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

Report to the

Water Research Commission and Coaltech

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EXECUTIVE SUMMARY

Introduction

Mining in South Africa generates large volumes of mine wastewater that have the potential to adversely affect an already scarce water resource if not properly managed (Tanner et al., 1999). The type of wastewater emanating from mines depends largely on the chemical properties of the geological materials that come into contact with the water (Thompson, 1980). The concentrations of salts and other constituents frequently render such waters unsuitable for direct discharge to the river systems, except in periods of high rainfall when adequate dilution capacity is present and controlled release is permitted by the regulatory authorities (Pulles et al., 1996). Mine water treatment is a possible solution to prevent or minimize the pollution of water resources. However, it has become very expensive to treat the water to a condition acceptable for release into natural watercourses.

The potential of gypsiferous mine-water for use in crop irrigation was first evaluated in South Africa by Du Plessis (1983), using a steady-state chemical equilibrium model (Oster and Rhoades, 1975) to predict the amount of salt that leached, and could potentially contaminate groundwater. Over the last decade, quite considerable work has been done on the feasibility of irrigation with mine wastewaters (Jovanovic et al., 1998; Annandale et al., 1999b; Pretorius et al., 1999; Annandale et al., 2001; Annandale et al., 2002; Jovanovic et al., 2002; Jovanovic et al., 2004; Annandale et al., 2006). The use of gypsiferous mine wastewater in particular, presents an opportunity to stabilize dryland crop production and enable dry season production, whilst at the same time providing a cost-effective method of minimizing excess mine drainage.

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). 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 discharges 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, for instance Kleinkopjé Colliery (Witbank, Mpumalanga), currently has some 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).

A current concern in the water-scarce Olifants River Catchment is that if all excess mine-water is used for irrigation in future, then the basic ecological and domestic needs of downstream water users may not be met. It is likely that a compromise will need to be agreed between all stakeholders that provides for these basic needs, but also allows for irrigation with mine-waters as a cost effective way of providing food security and employment in the future, as the region diversifies its economy away from coal mining.

Objectives of the project

The objectives of the project were:

- To determine the impact of irrigation with several mine water qualities/soil combinations on soil conditions and groundwater quality;
- To further develop and refine the SWB model to better predict gypsum precipitation, crop response, soil water and salt balance, and leachate water quality under irrigation with saline mine water;
- To predict the likely long-term impact of irrigation with gypsiferous water on the groundwater system;
- To determine whether these waters can be used to produce crops on a commercial basis; and
- To predict the sustainability of irrigation with gypsiferous mine water using the data collected from the field trial.

Materials and methods

The study was carried out on three mines: Kleinkopjé Colliery near Witbank, New Vaal Colliery near Vereeniging, and Syferfontein near Secunda. All sites were centre pivot irrigated. The Institute for Groundwater Studies at the University of the Free State was appointed to establish and undertake groundwater monitoring at these Collieries to ascertain the effect of the irrigation with mine water on groundwater levels and quality.

Kleinkopjé is in Mpumalanga (Latitude 26^{o}28'S, Longitude 28^{o}75'E, Altitude 1570 m), and was included in the previous WRC project. Pivot Major (30 ha) is undermined, and Pivot Tweefontein (20 ha), abbreviated as TWF, is on rehabilitated open cast. 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. New Vaal Colliery is in Gauteng (Latitude 26^{o}42' S, Longitude 27^{o}55' E, Altitude 1432 m), and is located on the northern bank of the Vaal River. The 10 ha field is undermined and close to the river. Syferfontein is in Mpumalanga (Latitude 23^{o}64' S, Longitude 29^{o}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.

All the fields except Pivot Four, experienced poor internal drainage problems, which reduces yields and could affect the accumulation of salts. Pivot TWF shows a marked reduction in hydraulic conductivity at the soil-spoil interface, and this has resulted in regions of water-logging, especially in the summer when we have 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 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.

The irrigation water quality was monitored throughout the trial period both by the mines and the mine water irrigation research team at the University of Pretoria. The EC of the irrigation water used at 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. Sulphate levels over this period climbed from 1500 mg l^{-1} to 3000 mg l^{-1}. Tweefontein Pan is the water source for Pivots Four and TWF, and here the EC started off a little higher than the water used for Major at around 300 mS m^{-1} 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. Sulphate levels over this period went from 2500 mg l^{-1} to 4000 mg l^{-1}.

At New Vaal, the irrigation water used was dominated by SO_4, and to a lesser degree by Na. On the other hand, Ca, Cl, Mg and K were in smaller quantities in the irrigation water. At Syferfontein, Na and SO_4 were the dominant ionic species while Ca, Mg, Cl and K were in small quantities in the irrigation water. The Syferfontein water had a higher EC than New Vaal.

Monitoring

Plant samples were taken at critical crop growth stages to determine possible nutritional deficiencies to be corrected through fertilization. Amounts of irrigation and rainfall were recorded with tipping bucket (raingauges). Volumetric soil water content at each site was monitored with a neutron water meter. 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). Ceramic cup water samplers at depths of 0.30, 0.60 and 0.90 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 were also installed at a later stage to a depth of 0.30, 0.60 and 0.90 m to get additional soil water samples. Runoff weirs designed by Prof Lorentz of UKZN were constructed to monitor the quantity and quality of runoff at the site. Boreholes were drilled so that groundwater levels and qualities could be monitored every 2 to 6 months. Boreholes were not needed at field TWF (Kleinkopjé Colliery), which is on rehabilitated land.

General findings

Crop production

Maize yield obtained were lower than dry land produced crops, particularly on the rehabilitated lands. This reduction in yield could be due to the rapid increase in EC of the irrigation water and poor drainage of the irrigated sites, whilst wheat production was not affected by the water quality on both virgin and rehabilitated lands. Wheat is reportedly more tolerant to soil salinity than maize (Maas, 1986), but maize yield reduction starts once the EC of the irrigation water reaches 200 mS m^{-1}. The difference in yields obtained between seasons could be related to pests and diseases, rainfall and temperature, and the amount of irrigation water applied. For instance, maize crops were damaged in the 2000/2001 season at TWF and Pivot Four, when an excess of herbicide (up to 3 times the planned rate) was mistakenly applied to all three pivots by the farming company. This resulted in severe yield losses. The expected yields were between 6 and 10 Mg ha^{-1} for the short-season cultivar.

In Syferfontein annual and perennial pasture crops were grown and the yield obtained was satisfactory for the trial period. At New Vaal field crops of maize, wheat and soybean, and

vegetables like peas, sweetcorn and pumpkin were planted. The yield obtained was not satisfactory for the trial period, which is related to poor irrigation site selection. 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 failures, but rather the long periods of waterlogging.

During the trial period, larger volumes of water were irrigated during the winter seasons than during summer months. No symptoms of foliar injury due to centre pivot sprinkler irrigation with Na_2SO_4 and gypsiferous water were observed for all crops.

Plant nutrition

The aims of the analyses were to evaluate nutrients in the soil-plant system and to evaluate the effectiveness of fertilizers applied to the mine water irrigated soils. The results were interpreted by the Sufficiency Range (SR) approach; the SR is defined as the range in concentration that can result in 95 to 100% of maximum yield (Reuter and Robinson, 1986). The SR given is related to a particular crop, plant part, and time of sampling. In general, the results indicated that the nutrient concentrations were found to be within the SR.

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. The nutrient concentrations within plants were also not uniform and varied with time through the growing period. In all Pivots, maize leaf analysis showed a decrease in K levels starting from the end of summer 2003/04. In the same period, however, ammonium acetate extractable K (K-NH_4Aoc), in the soil was observed to increase. The suppressed uptake of K in the plants could be related to the high concentration of Ca and Mg in the solution, this was particularly coincidental with an increase in Mglevels, which suggests Mg suppressed K uptake to some extent.

The high calcium levels in irrigation water did not seem to suppress uptake of essential nutrients by potatoes. Good processing tuber quality was realized, 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.

At New Vaal, plant samples were only taken from parts of the field that where not waterlogged, as analysis of plant tissue from drowning crops would be meaningless. The possibility to incur deficiency and toxicities 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 quality of the Na_2SO_4 rich irrigation water on forage quality of the planted pastures (fescue and lucerne) was negligible for the growing period.

Plant analysis results are useful to diagnose nutrient toxicities and to reveal imbalances between nutrients that can cause unfavorable 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.

Normal agronomic fertilizer guidelines may, in many instances, not be applicable to crops irrigated with waters enriched with certain ions.

Soil chemical properties

Seasonal soil pH data of the pivots showed a general increasing tendency. The pH (H_2O) increased slightly during the course of the irrigation trial in Pivots Major, Pivot Four and TWF. EC_e fluctuated depending on seasonal rainfall, as well as on the irrigation and rainfall events prior to soil sampling. At Pivot Four and TWF at depths >60 cm, EC_e exceeded 400 mS m^{-1} in 2005. According to Maas and 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. The concentration of Ca, Mg and S increased at Pivot Major and Pivot Four compared to samples collected outside the pivots. At Kleinkopjé, more SO_4 is added through irrigation than Ca and Mg. At New Vaal, the sandy nature of the soil is able to allow water and nutrients to run through the profile very quickly. EC_e fluctuated in the range of 80-150 mS m^{-1}. According to Maas and Hoffman (1977), most sensitive crops can be grown at this range of salinity.

Field scale modelling of crop growth, soil water and salt balances

At Kleinkopjé Colliery, crops were rotated for 15 seasons at Major and 16 seasons at TWF. Each season's data was used to simulate the soil water and salt balance for these pivots. Only 12 seasons for Pivot Four were simulated, as this site was established later than the other two. At Syferfontein 9 pasture harvests and at New Vaal 7 crop rotations were simulated.

Improvements to SWB were made to be able to simulate multiple crop rotations, and the growth and harvest cycles of pastures. The SWB model was refined and successfully validated by comparing simulations to measurements of crop growth, soil water and salt redistribution obtained in the field trial. The simulation of crop growth (canopy cover) can be considered to be sufficiently accurate to give reasonable estimates of the soil water balance. The model predicted soil solution concentrations were reasonably close to measured values. This indicates the predictive capacity of the model for long-term impact assessments of irrigation with gypsiferous mine waters.

Thermodynamic proof, in the form of calculated Ca and SO_4 activities, showed that gypsum is present in the soils irrigated with neutralised acid mine drainage. The saturation ranges were similar to that reported in literature for natural gypsiferous soils. SWB underestimated the mass transfer of Ca and SO_4 to the sub-soil (depth >30 cm). The temporal stability of gypsum in the top

30 cm, the interface with the atmosphere, is overestimated by SWB, probably because tillage (surface soil mixing between crops) is not simulated. However, S and Ca content in the top 30 cm, as a fraction of the S and Ca in the 120 cm soil profile, is still the greatest.

Surface runoff

The runoff curve number is specific for each site, as soils, topography and rainfall are extremely important in determining runoff. In order to get reliable simulations of the components of the water and salt balance, runoff measured at Pivot TWF, Major and Syferfontein during the trial period were used to validate the runoff subroutine of SWB. SWB, once calibrated, simulated runoff to be quite close to the measured values.

Salt runoff

The runoff data from TWF and Syferfontein was used to validate the salt runoff subroutine of the model. SWB somewhat under estimated salt runoff and will receive attention in future. However, the model should still be able to simulate the field scale salt balance well enough for initial estimates of regional scale salt balances.

The impact of large scale irrigation on groundwater resources

Irrigating large areas with gypsum-rich mine wastewater could be feasible and sustainable if careful attention is paid to the specificity of each situation. It is also clear, however, 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 salinisation of the rootzone. This will necessitate the installation of expensive drainage systems, or ultimately, result in the failure of the irrigation scheme. In order to improve on the analyses and results presented, it is essential that soil water balance and groundwater models are coupled in a way that includes the feedback needed between them to more accurately describe the system to be managed. This will ensure that irrigation with gypsiferous mine-water can be seriously 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. The importance of proper site characterisation for the successful application of mine water irrigation is also evident.

Groundwater monitoring

The water levels at all the pivots have varied very little over time. The water levels at New Vaal are deeper than most other irrigation schemes. This can be attributed to the high conductivity in the soils above the clay layers, resulting in faster drainage towards the river. The water levels at the other irrigation sites are very shallow due to the increased recharge locally.

The overall water quality trend in the deeper aquifer indicates that the water quality has not shown significant deterioration over the monitoring period.

The irrigation water has, as yet, shown a minimal impact on the groundwater. Some exceptions occur, but the boreholes lying outside the pivot areas have all shown no meaningful change in water quality from leaching from the irrigated area. This implies very slow movement of the constituents in the irrigation water, and that these are attenuated by different mechanisms between the surface and the aquifers, often in the clay layers present. The amount leaching through the soil is small enough to be easily diluted by the regional groundwater flow. It thus appears that the soil type and morphology plays a very important role in the vertical movement of the irrigation water constituents.

It is not known how long this accumulation of salts in the upper layers can continue before leaching into the underlying aquifers will occur, but in the short to medium term, the evidence from the groundwater monitoring shows that irrigation with mine water does not hold significant threats to regional groundwater quality.

The trial pivot sites investigated thus far indicate that in the short to medium term the groundwater impacts are limited, and more importantly, localised. Research is underway, through the Water Research Commission and Coaltech 2020, to establish the impacts of mine water irrigation on the groundwater resources. For consideration of future large-scale irrigation with mine water, the following aspects should be noted:

Site selection is very important. Careful consideration of the applicability of the site to irrigation, local geology and geohydrological properties, the proximity of sensitive water users for 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.

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 DWAF, to fix different levels or guidelines at which action should be taken to mitigate the impact or even to cease irrigation activities, must be part of such a monitoring plan.

The regulatory framework regarding the “polluter pays”-principle should be negotiated between the mine providing the water, the regulator and the party irrigating with the mine water.

Detailed guidelines on the site selection, monitoring guidelines and operational considerations from a groundwater perspective will be provided by the outcomes of WRC project K5/1507 that will be completed in 2007.

Conclusions and recommendations

Crop production under irrigation with mine water rich in Ca and SO_4 is feasible and sustainable, if properly managed. No symptoms of foliar injury due to centre pivot sprinkler irrigation with gypsiferous mine water were observed for all crops. The presence of high Ca and Mg in the water, however, suppressed the uptake of K by the plant. This could be related to the physical properties of the soil and low plant available water that hampered nutrient uptake even though the

soil had sufficient nutrients. This could be corrected by regular application of K containing fertilizer and following proper irrigation management.

