - thickness of layer 1 (mm)

Rop - the runoff parameter (mm)

The water that runs off an irrigation site was assumed to have the same salt concentration as the rainfall or irrigation in the original version of SWB (Annandale *et al*., 1998). However, runoff salts can vary greatly from the rainfall or irrigation salinity, especially after dry periods, as salt at the surface concentrates due to evaporation. When a rainfall event occurs, accumulated salts near the surface of the soil, mix with the storm flow and result in a higher salinity than that of the rainfall. Therefore, a thin surface layer component, the salt mixing depth was included into the runoff procedure, in order to take this into account. The mixing layer is part of the top layer used in the daily water balance calculation. This concept was adopted from ACRU (Schulze, 1986), where the salt mixing layer is treated separately. In SWB the salt mixing layer is considered to be within the top layer. A diagrammatic representation of runoff and salt mixing is shown in Figure 7.1.

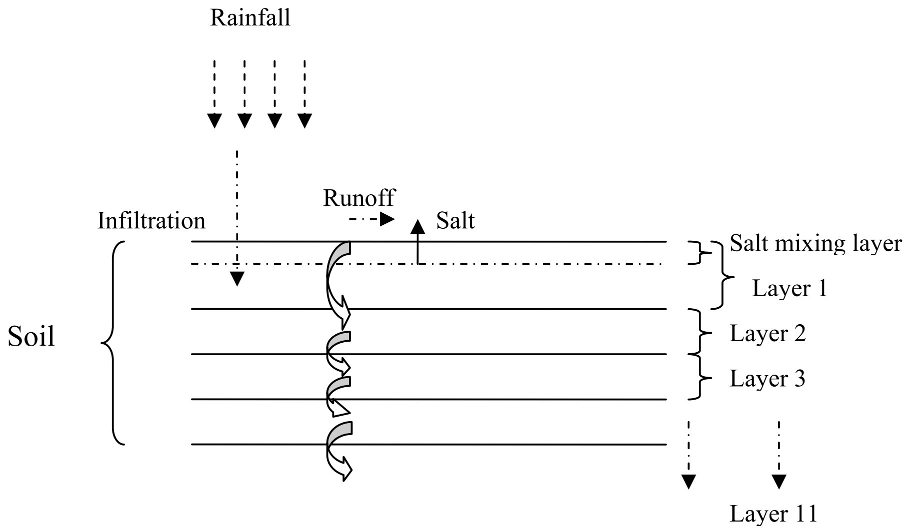


Figure 7.1 Diagrammatic representation of runoff and salt mixing with runoff

Salts in solution in the salt mixing layer are added to the salts in the runoff water.

7.3 Model calibration

Crop related model parameters are discussed in Chapters 3 and 6. Required weather and management input data are, planting date, latitude, altitude, rainfall and irrigation water amounts and quality, as well as maximum and minimum daily temperature, were used as input to the model. In the absence of measured data, SWB estimates solar radiation, vapour pressure and wind speed according to the FAO recommendations (Allen *et al.*, 1998). Required soil input data include volumetric field capacity, permanent wilting point and a runoff parameter to calculate runoff based on the SCS method (Stewart *et al.*, 1976). In addition, initial volumetric soil water content, the content of soluble and exchangeable ionic species, as well as initial gypsum and lime are required for each soil layer.

The runoff parameter (Rop) was estimated for the sites, as shown in Figure 7.2. Salt interception by the crop canopy was ignored, as it is assumed to be washed off with the next irrigation or rainfall event. Runoff was assumed to take place only when rainfall after interception is subtracted, fills up layer 1 to saturation. The salt mixing depth was assumed to be within this layer.

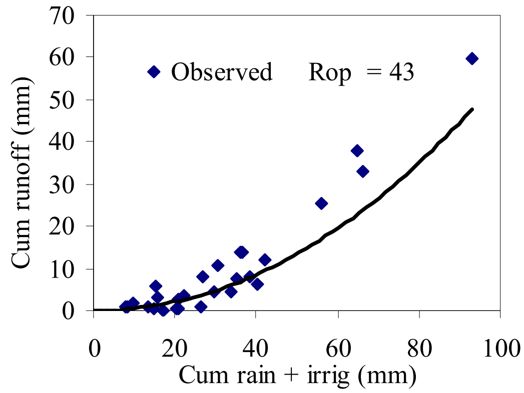


Figure 7.2 Runoff parameter (Rop) estimated from cumulative (cum) rainfall plus irrigation and cumulative runoff for several storm and runoff events

The model was run with the Rop value selected a number of times to evaluate simulated runoff quantity by changing the thickness of layer 1. Once this estimate seemed satisfactory, a number of simulations were again run, this time changing the salt mixing depth while keeping the thickness of layer 1 constant. Only the first year's runoff measurements were compared with modelled output values for the calibration exercise. The salt mixing depth that statistically produced the best runoff estimates was selected and used to validate the model.

Independent data sets, not used in the calibration exercise, were used for model evaluation. Predicted and measured values were compared using qualitative (graphical) and quantitative (statistical) criteria to evaluate the model's capabilities. To assess goodness of fit and accuracy of simulated values, mean absolute error (MAE), expressed as a percentage was determined. MAE is calculated as:

$$MAE = 100\sum_{n=1}^{n=N}\left[(P_i - O_i) / NO_m \right]$$

Where P_i and O_i are the ith predicted and observed values of the runoff data, O_m mean observed values and N is the number of observed values. Willmott's index of agreement (D) was also used to show how well the predicted and observed deviations correspond to each other. It varies between one and zero, with one representing perfect agreement and zero a complete disagreement, and is expressed as:

$$D = 1 - \left[\frac{\sum_{i=1}^{N} (P_i - O_i)^2}{\sum_{i=1}^{N} \left[/ P_i^{'} / + / O_i^{'} / \right]^2} \right]$$

Where $P_i^{'} = P_i - O_m$, $O'_i = O_i - O_m$ and O_m is the mean of the observed values.

According to De Jager (1994), the acceptable reliability criteria for these parameters are D >0.8 and MAE < 20%.

The results of the simulations indicated that runoff generation was sensitive to water content of the top layer, bulk density, Rop and salt mixing depth. The model's predictions were generally quite close to measured values. Results of model calibration for runoff quantity and quality simulated with a top soil layer thickness of 0.2 m and salt mixing depth of 0.002 m are indicated in Figures 7.3 a-d.