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 is 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.

The sustainability of irrigation with gypsiferous mine water on a commercial scale was assessed. The data collected were also used to validate the SWB model, which has been used for long-term predictions of the likely impact of irrigation with gypsiferous mine-water on soil and groundwater resources. Crops like sugarbeans, wheat, maize, potatoes and pastures were very successfully produced. Land preparation and fertilization management are critical for successful crop production, especially on rehabilitated soil. In the short to medium term (eight years) irrigation with gypsiferous mine-water proved to be sustainable with a negligible impact on groundwater. In the field trial carried out at Kleinkopjé Colliery, several crops were successfully irrigated with gypsiferous mine water on a commercial scale. No significant impact on soil, surface and groundwater resources was observed, at least in the short-medium term (eight years).

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. Unfortunately, the waters do 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 mines irrigated twice volumes of water during winter seasons than during summer months in all the sites. The opportunity is, therefore, greater for the mines to use water in winter than in summer.

The SWB model was refined and successfully validated by comparing simulations to measurements of crop growth, soil water balance and salt redistribution obtained in the field trial. The simulation of crop growth (canopy cover) can be considered to be sufficiently accurate to give reasonable estimates of the soil water balance. The model also predicted soil solution concentrations reasonably well, and this gives some confidence in the predictive capacity of the model for long-term impact assessments of irrigation with saline mine waters. SWB model outputs should, therefore, be useful to ground- and surface water modellers interested in predicting the impact of large-scale mine water irrigation on water resources.

The overall water quality trend in the deeper aquifer indicates that the water quality has not shown significant deterioration over the monitoring period. The irrigation water has, as yet, therefore shown a minimal impact on the groundwater. Some exceptions did occur, but the boreholes lying outside the pivot areas have all shown no meaningful change in water quality as a result of leaching from the irrigated areas. This implies very slow movement of the constituents in the irrigation water, and that these are attenuated by different mechanisms between the surface and the aquifers, often in the clay layers present. The amount leaching through the soil is also small enough to be easily diluted by the regional groundwater flow. It thus appears that the soil

type and morphology plays a very important role in the vertical movement of the irrigation water constituents, at least in the short to medium term.

The groundwater impact seems to be minimal, manageable and reversible. If large-scale irrigation is permitted, threshold groundwater values should be established to determine if irrigation should be allowed to proceed, or whether mitigation measures are required. It is not known how long this accumulation of salts in the upper layers can continue before leaching into the underlying aquifers will occur, but in the short to medium term, the evidence from the groundwater monitoring shows that irrigation with mine water does not hold significant threats to regional groundwater quality.

The likely long-term impact of irrigation with gypsiferous water on the groundwater system was also assessed in this project by running long-term simulations with SWB and groundwater model. Irrigating large areas with gypsum-rich mine wastewater could be feasible and sustainable if careful attention is paid to the specificity of each situation. It is also clear, however, 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, waterlogging and salinisation of the root zone. This will necessitate the installation of expensive drainage systems, or ultimately, result in the failure of the irrigation scheme. In order to improve on the analyses and results presented, it is essential that soil water balance and groundwater models are coupled in a way that includes the feedback needed between them to more accurately describe the system to be managed. This will ensure that irrigation with gypsiferous mine-water can be seriously 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. The importance of proper site characterisation for the successful application of mine water irrigation is also evident.

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AMD	Acid Mine Drainage
Ave	Average
CP	Crude Protein
cv	Cultivar
DAP	Day After Planting
DM	Dry matter
EC	Electrical conductivity
EC_e	Saturated soil salinity
FAO	Food and Agricultural Organization
HDM	Harvestable dry matter
IAPs	Ion Activity Product
IGS	Institute of Groundwater Studies
K_{sp}	Solubility product
LAI	Leaf area index
$\log\frac{IAP}{K_{sp}}$	Saturation index
MAE	Mean annual evaporation (mm)
MAP	Mean annual average rainfall (mm)
MAR	Mean annual runoff (mm)
Max	Maximum
Min	Minimum
NAMD	Neutralised Acid Mine Drainage
NWM	Neutron water meter
PET	Potential evapotranspiration
SA	South Africa
SAR	Sodium Adsorption Ratio
SR	Sufficiency Range

SWB	Soil Water Balance
TDM	Top dry matter
TWF	Tweefontein
UKZN	University of KwaZulu-Natal
US-SCS	United State-Soil Conservation Service
WRC	Water Research Commission

CHAPTER 1

1. INTRODUCTION

1.1 Statement of the problem

Mining in South Africa generates large volumes of mine wastewater that have the potential to adversely affect an already scarce water resource if not properly managed (Tanner et al., 1999). Disposal of mine wastewater is a worldwide problem, occurring wherever operating mines, as well as closed underground and opencast workings, are found (Pulles et al., 1995). The type of wastewater emanating from mines depends largely on the chemical properties of the geological materials that come into contact with the water (Thompson, 1980). The concentrations of salts and other constituents frequently render such waters unsuitable for direct discharge to the river systems, except in periods of high rainfall when adequate dilution capacity is present, and controlled release is permitted by the regulatory authorities (Pulles et al., 1996). In many cases the mine effluent is gypsiferous, meaning that it is dominated by calcium and sulphate ions. This occurs when acid mine drainage (AMD) is neutralized by naturally occurring calcite or dolomite, or by active liming, which may be required to correct pH and precipitate out metals (Van Staden, 1979).

Mine water treatment is a possible solution to prevent or minimize the pollution of water resources. However, it has become very expensive to treat the water 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.

The potential of gypsiferous mine-water for use in crop irrigation was first evaluated in South Africa by Du Plessis (1983), using a steady-state chemical equilibrium model (Oster and Rhoades, 1975) to predict the amount of salt that leached, and could potentially contaminate groundwater. Simulation results indicated that irrigating with gypsum-rich water would result in lower soil- and percolate salinity compared to 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 mine-water quality for irrigation (Du Plessis, 1983).

Over the last decade, considerable work has been done on the feasibility of irrigation with mine waste waters (Jovanovic et al., 1998; Annandale et al., 1999b; Pretorius et al., 1999; Annandale et al., 2001; Annandale et al., 2002; Jovanovic et al., 2002; Jovanovic et al., 2004; Annandale et al., 2006) The use of gypsiferous mine wastewater in particular, presents an opportunity to stabilize dryland crop production and enable dry season production, whilst at the same time providing a cost-effective method of minimizing excess mine drainage. By irrigating with gypsiferous wastewater, a large fraction of the salts can be removed from the water system through precipitation of gypsum in the soil profile, as the soil solution is concentrated by root water uptake. This reduces the likelihood of off-site environmental impact. Comparisons of the capital costs of irrigation as a mine-water management option, to those of several treatment options, show irrigation to be lower by an order of magnitude. Running costs are not only covered by the income generated from the sale of produce, but

profits can be made and jobs created, which is particularly important in the post-closure period.

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). 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 discharges 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, for instance Kleinkopjé Colliery (Witbank, Mpumalanga), currently has some 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).

The South African National Water Act (No. 36 of 1998) classifies irrigation, including irrigation with excess mine-water, as a controlled activity that can only be practiced under license. A current concern in the water-scarce Olifants River Catchment is that if all excess mine-water is used for irrigation in future, then the basic ecological and domestic needs of downstream water users may not be met. It is likely that a compromise will need to be agreed between all stakeholders that provides for these basic needs, but also allows for irrigation with mine-waters as a cost effective way of providing food security and employment in the future, as the region diversifies its economy away from coal mining.

1.2 Background

The use of gypsiferous mine water for irrigation was investigated in a previous Water Research Commission (WRC) project, where a wide range of crop and pasture species were screened for tolerance to irrigation with lime-treated AMD at Landau Colliery (Anglo Coal, Witbank, Mpumalanga Province) from 1993 to 1996 (Barnard et al., 1998; Jovanovic et al., 1998). The results of the screening trial indicated that:

- Higher crop yields can be obtained under irrigation with mine water compared to dry land production and dry season production is possible.
- No foliar injury was observed due to sprinkle irrigation with gypsiferous mine water.
- 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.
- Soil salinity increased compared to the beginning of the trial, but the values of soil saturated electrical conductivity fluctuated around 200 mS m^{-1}, which is typical for a saturated gypsum solution.

In a follow-up WRC project, commercial production of several crops irrigated with gypsiferous mine water was tested in a field trial at Kleinkopjé Colliery (Anglo Coal, Witbank, Mpumalanga Province) from 1997 to 2000 (Annandale et al., 2001). Data collected in the field trial at Kleinkopjé were used to validate the Soil Water Balance (SWB) model (Annandale et al.,

1999b) to be used for long-term predictions of the impact of irrigation with gypsiferous mine water on soil and groundwater resources. The results of this project indicated that:

- Crops like sugarbeans, wheat and maize can be commercially produced under irrigation with gypsiferous mine water.
- Land preparation and fertilization management are critical for successful crop production, especially on rehabilitated soil.
- The SWB model was validated for the sites where the field trial was carried out.
- The use of gypsiferous mine water for irrigation proved to be sustainable in the short term (three years) with negligible impact on the groundwater.
- The system is flexible and can be managed depending on the objectives that one wants to achieve, be it maximum crop production, water use, job creation, economic return or maximum gypsum precipitation and minimum salt leaching.

The main recommendations emanating from this project were:

- To continue to evaluate fields irrigated with this water to confirm findings over a longer time period than three years.
- To initiate trials at new sites that will have different climates, water qualities, soils and cropping systems in order to extend the scope of the SWB model and possibly explore the feasibility of alternative management practices, like for example serial biological concentration.
- To improve the SWB model for long-term predictions of the soil water and salt balance, in particular by introducing the convection/dispersion equation for solute movement and by improving the chemical equilibrium subroutine.
- To focus on the impact of irrigation with gypsiferous mine water on groundwater quality.

Based on these recommendations, this WRC project was initiated in 2001, as a logical development of this technology. The research was hereby extended to new soils, waters and crops in order to validate SWB for different environmental conditions. It was envisaged that the final product would be an improved version of SWB to be used by different mines and/or regulatory authorities for long-term predictions of the effect of various management scenarios on soil water and salt balances. The results generated with SWB should indicate the feasibility, and facilitate the management of irrigation with mine wastewater. The output of SWB can also be used by groundwater modellers to predict the long-term effect of the leachate on groundwater quality at different sites (Annandale et al., 2001). In turn, output of both the root zone and groundwater models, could be used by surface water resource modellers to predict the impact of large scale, long-term irrigation on surface water bodies. The outputs of such simulations should be invaluable in facilitating informed decision making on this important topic.

1.3 Objectives of the project

The objectives of the project were:

1) To determine the impact of irrigation with several mine water qualities/soil combinations on soil conditions and groundwater quality;
2) To further develop and refine the SWB model to better predict gypsum precipitation, crop response, soil water and salt balance, and leachate water quality under irrigation with saline mine water;
3) To predict the likely long-term impact of irrigation with gypsiferous water on the groundwater system;
4) To determine whether these waters can be used to produce crops on a commercial basis; and
5) To utilize the information gained in Aims 1) to 4) to predict the sustainability of irrigation with gypsiferous water.

1.4 Approach

The general approach was to establish several commercial scale experimental sites that could offer a range of soil, crop and water quality conditions. This was to determine the impact of irrigation with several mine water qualities/soil combinations on soil conditions and groundwater quality (Objective 1) and was addressed in Chapters 2 to 5. To this end, four experimental sites were established on the Kleinkopjé, Syferfontein, New Vaal and Optimum Collieries. Kleinkopjé (Anglo Coal) included three center pivot irrigated fields of between 20 and 30 ha each, and at New Vaal, the other Anglo Coal mine in this study, a single 10 ha pivot was set up. The Sasol mine, Syferfontein, had a 20 ha pivot site, and at Optimum (BHP Billiton), two 30 ha irrigated fields were established.

Farming companies operating close to the mine, or a representative from the mine in the case of Syferfontein, were identified to take responsibility for cropping the irrigated fields. They were also expected to keep records of farming activities. This was to determine whether these waters could be used to produce crops on a commercial basis (Objective 4), which is addressed in chapter 3 and 4. Crops were selected depending on the interest of the mines and/or farmers, and fortunately this resulted in quite a wide variety of cropping systems to study. Agronomic field crops were chosen at Kleinkopjé and initially at New Vaal. Towards the end of the trial, an intensive cycle of 3 vegetable crops (peas / sweetcorn / pumpkins) was attempted at New Vaal, but waterlogging due to poor site selection was problematic. 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, the field trials at Syferfontein were discontinued after two years of monitoring. Inclusion of Optimum presented an opportunity to study a pasture system on rehabilitated land that seems to have more favourable internal drainage characteristics than those encountered at Kleinkopjé. Unfortunately, due to logistical reasons, these sites were set up and established to fescue and clover only at a very late stage, and therefore no data for this colliery is presented in this report.

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

(Objective 5, addressed in Chapters 3 to 5) as well as to validate the chemical equilibrium subroutine of the SWB model (Objective 2, which is addressed in Chapter 6). Kleinkopjé generates two waters of similar qualities 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 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. At Tweefontein Pan, the EC started off a little higher than the water used for Major at around 300 mS m^{-1} 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. Syferfontein generates quite saline water (electrical conductivity or EC around 330 mS m^{-1}) with high concentrations of Na and SO_4. It is, of course, difficult to precipitate gypsum in the profile with this 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. Optimum generates the least saline water, with the EC around 90 mS m^{-1}, which is predominantly rich in $CaSO_4$ with some Mg, Na and Cl.

We were also fortunate in that we were able to monitor crop response on a wide range of soil types. Soils ranged from very sandy (<10% clay) at New Vaal to a very heavy clay (>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 soil water and salt balance, crop growth and groundwater qualities under these widely varying conditions, and then to attempt to model the dynamics of the system. Long-term simulations were then carried out and used as input into a groundwater model to illustrate the possible effect of large-scale irrigation on groundwater resources (Objective 3), which is addressed in Chapter 7.

CHAPTER 2

2. FIELD SITES, MONITORING AND MODELLING

Introduction

In this Chapter, a brief description of the field sites included in this study, the monitoring undertaken and the modelling effort, is presented.

For the *field site* description, we allude to the location and experimental layout, the soil conditions, irrigation water qualities and cropping systems. This will highlight the wide range of conditions investigated in this study. No details are given here for Optimum, as no data from these fields is presented in this report due to the late start-up of this site.

Under *monitoring*, we describe the equipment used and the measurements taken on atmospheric evaporative demand, crop growth and nutritional status, soil water balance components, salt balance measurements and groundwater monitoring.

Finally, in the brief description of the *modelling* effort, the approach taken to model the root zone soil water and salt balance, is given.

2.1 Field site location and experimental layout

Three mines were included in this study, Kleinkopjé Colliery near Witbank, New Vaal Colliery near Vereeniging, and Syferfontein near Secunda. All sites were centre pivot irrigated. The Institute for Groundwater Studies at the University of the Free State was appointed to establish and undertake groundwater monitoring at New Vaal Colliery, Syferfontein Colliery and two irrigation sites at Kleinkopjé Colliery, to ascertain the effect of the irrigation with mine water on groundwater.

2.1.1 Kleinkopjé

This Anglo Coal mine is in Mpumalanga Latitude 26^{o}28'S, Longitude 28^{o}75'E, Altitude 1570 m), and was included in the previous WRC project. Pivot Major (30 ha) is undermined, and Pivot Tweefontein (20 ha), abbreviated as TWF, is on rehabilitated open cast. 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 2.1 shows the position of the pivots (Pivot Major and Pivot Four) and Figure 2.2 shows the experimental layout of Pivot Major, Pivot Four and Pivot TWF. The two virgin irrigation sites are being monitored for groundwater studies (Pivot Major and Pivot Four). Figure 2.2 includes the position of groundwater monitoring boreholes, 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.

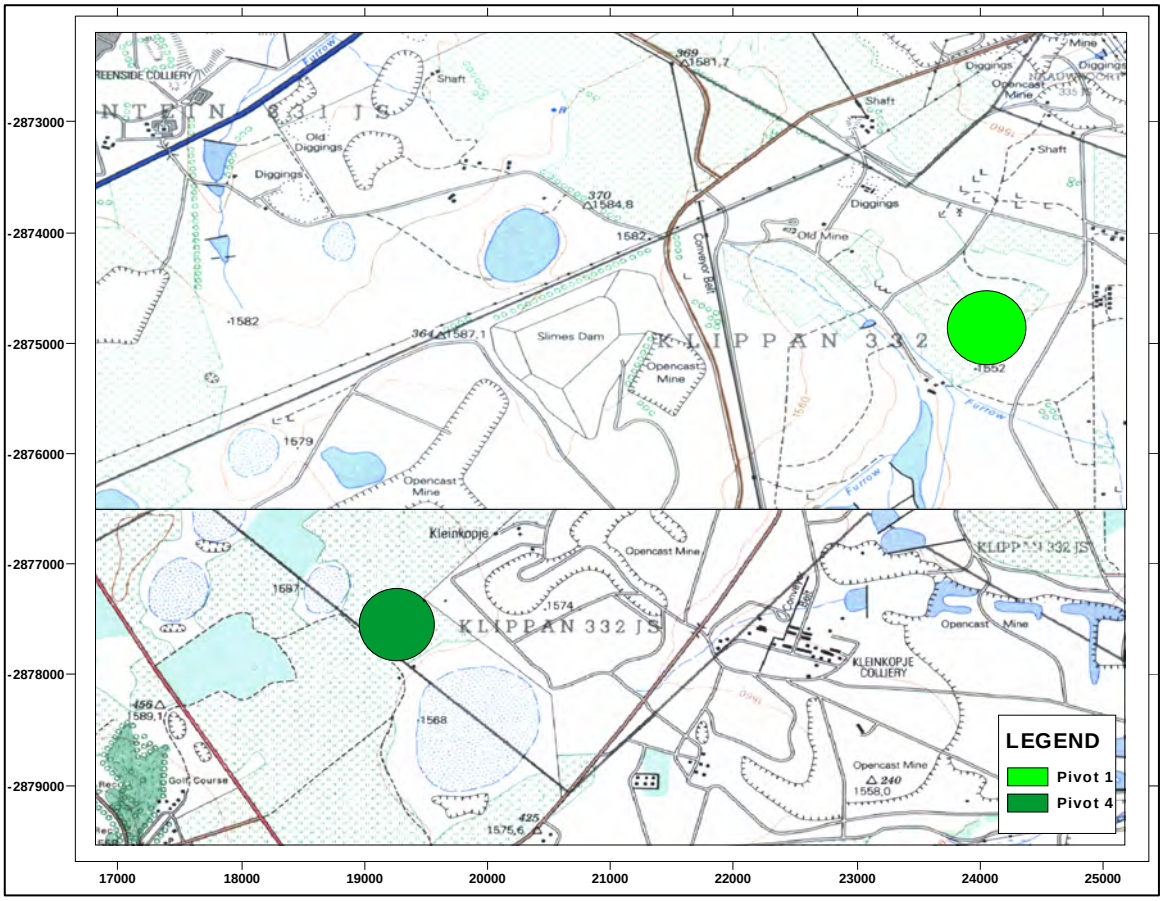
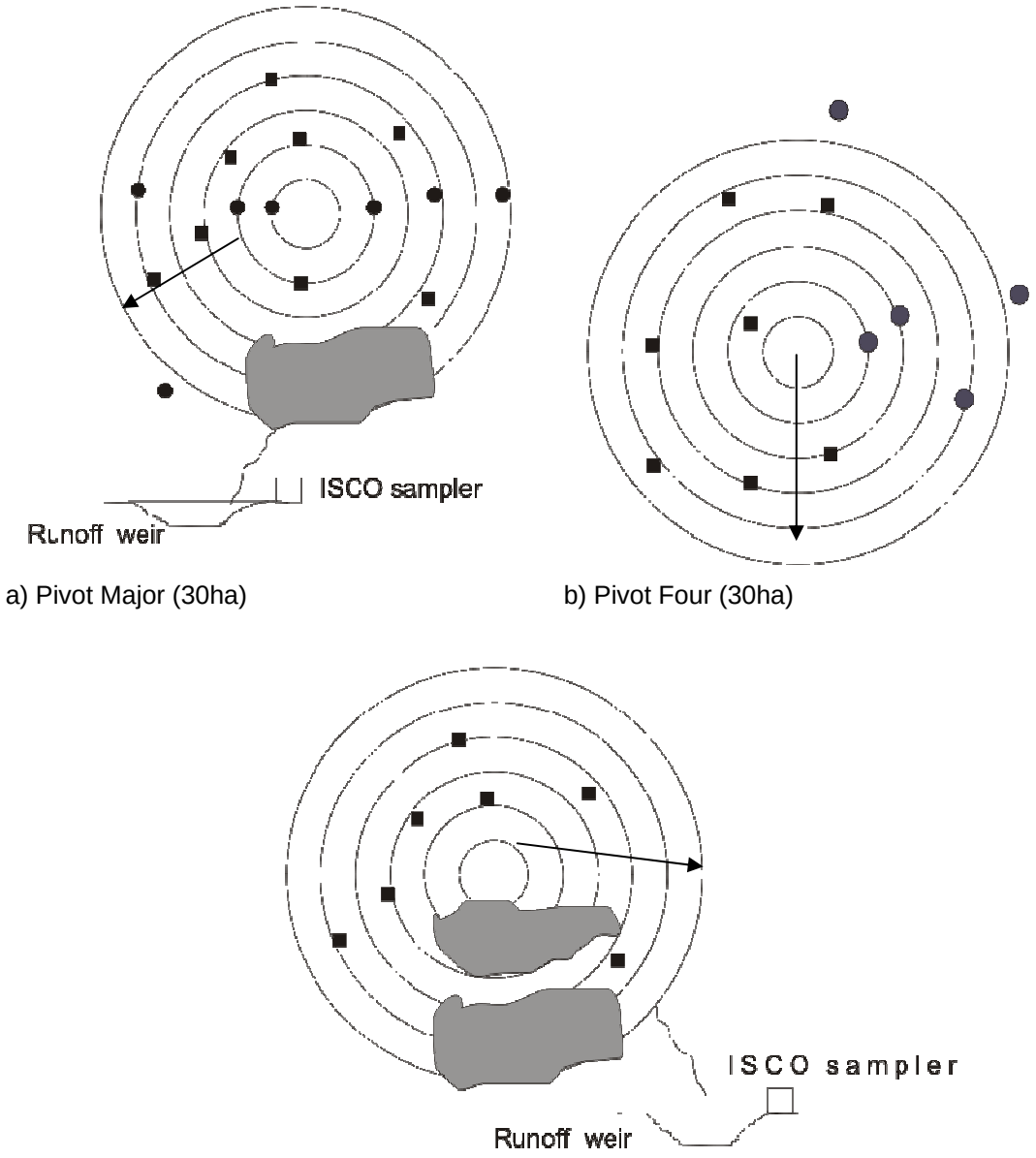


Figure 2.1 Topographic map of the Kleinkopjé area, indicating the position of Pivot Major and Pivot Four.



a) Pivot Major (30ha)

b) Pivot Four (30ha)

c) Pivot TWF (20ha)

Figure 2.2 Experimental layout of the irrigated fields at Kleinkopjé.

Surface Hydrology

The annual average rainfall (MAP) for the greater catchment area B11G (368 ha) is 698 mm (SA Weather Service - Rainfall station Witbank no. 0515412-2). The mean annual evaporation (MAE) for the area is 1600 mm, and the mean annual runoff (MAR) is 36 mm (Midgley et al., 1994). Annual baseflow is calculated at 13 mm.

Geology

Kleinkopjé Colliery lies in the Springs-Witbank Coalfield and is flanked by the Highveld and Ermelo Coalfields. The coalfield extends over a distance of approximately 180 km from the Brakpan/Springs area in the west to Belfast in the east, and about 40 km in a north-south direction. It is currently the most important coalfield in the country.

2.1.2 New Vaal

This Anglo Coal mine is in Free State (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 undermined and close to the river. Figure 2.3 shows the position of the field and Figure 2.4 shows the experimental layout of the Pivot. Monitoring at this site started in November 2001. Unfortunately, the positioning of this site was inappropriate, as internal drainage problems plagued both the farmers and researchers.

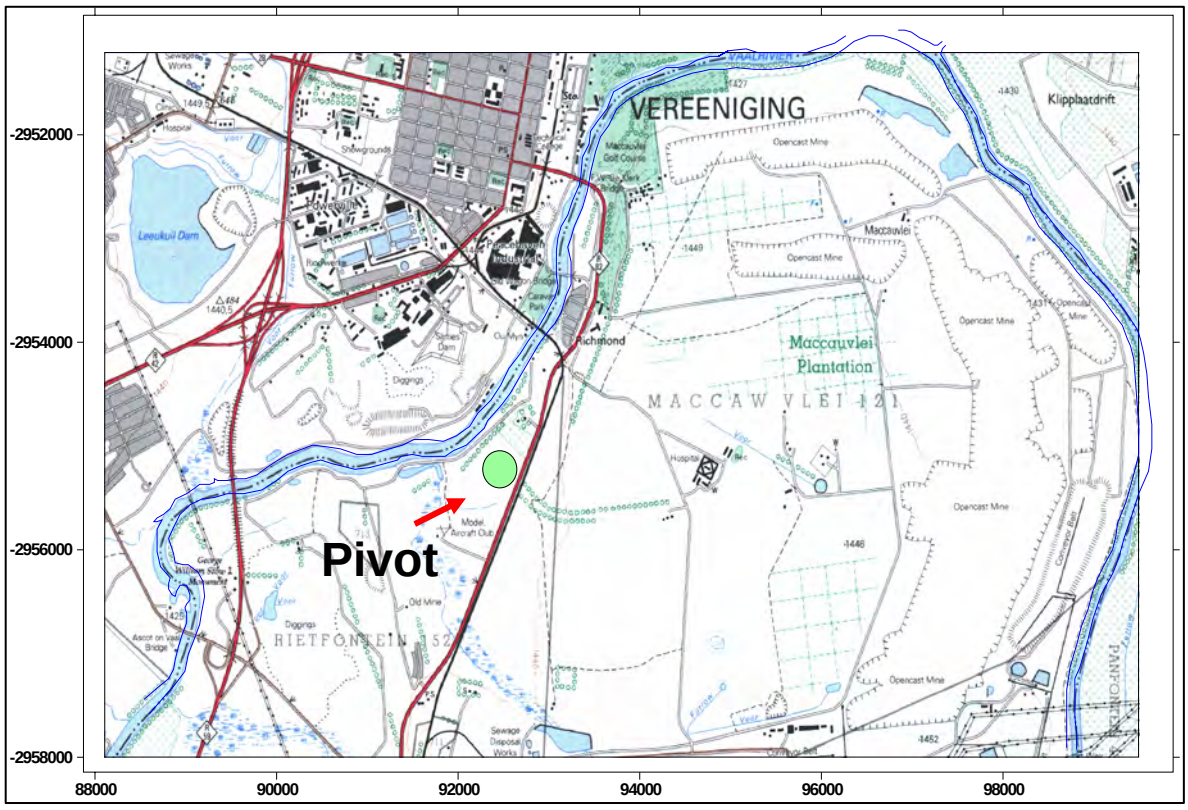


Figure 2.3 Topographic map of the New Vaal area.