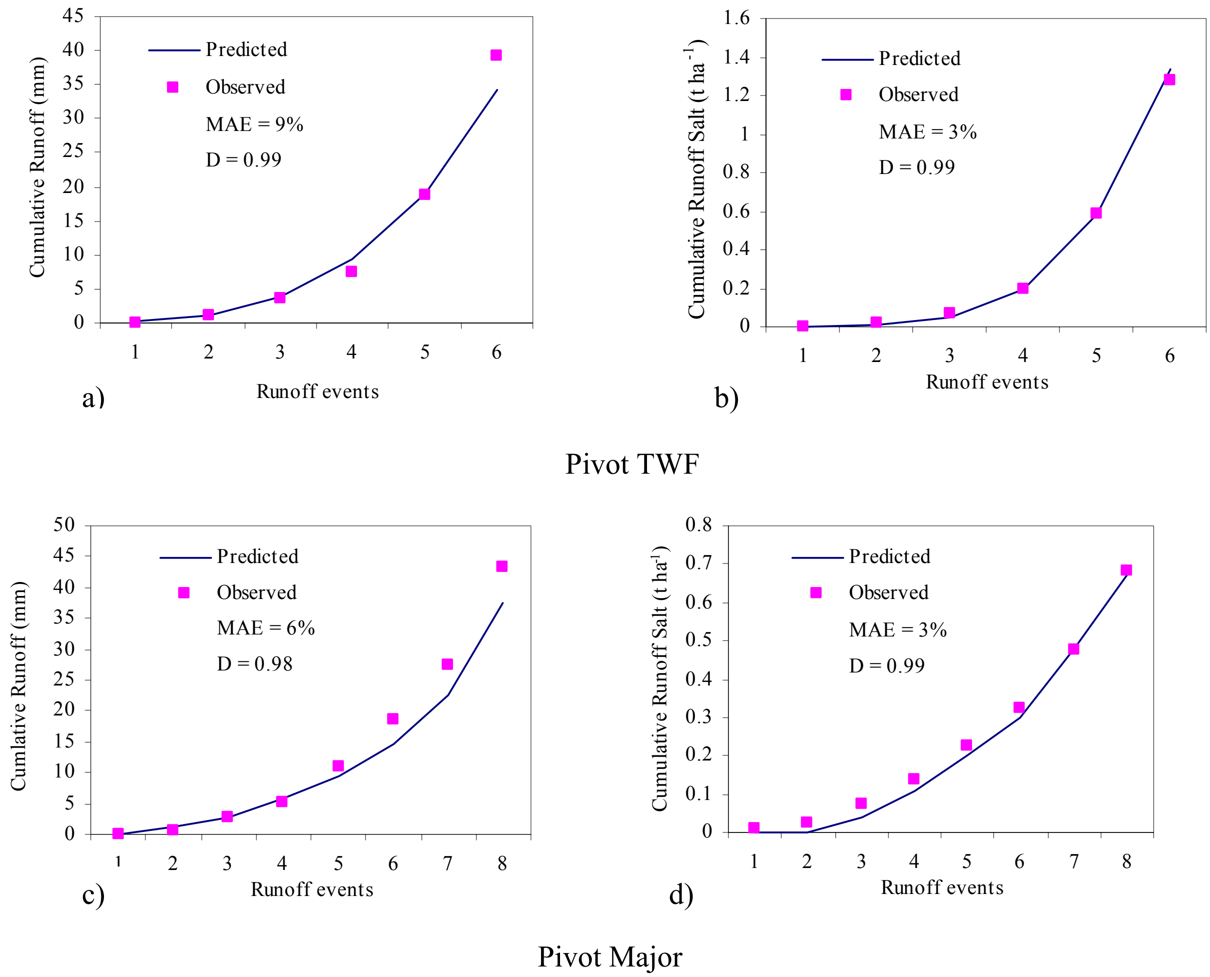


Figure 7.3 Model calibration for runoff quantity and quality for Pivot TWF (a) and (b), and Pivot Major (c) and (d), Summer season 2000/01. MAE is mean absolute error and D is Wilmotts' index of agreement

7.4 Measured runoff

Measured runoff totaled 8% of the overall rainfall at TWF, and 6% for Major for the trial period (Table 7.1). The differences in runoff are most likely due to differences in slope between the two fields. The total salt added to the sites depended on the amount of irrigation applied to each field. Table 7.1 summarizes rainfall and amount of irrigation applied and salts added to the irrigated fields. The first runoff events after the dry winter season always carried the highest amount of salts, on average 75% of the total salt load.

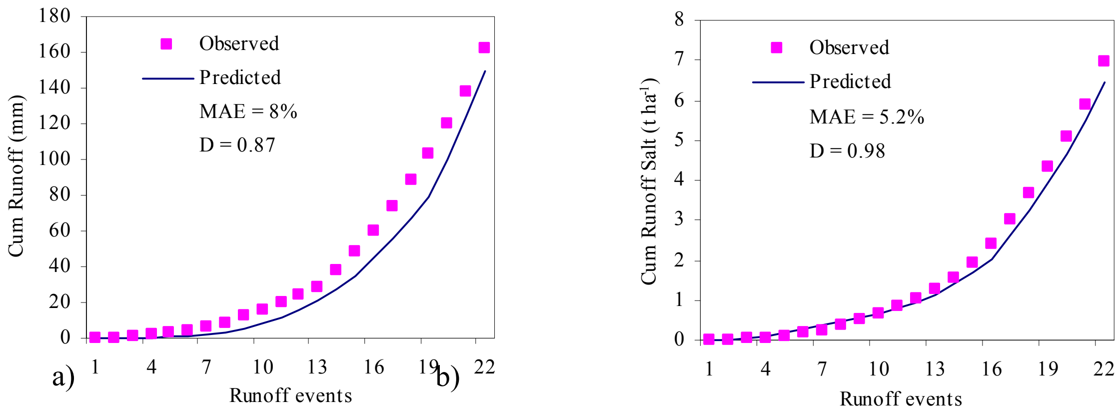
Table 7.1 Summary of measured rainfall, irrigation and salt added between 2000 and 2006 at TWF and Major

Parameters (measured)	Tweefontein (20 ha)	Major (30 ha)
Irrigation	4126 mm	4770 mm
Rain	3986 mm	4067 mm
Salt added	2059 t (103 t/ha)	2748 t (91.6 t/ha)
Salt runoff	192 t (9.6 t/ha)	231 t (7.7 t/ha)
Runoff	310 mm (8%)	226 mm (6%)