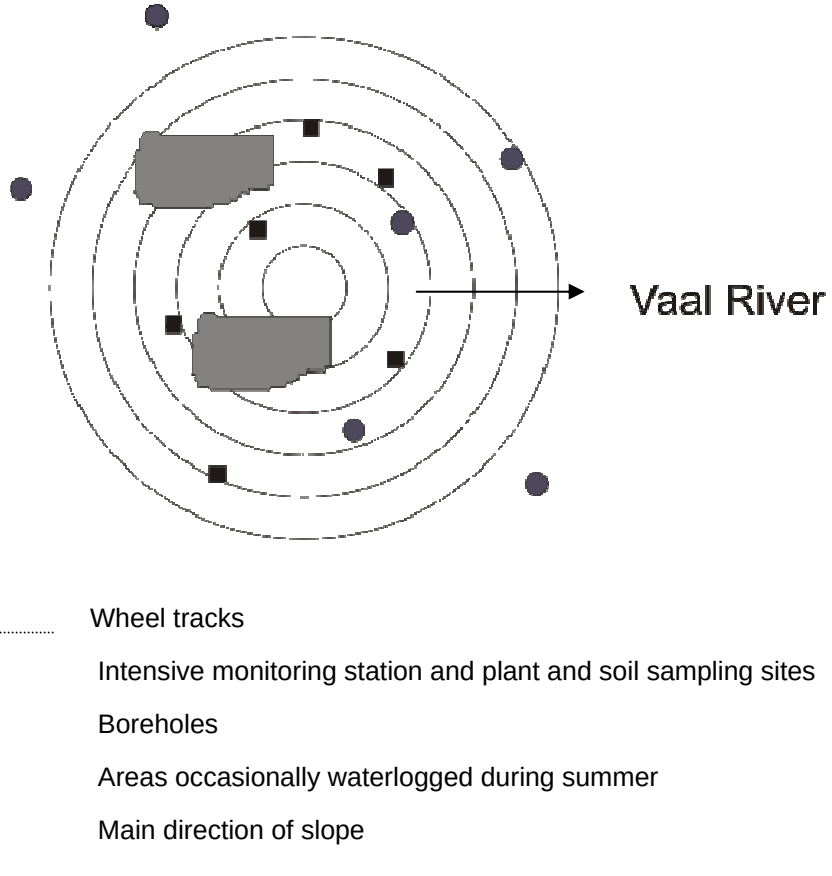


Figure 2.4 Experimental layout of the irrigated fields at New Vaal.

Surface Hydrology

The annual rainfall (MAP) for the greater catchment area C22F (444 ha) at a 50% percentile is 643 mm (SA Weather Service - Rainfall station Vereeniging no. 0438784-3). The mean annual evaporation (MAE) for the area is 1650 mm, and the mean annual runoff (MAR) is 24.3 mm (Midgley et al., 1994). Annual baseflow is calculated at 10.85mm.

Topography

The surface slope of the irrigation area is flat with a very slight dip towards the west and towards the river. The surface contours in Figure 2.5 illustrate this very clearly. Very little run-off will occur in this sandy area. All surface flow and expected groundwater flow is in a westerly direction towards the Vaal River.

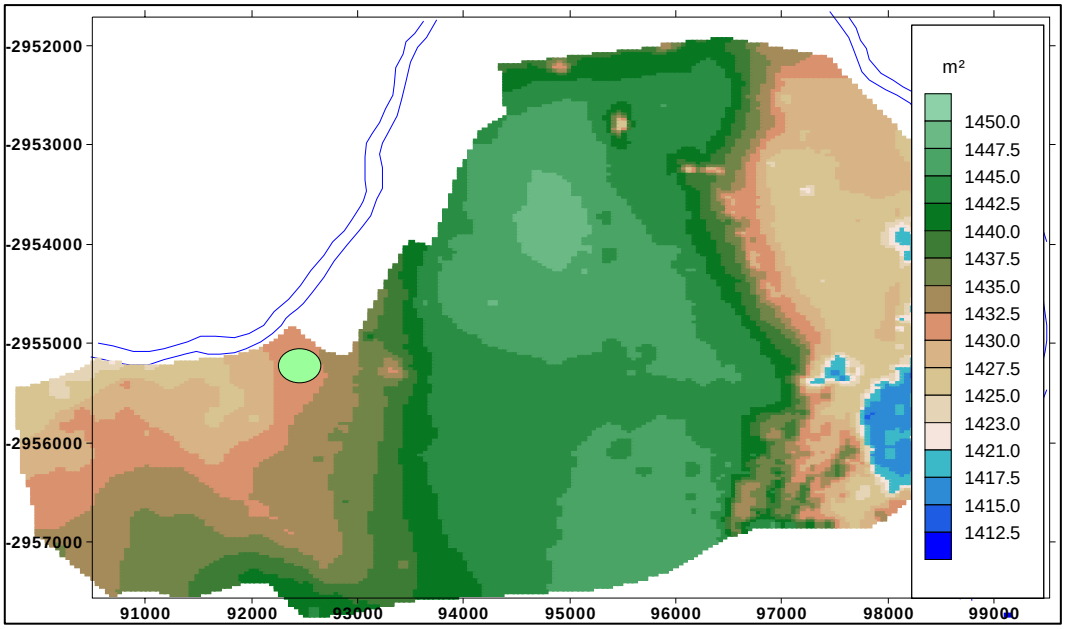


Figure 2.5 Surface contours for the New Vaal area.

Geology

New Vaal Colliery lies regionally in the Sasolburg-Vereeniging Coalfield. The statigraphy of the coalfield is typical of the coal-bearing margins of the Karoo Sequence.

The succession consists of pre-Karoo rocks (dolomites of the Chuniespoort Group of the Transvaal Sequence) overlain by the Dwyka Formation (2-15 m thickness), followed by the Ecca Group sediments, of which the Vryheid Formation is the coal-bearing horizon. In some places the lava of the Ventersdorp Supergroup underlies the coal. The latter is present over the whole area and consists mainly of sandstone, shale and coal of varying thickness. An alluvium (sand) layer is present along the Vaal River. Dolerite intrusions in the form of dykes and sills are present over the entire coalfield and cause structural complications.

2.1.3 Syferfontein

This Sasol Coal mine is in Mpumalanga (Latitude 23^{o}64' S, Longitude 29^{o}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 2.6 shows the regional setting of the irrigation site and Figure 2.7 shows experimental layout of this field, which includes intensively monitored plots and the groundwater monitoring boreholes.

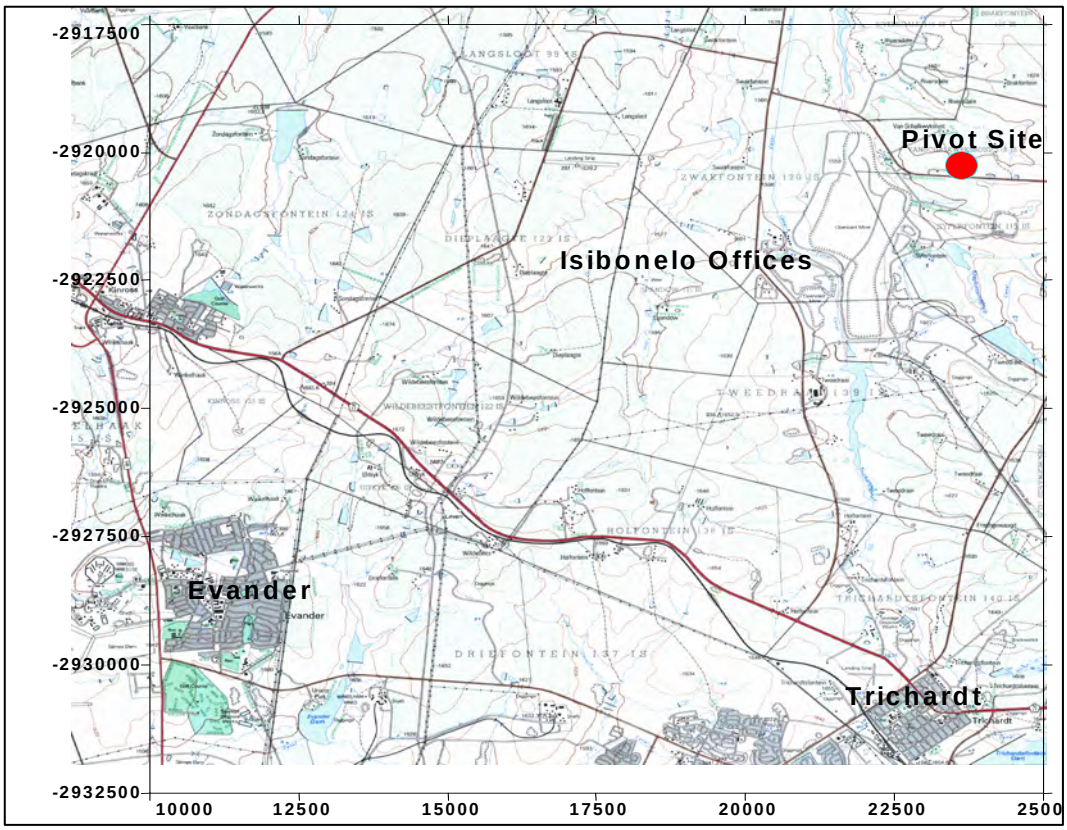


Figure 2.6 Regional setting of Syferfontein irrigation site.

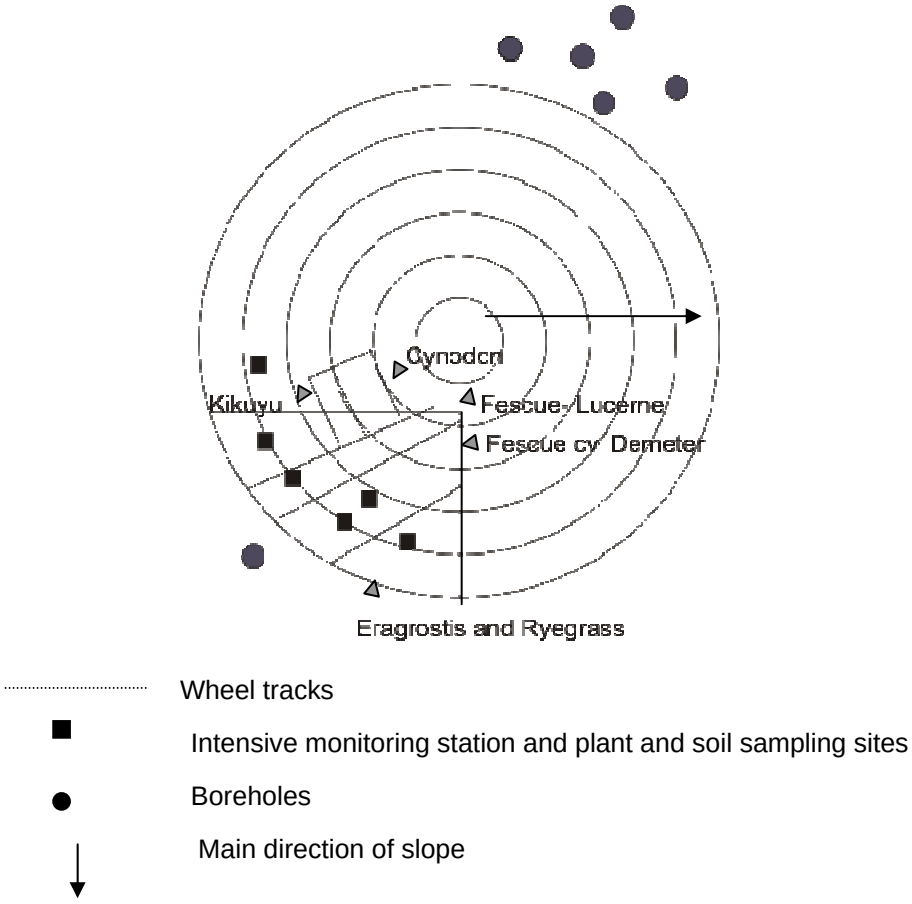


Figure 2.7 Experimental layout of the irrigated fields at Syferfontein.

Surface Hydrology

The annual rainfall (MAP) for the area at a 50% percentile is 708 mm (SA Weather Service - Rainfall station: Secunda no. 047830-3). The mean annual evaporation (MAE) for the area is 1550 mm, and the mean annual runoff (MAR) is 50 mm (Midgley et al., 1994). Annual baseflow is calculated at 13 mm.

Geology

Syferfontein lies in the Highveld Coalfield and is flanked by the Springs-Witbank and Ermelo Coalfields. The Karoo Sediments at Syferfontein comprise the Ecca Group (which includes the coal seams) and Dwyka Formation. The total thickness of the Karoo Sediments ranges from 15 - 120 m. Regionally the Ecca Sediments consist dominantly of sandstone, siltstone, shale, interbedded siltstone, mudstone and coal. Dolerite dykes and undulating sills are present.

The geology at Syferfontein is relatively homogeneous with the weathered sediments up to 10 m deep. The strata consist mainly of 2 - 6 m soil, followed by dolerite to 10 m, with a thin impermeable layer of shale below the weathered zone. The shale is underlain by fresh

sandstone with a white appearance. At the depth of 32 - 35 m the sandstone is again underlain by shale. (Geological logs for all the boreholes are presented in Appendix).

Figure 2.8 illustrates an integrated geological model for the underlying lithologies at the Syferfontein pivot, based on the logs from the existing boreholes. A fence diagram in Figure 2.9 provides a more detailed cut through the model indicating the consistency of the different layers.

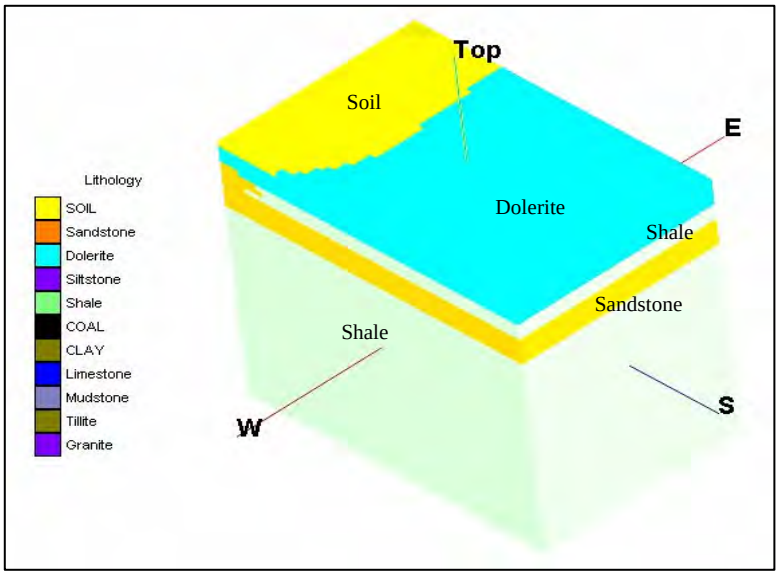


Figure 2.8 A Model diagram of the geology at Syferfontein pivot, viewed from the south.

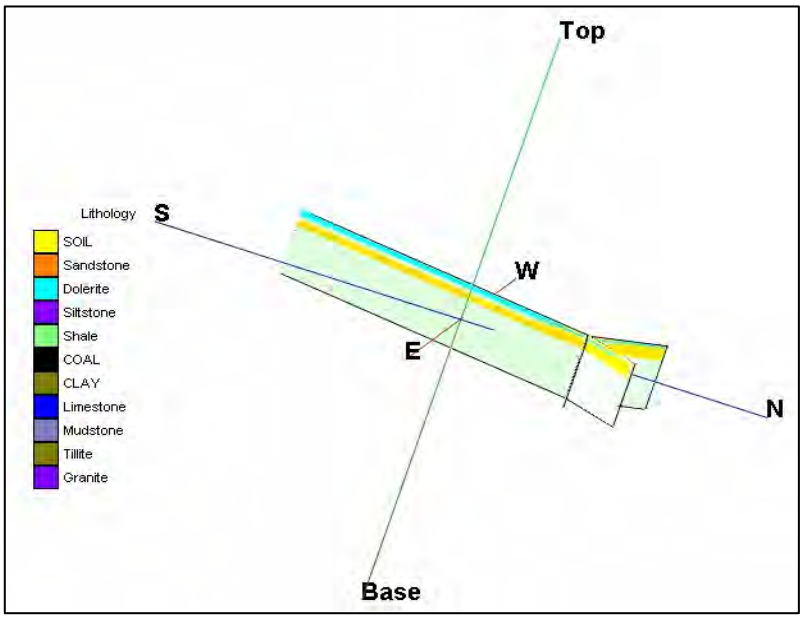


Figure 2.9 A fence diagram of the geology at Syferfontein pivot.

Geohydrology at Syferfontein Pivot

From the water strikes encountered in the drilling and from subsequent slug testing of the boreholes, it is clear that the underlying sediments have got very poor water-bearing properties. Generally the boreholes yielded no water during drilling, with minute quantities encountered above the shale layer lying at around 35 m.

Slug testing indicated that the sediments have a very poor response and a low hydraulic conductivity is inferred. In certain boreholes moisture (as opposed to definite water strikes) was associated with the shallower shale layer at approximately 15 - 20 m. These shale layers therefore can be considered as barriers to vertical flow and any water moving vertically from the irrigation should be impeded by this deeper lying shale layer. The shallower layers all show some signs of weathering and groundwater would be able to move vertically and laterally in these layers.

The low yields and aquifer parameters as obtained in the testing suggest that groundwater would migrate very slowly from the pivot. Any degradation in quality due to the irrigation and fertilizer application will consequently be a largely localised phenomenon.

2.2 Cropping systems

A brief description of the crops planted is presented below, with more detail on cultivars, planting dates and density, fertilization and herbicide applications in Appendix E & F. The cropping systems include 16 growing seasons for TWF, 15 growing season for Major and 12 seasons of different cropping systems at Pivot Four, 7 growing seasons at New Vaal and nine harvests at Syferfontein. Each growing period includes 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.

2.2.1 Kleinkopjé

The fields at Kleinkopjé were at first managed by Anglo American Farms until they were disbanded, and thereafter the contract was awarded to Smith Brothers. The fields were cropped to annual cash crops, and these included maize, wheat, sugarbeans and potatoes. There is now interest in planting pastures on Pivot Tweefontein, as the internal drainage problems are consistently resulting in unacceptably low yields, and a field that is difficult to manage. Again, the issue of appropriate site selection is crucial, and such problems will need to be addressed before large-scale irrigation of rehabilitated land can be recommended.

Very valuable research sites have now been established at Kleinkopjé, as Pivot Four has been continuously cropped and monitored for 11 seasons now, and in the case of TWF and Major, for 15 consecutive seasons. Ideally the monitoring should continue as long as is practical.

Figure 2.10 Maize irrigated with gypsiferous mine water at Pivot Major

Figure 2.11 Wheat irrigated with gypsiferous mine water at Pivot Four

Figure 2.12 Potato irrigated with gypsiferous mine water at Pivot Four

2.2.2 New Vaal

The New Vaal pivot was first managed by Soetvelde Farms, and then Mr Hugie took over the contract in 2002/03. At first wheat and maize were the crops of choice, and then an attempt was made to produce vegetables under contract (peas / sweetcorn / pumpkin). Finally in 2005 soybean was planted, but unfortunately this site had to be abandoned due to waterlogging problems.

2.2.3 Syferfontein

The Syferfontein pivot was managed by the mine themselves, in person, Mr Ernie van Biljon under the guidance of Mr Bertie Botha. Due to the heavy clay soil that would make cultivation extremely difficult, the mine decided to establish a perennial Fescue pasture. The research team then established five temperate and subtropical, annual and perennial pastures in small plots that were fenced off separately to prevent grazing animals from eating the fodder and damaging instruments (Figure 2.13). The pastures planted are listed in Table 2.1.

Table 2.1 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*	Perennial Temperate

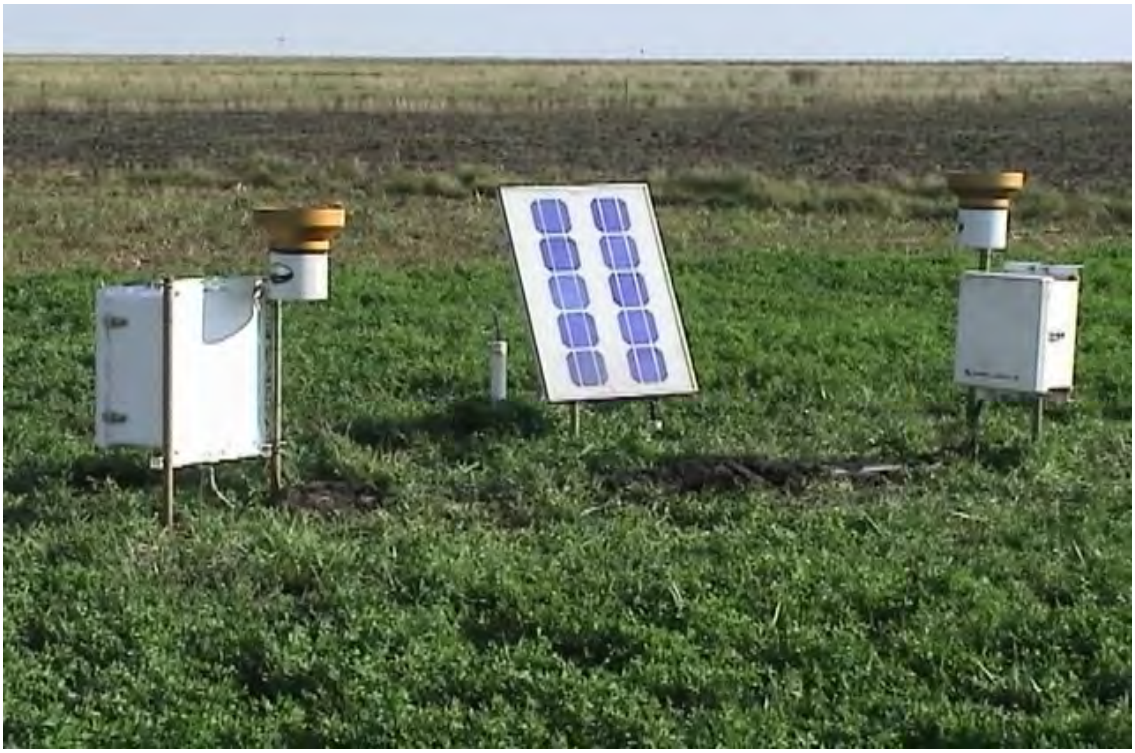


Figure 2.13 Lucerne irrigated with sodium sulphate rich mine water at Syferfontein

2.3 Soils

This section discusses the soil classification, depth, texture and initial soil salinity of the irrigated fields at the different mines and is given in Table 2.2.

Table 2.2 Soil classification, depth, texture and initial saturated soil salinity (ECe) of the irrigated fields on the different mines.

Mine 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	10 (2001)

More detail on soil chemical properties for each season of the soils under study is presented in Appendix C.

All the fields except Pivot Four, experienced poor internal drainage problems, which reduces yields and could affect the accumulation of salts. Pivot TWF shows 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 have 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 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 2.14).

Figure 2.14 Waterlogging at New Vaal during the early growth stage of Pumpkins.

2.4 Water qualities

Average, maximum and minimum irrigation water qualities (pH, electrical conductivity (EC) and concentrations of dominant ionic species) at different mines are indicated in Table 2.3.

Table 2.3 Average irrigation water qualities (pH, electrical conductivity (EC) and concentrations of dominant ionic species) at different mines.

Mine and field		Statistics	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	TDS (mg ℓ^{-1})
Kleinkopjé	Major (Jacuzzi water) 1997-2005	Ave	7	316	513	196	40	2145	14	3452
		Max	8	408	764	309	132	2770	42	5256
		Min	5	209	259	107	7	1230	8	1728
	Major (New Vleishaft) 2003- 2005	Ave	6.3	306	475	205	71	2020	25	3498
		Max	7.5	398	734	312	128	2758	38	5195
		Min	5	214	215	98	13	1281	12	1801
	Tweefontein and Four (Tweefontein water) 1997-2005	Ave	8	342	450	266	73	2145	43	3489
		Max	9	516	818	499	143	4392	40	6677
		Min	6	124	79	38	35	379	3	794
Syferfontein (2000 –2004)		Ave	9.2	338	35	85	627	1379	28	2560
		Max	9.9	447	94	166	806	1941	58	3606
		Min	8.4	179	14	29	320	608	14	1190
New Vaal (2001-2005)		Ave	7.5	135	89	32	137	433	44	1088
		Max	8.5	297	196	94	250	737	132	2739
		Min	6.6	21	2	6.5	29	65	6	254

2.4.1 Kleinkopjé

The irrigation water quality was monitored throughout the trial period both by the mines and the mine water irrigation research team at the University of Pretoria. The EC of the irrigation water used at 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 2.15). Sulphate levels over this period climbed from 1500 mg ℓ^{-1} to 3000 mg ℓ^{-1}. Tweefontein Pan is the water source for Pivots Four and TWF, and here the EC started off a little higher than the water used for Major at around 300 mS m^{-1} 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. Sulphate levels over this period increased from 2500 mg ℓ^{-1} to 4000 mg ℓ^{-1}. Detailed irrigation water quality can be looked at Appendix A.

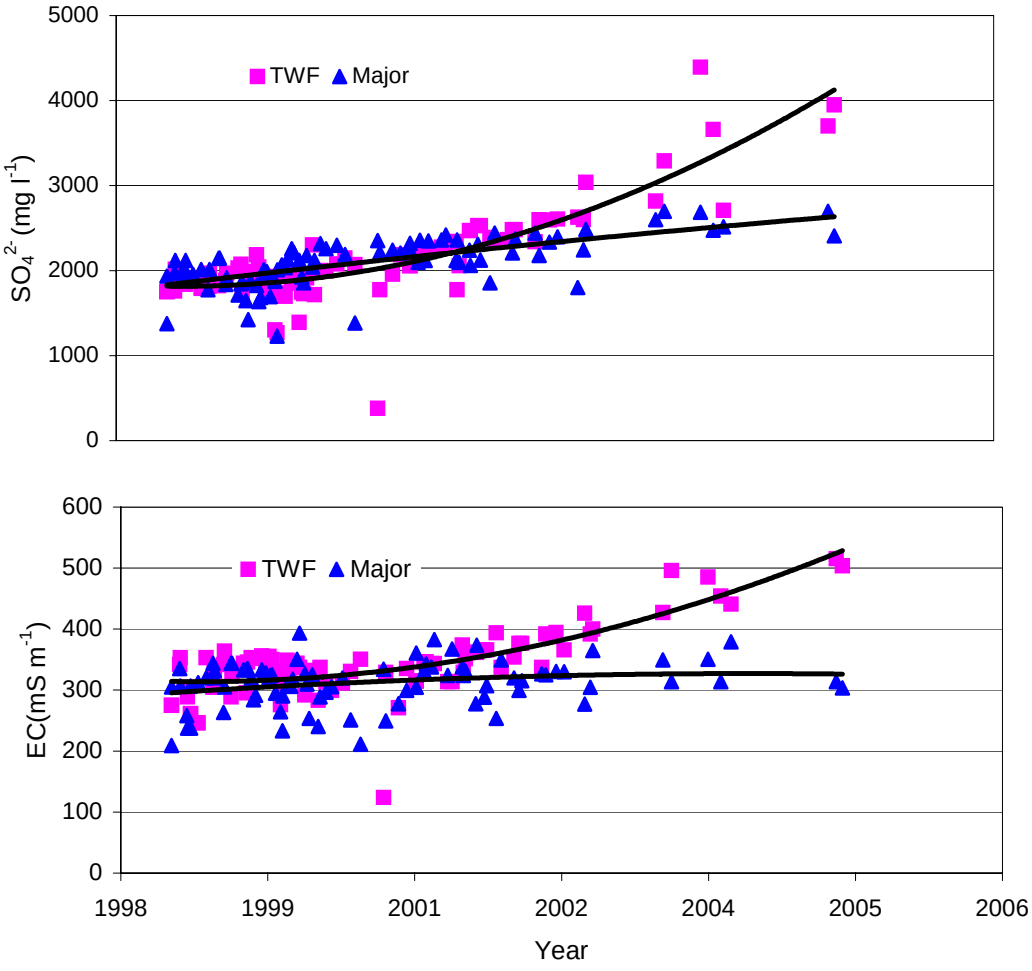


Figure 2.15 EC and sulphate trends of the irrigation water sources at Kleinkopjé

Irrigation is from treated water of the New Vleishaft Dam adjacent to Pivot Major. Water in the dam originates from the colliery, as is illustrated in the Durov diagram in Figure 2.16.