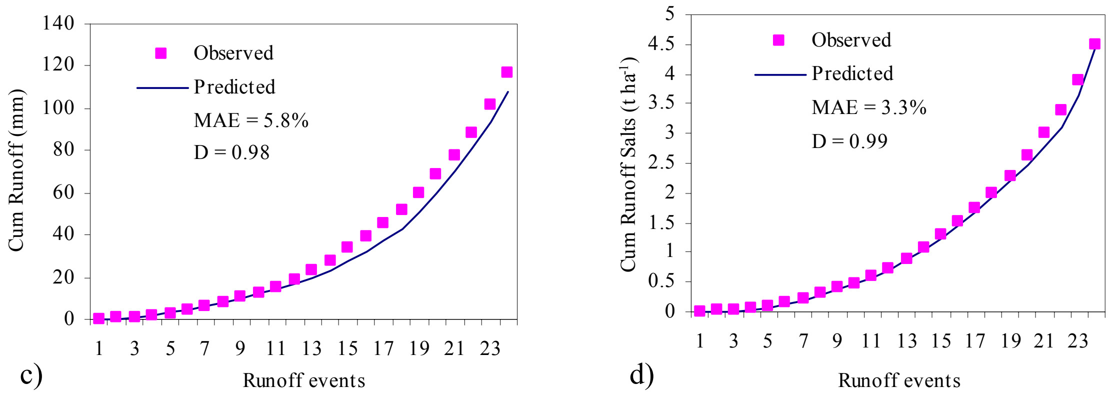
7.5 Model validations

Independent data sets of measured surface water and salt runoff was compared to SWB predictions. Runoff events due to irrigation system failures were excluded from the comparisons, as the pivot failed to move and applied the water in one position, and amount of irrigations could not be measured. The runoff water from such system failures also does not get the opportunity to interact with the whole field surface.

Runoff predicted by SWB generally followed the seasonal pattern of the observations. The model predicted a total of 149 mm of runoff for TWF and 107 mm for Major, while the measured runoff was 163 mm and 117 mm (Figure 7.4).



Pivot TWF



Pivot Major

Figure 7.4 Predicted and measured runoff quantity and quality 2002-2006

SWB also simulated the cumulative runoff salts to be 7 t ha^{-1} for TWF and 4.6 t ha^{-1} for Major, whereas the measurements for these sites were 6.8 and 4.4 t ha^{-1}. When individual runoff event predictions are compared with observations, the model tended to over predict smaller events and under predicted larger runoff events. Model sensitivity analysis 20% has been performed by increasing the mixing depth layer and layer 1. Simulations were performed and the percentage changes of several output values were recorded. A large salt mixing depth was, as expected, observed to increase salt runoff by more than 20% and a small increase in layer 1 increased the runoff volume by 20%. Generally, the model estimated the cumulative runoff fairly well for both sites.

Including a salt mixing depth and antecedent soil water content gave reasonable predictions of runoff quantity and quality. Runoff predicted by the SWB model seems quite reasonable after calibration, and can be used in the assessment of the impact of large-scale irrigation on water resources.

Conclusions

SWB was evaluated for runoff quantity and quality after introducing antecedent water content as a variable and salt mixing depth as a site specific parameter. The model gave good estimations of runoff quantity and quality after calibration. This will be helpful in modelling soil water and salt balances for several scenarios of long-term irrigation with mine water. SWB output can now be used as input into a surface water model to illustrate the possible effect of large scale irrigation on surface water resources. Further improvements can still be made to better represent runoff quantity and quality, but in its current improved form, SWB can provide credible estimates of runoff from coal-mine water irrigated fields.

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CHAPTER 8

GENERAL CONCLUSIONS AND RECOMMENDATIONS

For successful coal-mine water irrigation, the following, criteria's are essential: (1) selection of salt tolerant crops; (2) careful irrigation water management; (3) fertilization that accounts for the ions being added with irrigation water; and, (4) selection of a well drained site to facilitate leaching of slightly soluble salts.

The required leaching to prevent the unsustainable build up of salts in the soil profile could externalize the salt problem for the mine, except perhaps when rehabilitated soils are irrigated which could facilitate the interception of the leachate for reuse or further treatment.

8.1 Conclusions

The sustainability of irrigation with coal-mine water from the point of view of crop production and soil resources was assessed. Several crops and pastures species were able to grow successfully. The main findings are discussed below:

Crops like sugarbeans, wheat, maize, potatoes and pastures were very successfully produced. In the short to medium-term (eight years), irrigation with gypsiferous mine-water on a commercial scale proved to be agriculturally sustainable, with no noticeable negative impact on the soil. It is expected that soils will accumulate large masses of gypsum over time, but this is not seen as a problematic.

Particular attention should be given to K fertilization, as it becomes unavailable due to high Ca and Mg levels in the soil when irrigating with gypsiferous water. In this study, wheat yields were as high as 8 t ha^{-1}, potatoes produced over 50 t ha^{-1} and maize yields of 10 t ha^{-1} were achieved. It is clear, therefore, that good commercial production is feasible with gypsiferous water.

Pasture production with Na_2SO_4 rich mine effluent was also feasible, at least in the short term (three years) but would need a very well-drained profile and a large leaching fraction to prevent unsustainable salt build up. Unfortunately, these waters do not present much opportunity for gypsum precipitation, which is able to drastically reduce the salt load of the receiving waters in the case of calcium sulphate rich mine water irrigation.

The $NaHCO_3$ water studied was very concentrated and of extremely poor quality for irrigation. Salt tolerant crops can be grown with this water if a high leaching fraction is used, together with the application of gypsum as a source of Ca to displace adsorbed Na that causes dispersion, which results in serious soil physical problems. The likely environmental impact of the essential extreme leaching fraction, does not make this the best approach for mining to manage waters of these qualities.