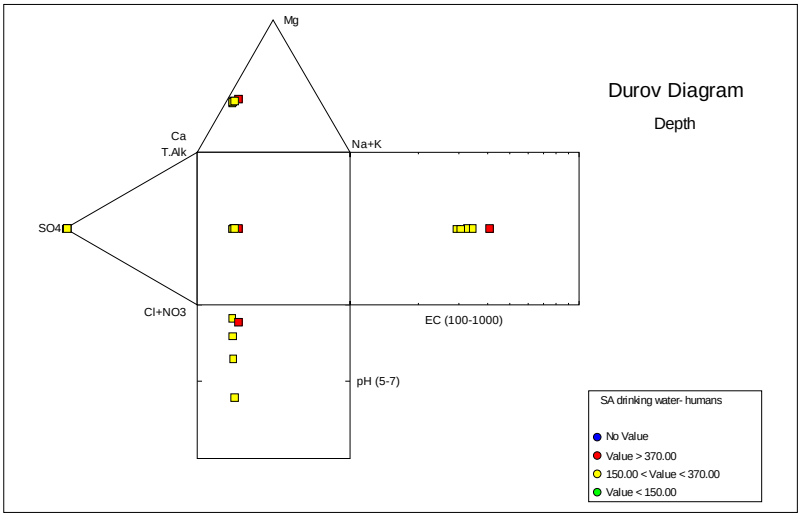


Figure 2.16 Durov diagram of the New Vleishaft Dam.

At Pivot Four irrigation is from Tweefontein Pan adjacent to the pivot. Water in the pan originates from the colliery, as is illustrated in the Durov diagram in Figure 2.17. The water is dominated by Ca, Mg and SO_4, which is typical of the collieries. The water was analysed in the chemical modelling program PHREEQC. The program indicated that the water is in equilibrium with gypsum, and saturated with dolomite and calcite.

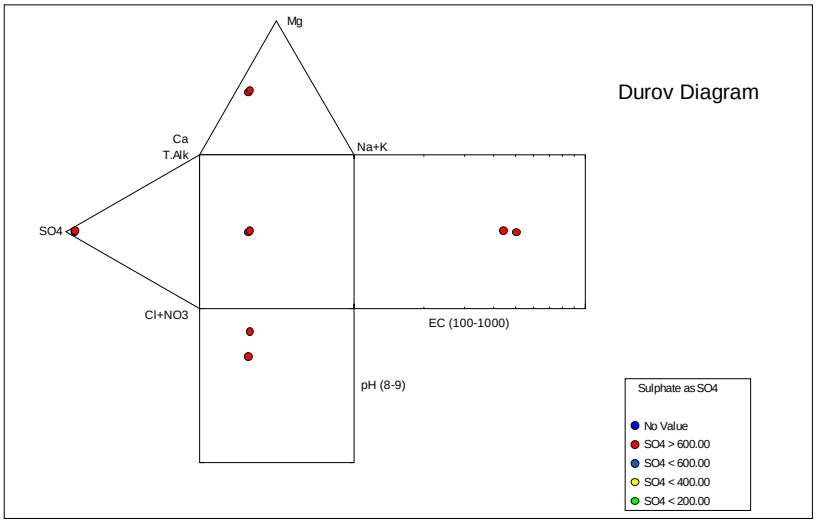


Figure 2.17 Durov diagram of Tweefontein Pan

2.4.2 New Vaal

Irrigation is from Dam 595, adjacent to the irrigation site. Water in the dam originates from the colliery, as is illustrated in the Durov diagram, showing the strong SO_4, and to a lesser degree, Na^+ dominance of the water in this dam and was observed to increase continuously up to 2004

(Figure 2.18). Ca, Cl, Mg and K were in small quantities in the irrigation water. For more detailed water quality data see Appendix A. At New Vaal the water quality was stable for the irrigation period.

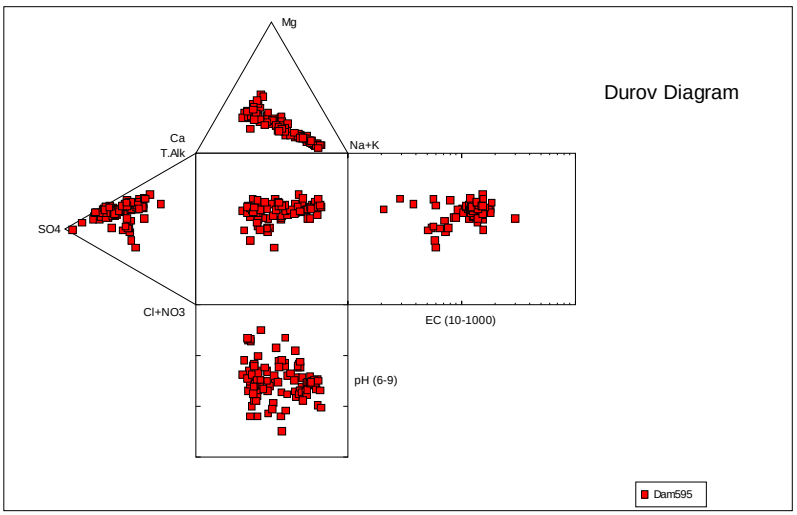


Figure 2.18 Durov diagram of the irrigation Dam 595 at New Vaal.

2.4.3 Syferfontein

Na and SO_4 were the dominant ionic species while Ca, Mg, Cl and K were in small quantities in the irrigation water. Water in the dam originates from the colliery, as is illustrated in the Durov diagram in Figure 2.19. In Syferfontein the water quality was stable for the irrigation period. For more detailed water quality data see Appendix A.

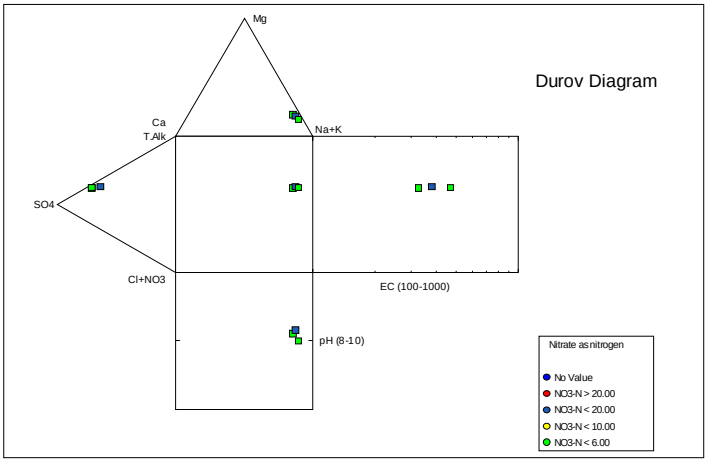


Figure 2.19 Durov diagram of the irrigation dam at Syferfontein

The EC of the irrigation water at Syferfontein and Kleinkopjé are similar, but fewer problems are expected with the gypsiferous water, as gypsum precipitation is expected to keep EC_e much lower than with the sodium sulphate rich water.

2.5 Monitoring the field water and salt balance

Intensive monitoring stations in representative sites of all fields were installed to monitor the soil water and salt balance during the cropping seasons. The intensive monitoring stations instrumentation and measurements made are described here.

2.5.1 Atmospheric Evaporative Demand

An automatic weather station was set up close to the cropped areas for each site. At all the sites where the weather station was set up, it was 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 station:

- 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, as well as averaged, maximized and minimized daily. Daily average, maximum and minimum relative humidity was also recorded. The data logger 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.

Figure 2.20 Automatic weather station at New Vaal during the trial period

2.5.2 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 (Figure 2.21), with 3 replications every 10-14 days. Two essential measurements were made, namely, leaf area index and above ground dry matter 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^{o}C. When plants senesced, they were harvested and final yield determined.

Plant samples were also taken at critical crop growth stages to determine possible nutritional deficiencies to be corrected through fertilization.

Figure 2.21 Intensive monitoring station at Pivot Four winter 2004

2.5.3 Soil water balance

Irrigation and rainfall

Amounts of irrigation and rainfall were recorded with tipping bucket (raingauges) connected to a CR10X (Campbell Scientific Inc, Utah, USA) dataloggers (Figure 2.21). Manual raingauges were also used as a back up at every site for each pivot and also used to separate out the rain from irrigation. There were two electronic and two manual raingauges for each site.

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. The NWM was calibrated for each of the soils on the site. The calibration equation developed for the site was used to calculate the soil water content in the profile. 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.

Surface runoff

Runoff weirs designed by Prof Lorentz of UKZN were constructed to monitor the volume and quality of water running off the fields. A pressure transducer measured the water level above the weir, and an **EC sensor** determined water quality. The instruments were connected to a CR-510 data logger (Campbell Scientific Inc., Logan, Utah, USA. The weirs were built at the lowest points of fields Major and TWF (Kleinkopjé Colliery). A weir was also built at Syferfontein during the winter of 2003.

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

2.5.4 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 analysis was completed in the Soil Science Laboratory of the University of Pretoria. The complete result of the soil analysis is presented in Appendix C. A summary of the soil analysis results obtained from the field trial is given in the Appendix C.

Soil water sampling and analysis

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 were also installed at later stage to a depth of 0.30, 0.60 and 90 m to get more soil water samples. Due to the shallow depth of the Syferfontein soil, ceramic cups were placed at a depth of 0.30 and 0.60 m, and an electronic wetting front detector 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 are 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.

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) and Syferfontein to sample runoff for detailed analysis (Figure 2.22). In September 2004 the field trial at Syferfontein was concluded and the sampler was moved to pivot Major. Campbell loggers, CR10X (Campbell Scientific Inc., Logan, Utah, USA) at TWF and Major, were used to trigger the ISCO sampler for measurement. The logger senses the height of water above the weir using a pressure traducer every second and converts it to flow rate, using an empirical equation that depends on the shape and size of the weir.

The logger stores the average flow rate over a period of 15 minutes, along with the date, time and voltage of the battery. The logger was programmed to signal the ISCO to take a sample for every 25 m^3 water that flows over the weir. The ISCO samples a volume of 450 mℓ, resets itself and then gets ready to sample again once the next 25 m^3 has flowed over the weir. The ISCO sampler also stores the bottle number, day, date and time of sampling. The ISCO stops sampling when water samples have been deposited in all the 24 available bottles, or if flow stops. The runoff waters sampled were analysed in detail and the data can be seen in Appendix A.

Figure 2.22 Runoff weir at Pivot TWF with a mounted Campbell logger and ISCO water sampler

2.6 Monitoring groundwater levels and quality

Boreholes were drilled so that groundwater levels and qualities could be monitored every 2 to 6 months. Boreholes were not needed at field TWF (Kleinkopjé Colliery), which is on rehabilitated land.

2.6.1 Kleinkopjé

Site –specific geology

No detail of the geology at Pivot Four is available. However, trenches dug showed that the Hutton soil is deeper than the current water level and that no consolidated rock affects the downward movement of irrigation water towards the aquifer. Locally the strata encountered in Pivot Major consist largely of soils, sandstone and coal below that. Geological logs for all the boreholes are presented in Appendix I**.**

A fence diagram in Figure 2.23 provides a detailed cut through the strata indicating the occurrence of the different layers.

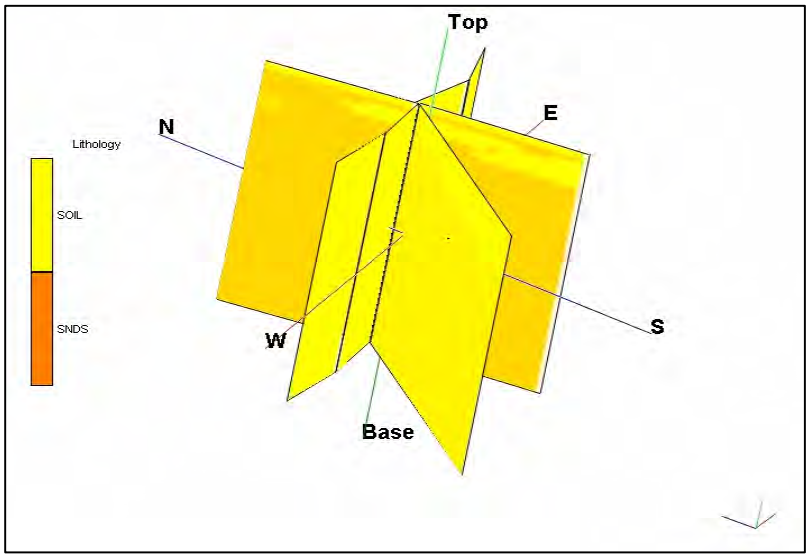


Figure 2.23 Fence diagram of geology at Pivot Major, drawn through the boreholes.

Positioning of the monitoring boreholes

Pivot Major

At this pivot, six of the 10 boreholes were monitored regularly for water levels (Figure 2.24), but only five are used for hydrochemical profiling and water quality. The other boreholes have been damaged and are inaccessible as far as the samplers and probes are concerned.

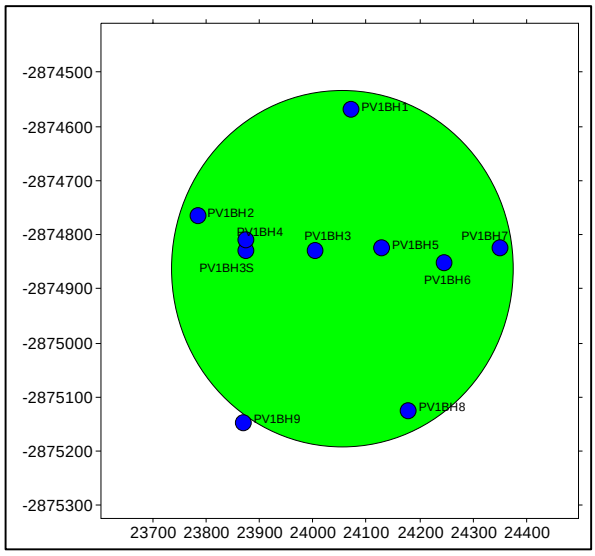


Figure 2.24 Position of the monitoring boreholes at Pivot Major

Pivot Four

At this pivot six boreholes were monitored regularly for water levels, profiling and water quality (Figure 2.25).

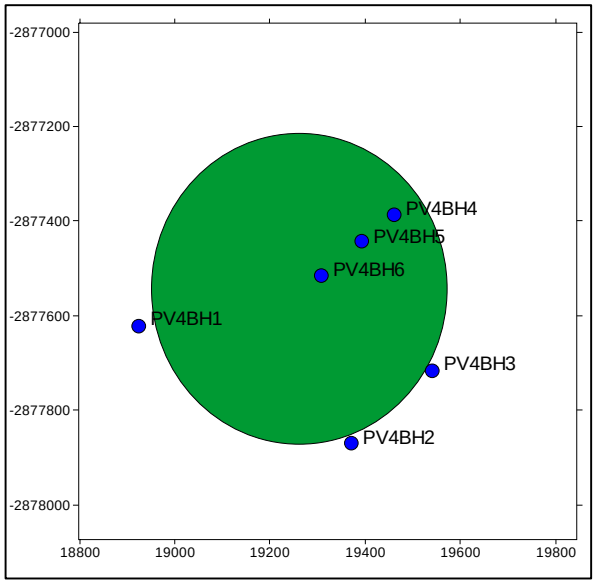


Figure 2.25 Position of the monitoring boreholes at Pivot Four.