Although, irrigation with coal-mine water involves complex interactions between crop, soil, water quality, hydrology and geohydrology, interest from farming companies to continue irrigating with this water indicates the commercial potential. The fact that gypsum precipitates in the soil, its slow redissolution, and the attenuation of leached salts below the root zone, makes irrigation with $CaSO_4$ and $MgSO_4$ rich waters a simple solution that could be used as a water reuse strategy in the mining industry.

Modelling

This modelling study evaluated the SWB model for its accuracy in simulating several crop rotations. SWB predicted crop growth, water balance and salt content of the soil reasonably well. This gives confidence that SWB can be used to predict various scenarios to determine the likely impact of the long-term use of such waters on crop production and soil properties. The validation of the chemical equilibrium and solute transport subroutines in SWB was done by comparing model estimates of soil solution ion concentration, to measurements from suction cups and wetting front detectors. The comparisons were made for six years of data. In general, the model predicted soil solution concentrations quite closely to the measured values. SWB was also evaluated for predictions of runoff quantity and quality, considering the antecedent water content as a variable and salt mixing depth as a parameter. The model estimates were quite reasonable, and this adds value to long-term scenario simulations, where credible estimates of leaching and runoff will be valuable inputs into surface and groundwater models. These, in turn, are needed to predict offsite effects of large-scale irrigation with mine water, should this be sanctioned one day. In future, further improvements can be made to better model runoff quantity and quality, but in its current improved form, SWB is a sound modelling tool for predicting runoff from coal-mine water irrigated fields.

8.2 Recommendations

This thesis investigating the field scale environmental impact and sustainability of irrigation with coal-mine water, has identified areas in which further investigation and research are required. Recommendations made are divided into two sections: the first deals with the monitoring component and recommends additional field studies; the second is oriented towards large-scale irrigation modelling, based on the knowledge gained through this study.

Field monitoring

It is recommended that monitoring at Kleinkopjé Colliery continues, as an extremely valuable research site with a well monitored history of irrigation (18 successive cropping seasons) with mine water has been established. Surface runoff and groundwater volumes and quality should also be monitored closely to generate more data to better model this process. In order to deal with the concentrated leachate from gypsiferous, Na_2SO_4 and $NaHCO_3$ rich mine water irrigated fields, other agricultural technologies should be considered. A Serial Biological Concentration (SBC) (Blackwell *et al*., 2001) approach could be used to concentrate up the water, so there would be less to treat, but it would be of a higher salinity. SBC requires substantial engineering to collect leachate waters for re-use or treatment. This may be conveniently and cost effectively implemented on rehabilitated open cast mine lands through careful site selection that ensures leachate reports to some known position. The cost-benefit analysis of SBC should be evaluated by the mining industry. It may be that the main aim of irrigation would not be to generate revenue out of agricultural production with this water, but rather to just have a green canopy using as much water as possible to concentrate up the leachate, and save on treatment costs.

Large-scale irrigation

For consideration of future large-scale irrigation with mine water, the following aspects should be noted. Site selection is very important. Careful consideration of sustainability of irrigation on the site selected is important. Local geology and geohydrological properties, the proximity to sensitive water users (human consumption and the environment), aquifer vulnerability, drainage properties and possibility of mitigation should be considered in detail prior to commissioning mine water irrigation sites (Vermeulen *et al*. 2008). If large-scale irrigation is implemented, groundwater monitoring must be an integral part of the operation plan. This should include monitoring within the irrigated areas and also boreholes down-gradient of such activities, which could be used for compliance monitoring. Negotiation with the regulators, such as the Department of Water Affairs and Forestry (DWAF), to fix threshold levels at which action should be taken to mitigate the impact or even to cease irrigation activities, must be part of such a monitoring plan.

Finally, engineering requirements should also be considered to assess the feasibility of implementation. In particular, the following need to be considered: siting of irrigated fields; areas required to utilize the available water; cost assessment; operational skill development; monitoring requirements; irrigation management; cost comparison with other options such as reuse on mine sites for road wetting and coal beneficiation; and, treatment of water to an acceptable level to supply to other users.

APPENDIX A

Table A1. Forage quality (Nitrogen (N) and Crude Protein (CP) contents) of Na_2SO_4 irrigated planted pastures, 2002-2003

Planted Pastures	Growing period	Mine water irrigated pastures			Fresh water irrigated pastures		
		Total Yield	Forage quality		Total Yield	Forage quality	
		(t ha^{-1})	N (g kg^{-1})	% CP	(t ha^{-1})	N (g kg^{-1})	% CP
Fescue (cv. Iewag)	Jan 02 - May 03	15.1	18.5	11.5	16-18	18-24	12-15
	Std err	± 0.4			-	-	-
Lucerne	Jan 02 - May 03	10.7	26.9	16.8	18-20	22-28	14-18
	Std err	± 0.05			-	-	-
Fescue (cv. Demeter)	Jan 02 - May 03	11.3	17.7	11.08	16-18	18-24	12-15
	Std err	± 0.04			-	-	-
Eragrostis	Jan 02 - May 02	10.2	16.6	10.4	16-18	18-20	12-13
	Std err	± 0.12			-	-	-
Kikuyu	Sep 02- Dec 02	11.4	_	_	20-24	35-38	20-24
	Std err	± 3.5			-	-	-

APPENDIX B

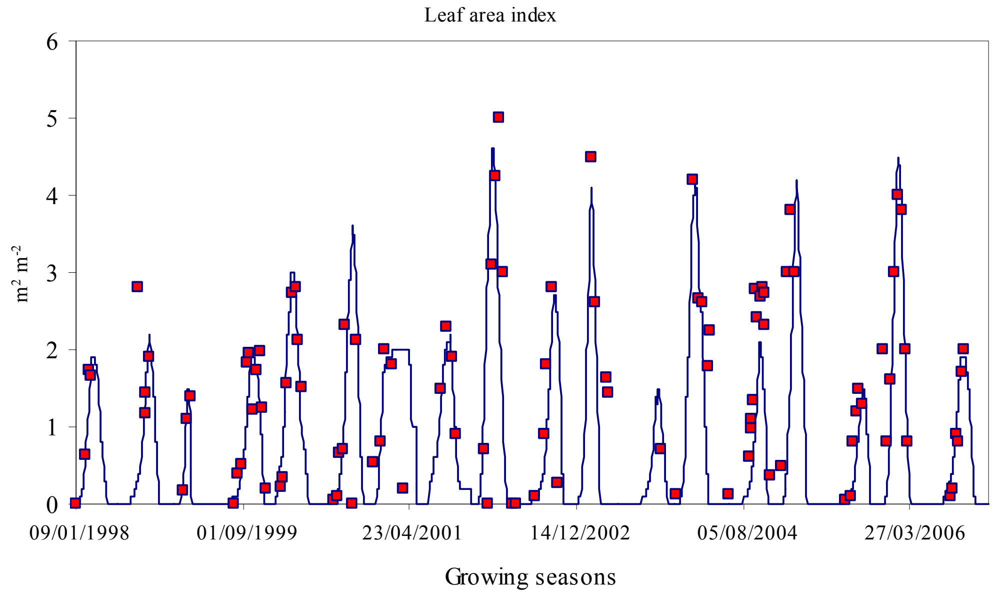

Figure B1. Simulated (solid lines) and measured (symbols) for LAI for Pivot TWF.

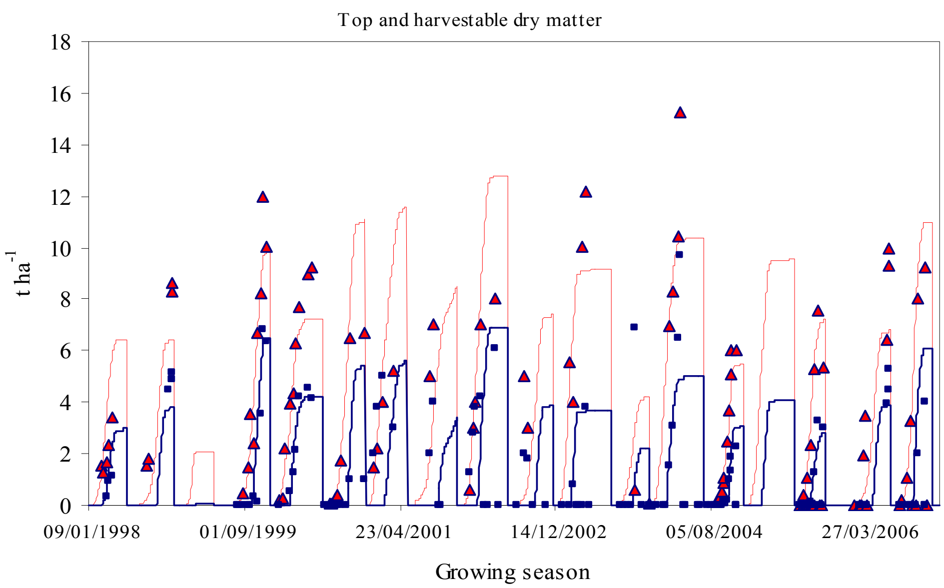

Figure B2. Simulated (solid lines) and measured (symbols) Top and harvestable dry matter for site TWF.