2.6.2 New Vaal

Site-specific geology

Locally the strata encountered consisted largely of soils, siltstones / shale and coal. Geological logs for all the boreholes are presented Appendix I. Figure 2.26 illustrates an integrated geological model for the underlying lithologies at the New Vaal pivot, based on the logs from the existing boreholes. A fence diagram in Figure 2.27 provides a more detailed cut through the model indicating the consistency of the different layers.

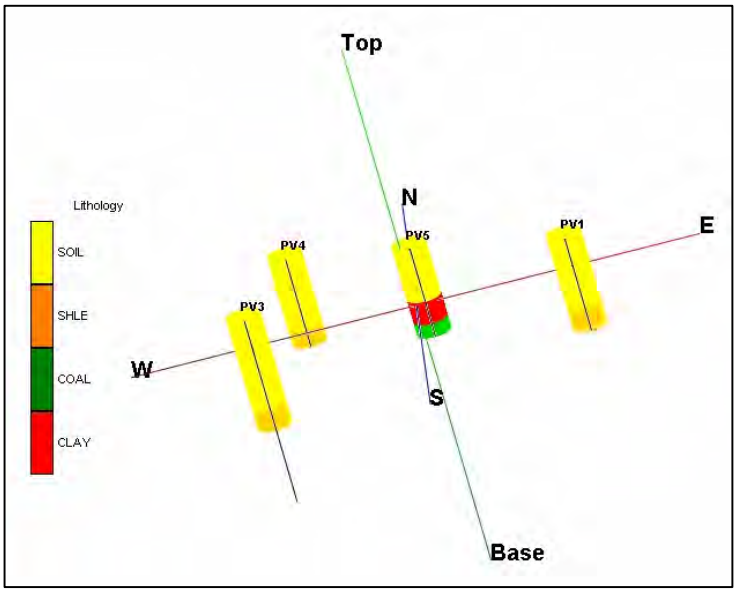


Figure 2.26 Log illustration of geology at New Vaal pivot.

A clay layer, which is illustrated in Figure 2.27 is present between 2.4 m and 4 m. This layer has a clay content of 24%, and has a great influence on the drainage system of the pivot area.

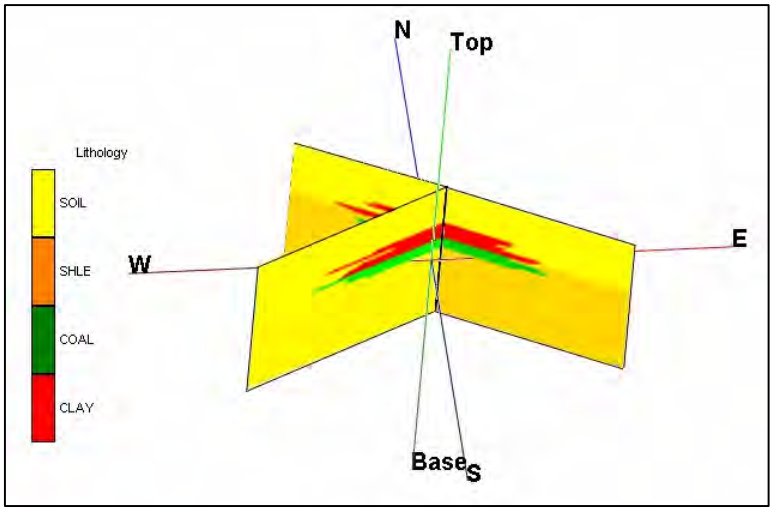


Figure 2.27 Fence diagram of geology at New Vaal pivot, drawn through the boreholes.

Positioning of monitoring boreholes

Five monitoring boreholes were drilled at this site. These were spaced as indicated in Figure 2.28. These five boreholes were sited according to expected water flow. Boreholes NVPV1 and NVPV2 were placed in order to gain background values. Boreholes NVPV3 and NVPV4 were located at the expected down-gradient side of the pivot, in order to gain any irrigation water information, while Borehole NVPV5 was located in the centre of the pivot to gain further water quality information on its expected path to the river.

The boreholes were all drilled to a depth of approximately 26 m. This depth was based on the on-site drilling, ensuring that the borehole was drilled approximately 10m into the geology below the alluvial system. Five boreholes were monitored (Figure 2.28) initially, but since 2004 PV1 PV2 and PV3 became blocked, possibly because of the sandy nature of the area.

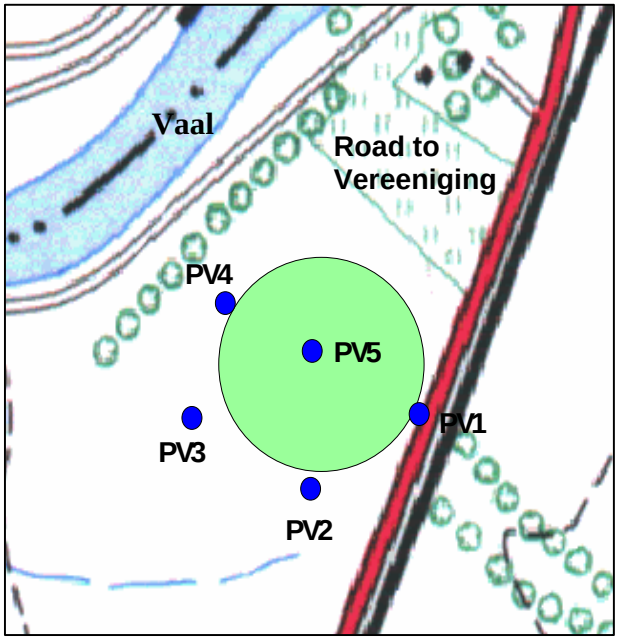


Figure 2.28 Position of the monitoring boreholes at the New Vaal Pivot.

2.6.3 Syferfontein

The surface slope through the irrigation area is to the north at an average gradient of 1:30. Boreholes were sited in such a way that any groundwater migration from the pivot would be intercepted by these boreholes (Figure 2.29). The borehole siting took the dyke positions and flow directions into account. Borehole OBH3 was intended to monitor background water quality. The remaining boreholes are situated in the northeastern corner of the pivot adjacent to the test quadrant being researched by the University of Pretoria. An existing borehole, REGM-86, is also close enough to serve as a monitoring borehole and has therefore been included in the monitoring system. Trenches were dug in 2001 to prevent the runoff water from the pivot area entering the boreholes from surface, thereby skewing the interpretation of results.

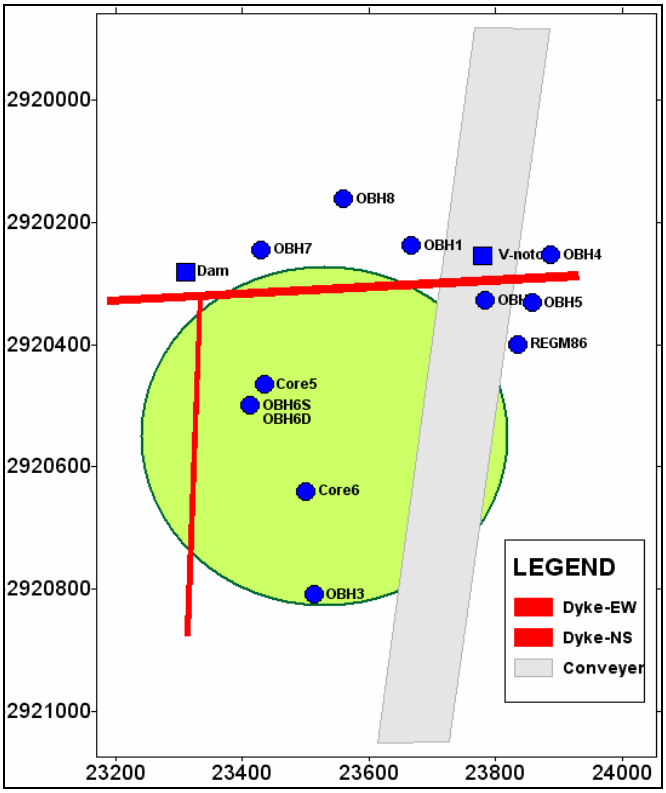


Figure 2.29 Pivot site showing the positions of the monitoring boreholes (with the positions of the dykes as provided by the mine's geologist).

2.7 Modelling

2.7.1 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.

Data collected in the field trials were also used for improvement, development, calibration and validation of the mechanistic soil water and salt balance model (SWB). The output of SWB can be used by a groundwater and surface hydrology model to predict the long-term effect of the surface runoff and leachate on surface water as well as groundwater quality at different sites.

2.7.2 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 and 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 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. 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 and 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

percolates from the bottom layer in one 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 specific crop growth parameters for a wide range of species (Annandale et al., 2002).

2.7.3 Model validation

One of the objectives of this project was to validate the SWB model using data from the field trial. Model simulations were carried out for all seasons, and compared to field measurements obtained in the intensive monitoring sites.

Daily weather data collected with the automatic weather station, irrigation water qualities, soil physical properties, as well as initial soil chemical properties were entered in the SWB database and used as model input. Soil water deficit to field capacity determined from NWM measurements, 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 under Chapter 6. All data used for calibration and validation is available in the SWB database.

Conclusions

The research team 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 balance 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. The field sites were also studied in detail for its topography, geology, groundwater and its relationship to the geology of the area.

CHAPTER 3

3. CROP PRODUCTION AND PLANT NUTRITION

Introduction

In this chapter, *crop production* and *plant nutrition* aspects of the research are discussed. The *crop production* section presents the yields obtained and suggests 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.

3 .1 Crop production

The results of the measurements taken for each site are tabulated and attached in Appendix A - H. The results include 16 growing seasons for TWF, 15 growing season for Major and 12 seasons of different cropping systems at Kleinkopjé, 7 growing seasons at New Vaal and nine harvests at Syferfontein.

Tables 3.1-3.3 present the crops, cultivars and yields obtained on the irrigated fields. The yields of maize and wheat are expressed as air-dry grain masses, whilst potato, sweetcorn, pea and pumpkin yields represent the fresh mass. The yields of maize, wheat and vegetables in Tables 3.1-3.3 were measured by the farming companies and are representative of the entire fields.

3.1.1 Kleinkopjé

At Kleinkopjé, three irrigation pivots were initially established in 1997/98 for the field trial namely Major, TWF and Jacuzzi. Jacuzzi was a rehabilitated land that presented enormous internal drainage problems and was abandoned after summer 1998/99. It was then replaced by Pivot Four, well-drained virgin site. On these sites, crops such as sugarbean, wheat, maize and potatoes were grown successfully with satisfactory yields. The crop rotation used throughout the trial period is indicated in Table 3.1.

Table 3.1 Crops, cultivars and yields irrigated with gypsiferous mine water at Kleinkopjé (1997/98 -2005). 1997/98 -2000 is from previous project (WRC Rep No.858/1/02).

Season	Pivot	Crops and cultivars	Planting date	Yield (Mg ha^{-1})	Comment
Summer 1997/98	Major	Sugarbeans	27/11/1997	2.95	
	TWF	Sugarbeans	09/01/1998	1.17	
	Jacuzzi	Sugarbeans	06/01/1998	0.83	
Winter 1998	Major	Wheat	24/06/1998	4.92	
	TWF	Wheat	30/06/1998	4.62	
	Jacuzzi	Wheat	30/06/1998	4.4	
Summer 1998/99	Major	Maize	29/12/1998	6.26	
	TWF	Sugarbeans	06/01/1999	1.17	
	Jacuzzi	Sugarbeans	04/01/1999	0.84	
Winter 1999	Major	Wheat	01/071999	5.76	
	TWF	Wheat	03/07/1999	4.21	
	Four	Wheat	07/071999	6.61	
Summer 1999/00	Major	Maize	13/12/1999	4.13	
	TWF	Maize	15/12/1999	3.5	
	Four	Maize	17/12/1999	3.20	
Winter 2000	Major	Wheat	26/06/2000	3.63	
	TWF	Wheat	28/06/2000	2	Total loss to hail
	Four	Wheat	27/06/2000	1.2	Total loss to hail
Summer2000/01	Major	Maize (cv. PAN 6710)	11/12/2000	7	Excellent yield
	TWF	Maize (cv. PAN 6710)	14/12/2000	3.68	Herbicide damage

	Four	Maize (cv. PAN 6710)	13/12/2000	5.34	Good yield
Winter 2001	Major	Wheat (cv. SST 825)	18/06/2001	7.2	Excellent yield
	TWF	Wheat (cv. SST 825)	20/06/2001	6.5	Excellent yield
	Four	Wheat (cv. SST 825)	20/06/2001	6.5	Excellent yield
Summer2001/02	Major	Maize (cv. PHI 32P75)	15/12/2001	4.71	Waterlogging
	TWF	Maize (cv. PHI 32P75)	15/12/2001	2.13	Waterlogging
	Four	Potato (cv. Up-to-Date)	20/08/2001	52	Good yield and quality
Winter 2002	Major	Wheat (cv. SST 825)	17/06/2002	5	Good yield
	TWF	Wheat	19/06/2002	5.2	Good yield
	Four	Wheat	19/06/2002	5.2	Good yield
Summer2002/03	Major	Potato (cv. Up-to-Date)	15/09/2002	62	Good yield and quality
	TWF	Maize (cv. PHI 32P75)	13/12/2002	3	Waterlogging and high EC (irrigation water)
	Four	Maize (cv. PHI 32P75)	13/12/2002	3	High EC of irrigation water
Winter 2003	Major	Wheat (cv. SST 825)	10/07/2003	3	Low irrigation amount
	TWF	Wheat (cv. SST 825)	15/07/2003	4.5	Low irrigation amount
	Four	Wheat (cv. SST 825)	15/07/2003	5	High K/Mg ratio
Summer2003/04	Major	Maize (cv. PHI 32P75)	12/12/2003	4.5	High K/Mg ratio
	TWF	Maize (cv. PHI 32P75)	13/12/2003	2.5	Electricity and water supply problems

	Four	Maize (cv. PHI 32P75)	13/12/2003	4.5	Stalk borer infestation
Winter 2004	Major	Wheat (cv. SST 825)	05/07/2004	4.2	Waterlogging
	TWF	Wheat (cv. SST 825)	07/07/2004	3.8	Low irrigation amount
	Four	Wheat (cv. SST 825)	07/07/2004	4.5	K deficiency
Summer 2004/05	Major	Maize (cv. PHI 32P75)	19/12/2004	3	Rust
	TWF	Maize (cv. PHI 32P75)	20/12/2004	2	Rust
	Four	Maize (cv. PHI 32P75)	20/12/2004	4	Stalk borer infestation
Winter 2005	Major	Wheat (cv. SST 825)	20/07/2005	2	Electricity and water supply problems
	TWF	Wheat (cv. SST 825)	13/07/2005	3	Low irrigation amount
	Four	Wheat (cv. SST 825)	13/07/2005	4	High K/Mg ratio

The yield of maize during the 2001/02, 2002/03, and 2003/04 seasons were unsatisfactory, and this could be due to the accumulation of salts in the root zone. According to Maas (1977), maize can attain potential yield (100%) when EC_e (soil saturated paste extract) is 200 mS m^{-1}. In this study, the EC_e of the soil was found to be on average 300 mS m^{-1}, which is higher than the maximum threshold for yield reduction. This yield reduction could also be related to the plinthic layer at one-metre depth that resulted in poor drainage and waterlogging problems. Plant nutrition related yield reduction is also discussed under the plant nutrition section.