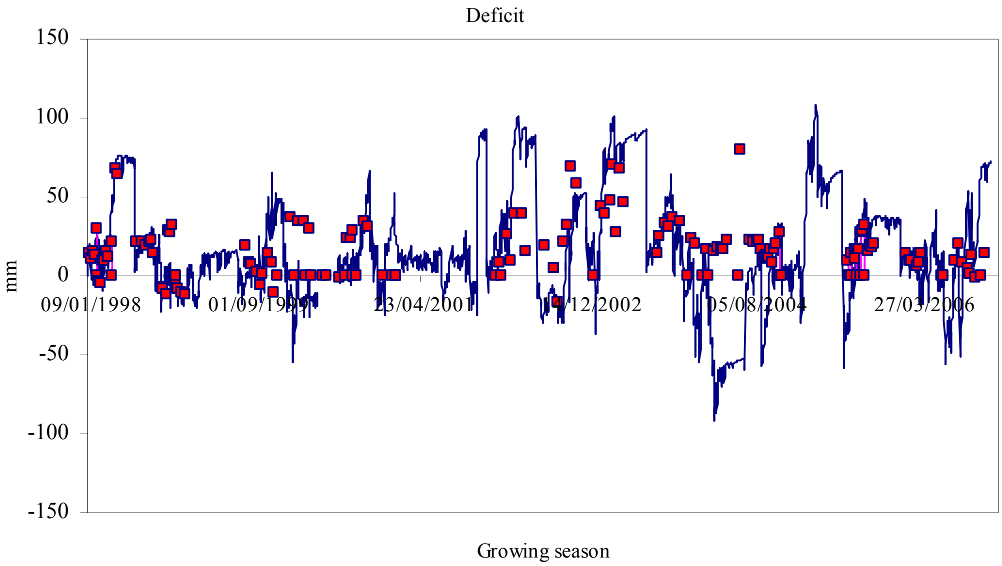

Figure B3. Simulated (solid lines) and measured (symbols) soil water deficit to field capacity (TWF, 1997/98-2006), positive values are deficit and negative values indicate profile wetter than field capacity

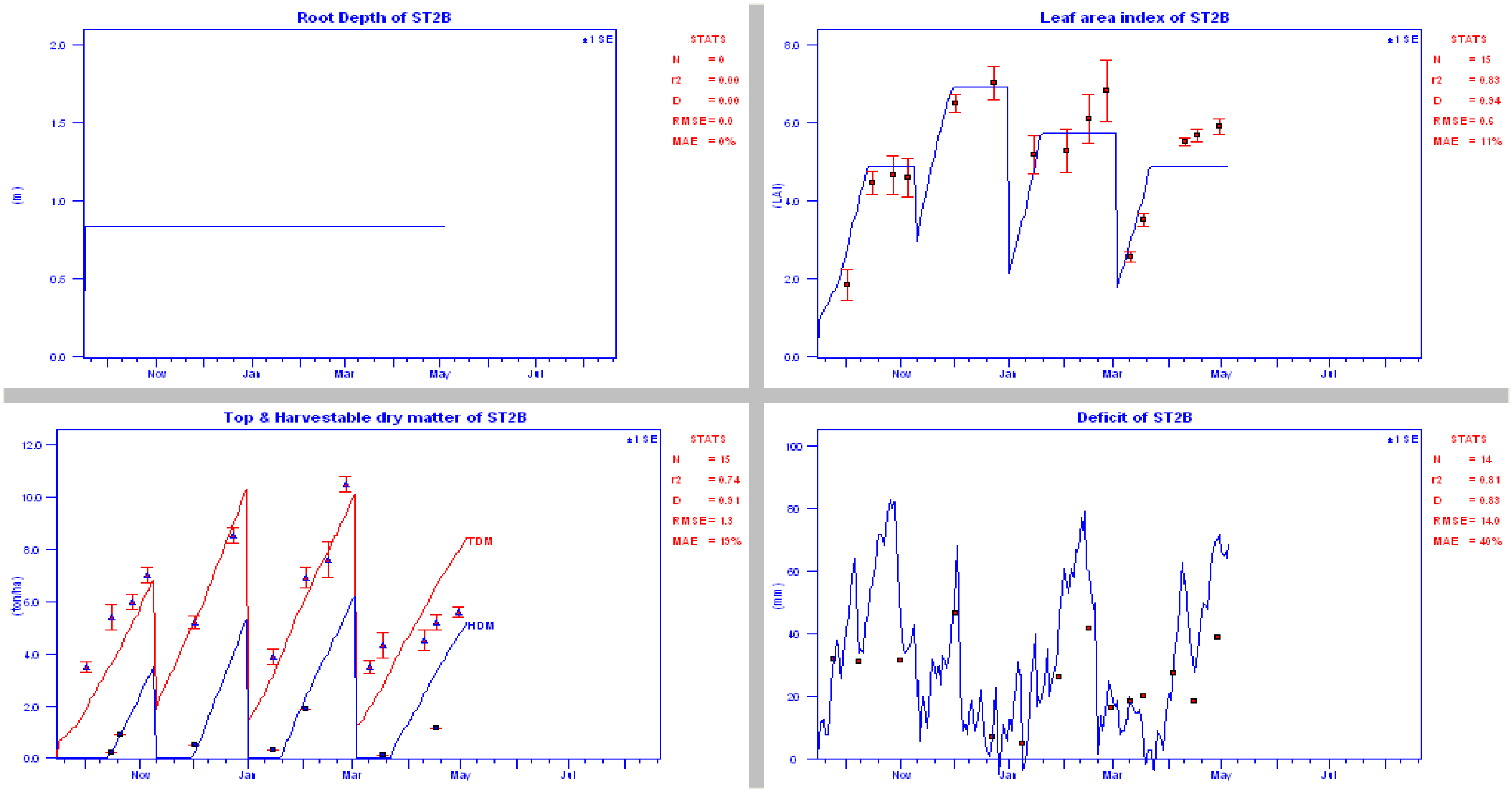

Figure B4. Simulated (solid lines) and measured values (symbols) of root depth (RD), leaf area index (LAI), top dry matter (TDM) and deficit to field capacity for Lucerne, September 2002 - May 2003

APPENDIX C

Table C1. Simulated seasonal values of the soil water balance components for each crop at the Syferfontein coal mine.

Crop	Growing period	Rainfall (measured) (mm)	Irrigation (measured) (mm)	Soil evaporation (simulated) (mm)	Crop transpiration (simulated) (mm)	Drainage (simulated) (mm)	Canopy interception (simulated) (mm)	Runoff (simulated) (mm)	Change in soil water storage (simulated) (mm)
Fescue (cv. Iewag)	01/10/2001 to 17/04/2002	574	321	174	522	65	78	0	56
	01/05/2002 to 31/5/2003	801	1 417	346	1 636	107	191	0	-62
	01/06/2003 to 31/05/2004	861	489	225	916	72	91	56	-10
	Total	**2236**	**810**	**745**	**1438**	**244**	**360**	**56**	**-16**
Lucerne-fescue (cv. Iewag)	01/10/2001 to 17/04/2002	574	278	121	659	21	91	0	-40
	01/01/02 to 31/5/2003	790	1 271	409	1203	54	209	121	65
	01/06/2003 to 31/05/2004	861	500	245	873	37	82	89	35
	Total	**2225**	**778**	**775**	**2735**	**112**	**382**	**210**	**60**
Fescue (cv. Demeter)	01/10/2001 to 17/04/2002	574	279	181	590	46	79	0	-43
	01/01/02 to 31/5/2003	828	1 797	320	1 818	265	221	0	-31
	Total	**1402**	**279**	**501**	**590**	**311**	**300**	**0**	**-74**
Eragrostis-ryegrass (cv. Iewag)	01/10/2001 to 17/04/2002	574	278	172	594	51	76	0	-41
	01/01/02 to 31/5/2002	340	478	279	416	73	58	0	-8
	Total	**914**	**756**	**451**	**1010**	**124**	**134**	**0**	**-49**
Kikuyu	01/09/02 to 31/5/2003	359	984	238	923	84	110	0	-12

Table C2. Simulated seasonal values of the salt balance components for each crop at the Syferfontein coal mine.

Crop and season	Salts added (measured) (Mg ha^{-1})	Salts runoff (simulated) (Mg ha^{-1})	Salts leached (simulated) (Mg ha^{-1})	Gypsum precipitated (simulated) (Mg ha^{-1})	Change in soluble salt content in the soil (simulated) (Mg ha^{-1})
Fescue (cv. Iewag) (from 01/10/2001 to 17/05/2004)	18.12	4.3	8.82	0.88	4.12
Lucerne-fescue (cv. Iewag) (from 01/10/2001 to 17/05/2004)	21.47	3	9.53	3.67	5.27
Fescue (cv. Demeter) (from 01/10/2001 to 17/04/2002)	7.00	0	0.57	0.95	5.48
Eragrostis-ryegrass (cv. Iewag) (from 01/10/2001 to 17/04/2002)	6.99	0	0.53	0.19	6.27
Average (from 01/10/2001 to 17/04/2002)	**13.39**	**1.825**	**4.86**	**1.42**	**5.28**