The farmer was also not happy with the yields obtained at TWF, as waterlogging on this rehabilitated site seriously affected the performance of the crops. The farmer expressed the wish to discontinue planting field crops on TWF, and to convert this field to a pasture system.

Yields and above ground dry matter of wheat produced were probably not affected by the EC of the irrigation water on both virgin and rehabilitated lands. Wheat is reportedly more tolerant to soil salinity than maize (Maas, 1977). Wheat can attain 100% yield when EC_e threshold is 600 mS m^{-1}. The EC_e of the mine water irrigated soils in winter reached a maximum value of 350 mS m^{-1}. The difference in yields obtained between seasons could be related to pests and diseases, rainfall and temperature, or amount of irrigation water applied. Maize crops were damaged in the 2000/01 season at TWF and Pivot Four, when an excess of herbicide (up to 3 times the planned rate) was mistakenly applied to all three pivots by the farming company. This resulted in severe

yield losses (Table 3.1). The expected yields were between 6 and 10 Mg ha^{-1} for the short-season cultivar.

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} (2001/02). In 2002/03 at Pivot Major, yields of 62 t ha^{-1} were produced. These can be regarded as very good yields for the Mpumalanga Highveld. Unfortunately no control fields (irrigated with normal water) were available for comparison of crop quality that was expected to be better for mine water as a result of the dominance of Ca in the irrigation water. More detail on potato yield and quality can be found in Appendix H.

The yields of maize obtained from Pivot Four were compared with average dry land yields in the Mpumalanga Province (personal communication, National Department of Agriculture, Pretoria). The yield of maize obtained from the mine water irrigated soils was higher than the dry land yields (Figure 3.1). In 2002/03 the yield obtained was lower than the dry land yield, in the same period of time high soluble K/(Ca+Mg) ratio was observed (Figure 3.20 (C)). The low yield of mine water irrigated maize was strongly related to low potassium for the growing period. K in the soil was sufficient enough for plant growth (Figure 3.18 (C)), however was not available for the plant as Mg suppressed the uptake of K.

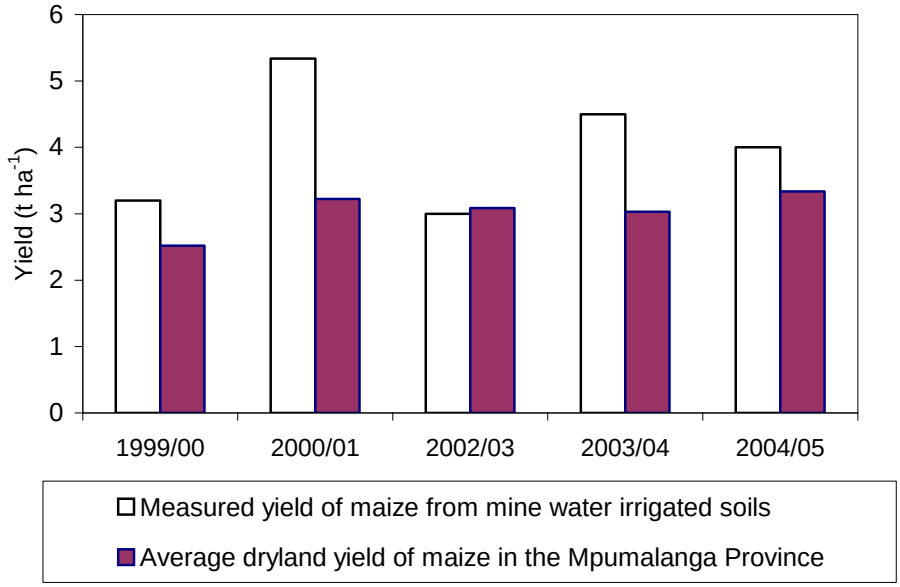


Figure 3.1 Yield of maize obtained at Pivot Four during the trial period and average dry land yield for the region

The yields of wheat obtained from Pivot Four were also compared with average yields of irrigated wheat in the Mpumalanga Province. Yields of wheat from mine water irrigated soils were comparable with those of wheat irrigated with good quality water (Figure 3.2). In winter 2000, crop failure was due to hail.

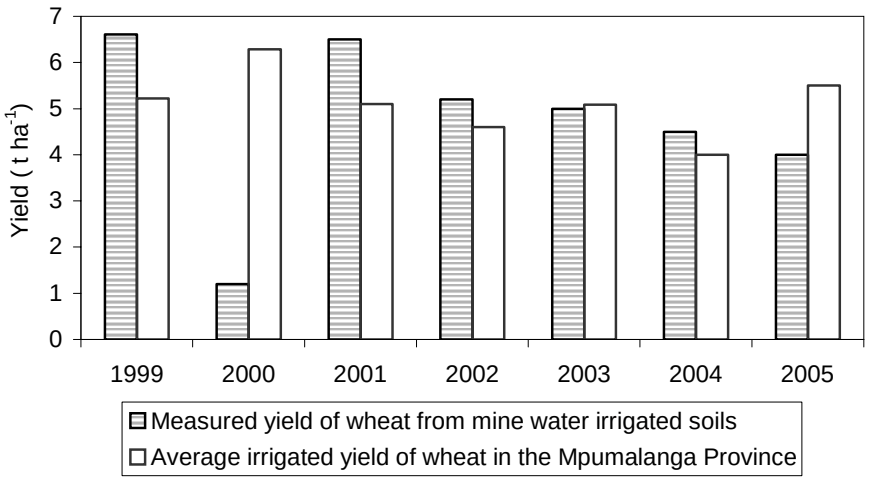


Figure 3.2 Yield of wheat obtained at Pivot Four during the trial period and average irrigated yield for the region

Pivots at Major and TWF were repeatedly out of order during the trial period, particularly between 2002 and 2005. The pivots would often not rotate but would rather sprinkle on the same place. This continuous localized irrigation caused waterlogging. Plants were also stressed due to shortage of irrigation water, as pivots often stand due to electricity supply problems on the mines. The amount of water applied to replenish soil water deficit to field capacity was not met in some winter seasons, example is indicated in Figure 3.3. As a result yields were often not satisfactory. It is clear that the irrigation management should preferably be independent of the mine, with his or her own electricity and water supply infrastructure. This is because the mine has other priorities than irrigation.

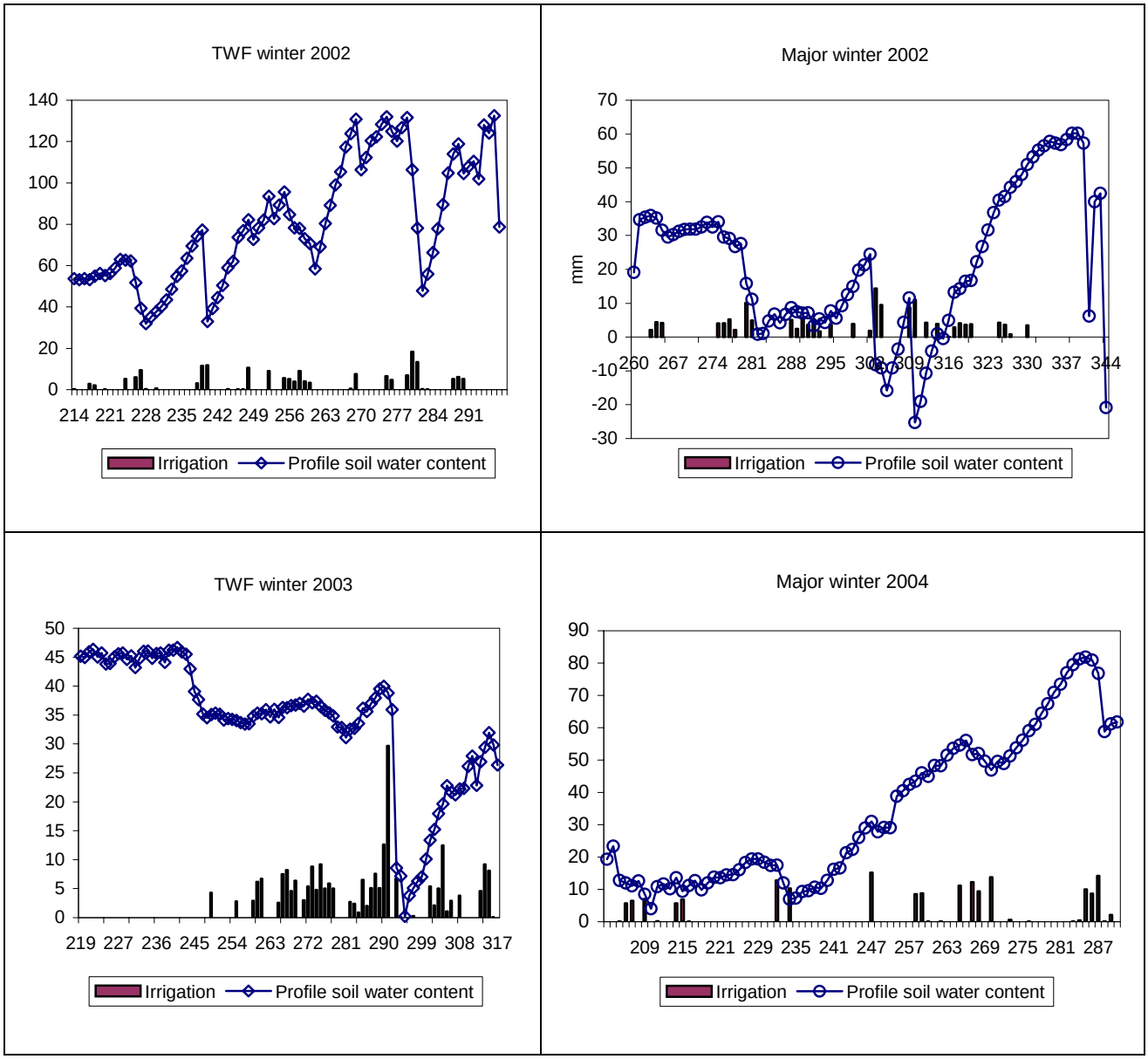


Figure 3.3 Irrigation amount applied (mm) and profile soil water content (mm) for Pivot TWF and Pivot Major

The yields of maize and wheat obtained from Pivot Major were also compared with average dry land yields of maize and irrigated yields of wheat in the Mpumalanga Province. Maize yields obtained from mine water irrigated soils were higher than the average dry land yields for the region (Figure 3.4). But lower than one could expect from good quality water irrigated crops. This is most likely due to the accumulation of salts above the threshold tolerance for the crops 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}. 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).

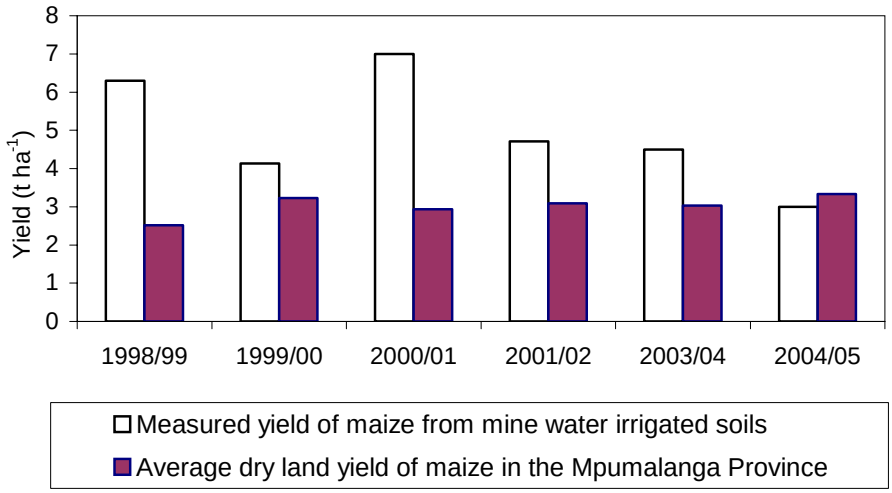


Figure 3.4 Yield of maize obtained at Pivot Major during the trial period and average dry land yield for the region

Pivot Major, poor drainage site, has been irrigated for a longer period of time than Pivot Four, which is well drained site. Nevertheless, the yields obtained from Pivot Major are comparable to those of Pivot Four. This is related to the high EC of the irrigation water. 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 (Figure 2.15). For Pivot Four, the EC of the irrigation water started at around 300 mS m^{-1} 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 tremendous effect on the yield of crops between 2002-2005.

Wheat yields from Pivot Major were also compared to average yields of irrigated wheat in the Mpumalanga Province. Yields of wheat from mine water irrigated soils were low in the winters of 2000, 2003 and 2005 (Figure 3.5). 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, more water could be used (500 mm) to get better yield.

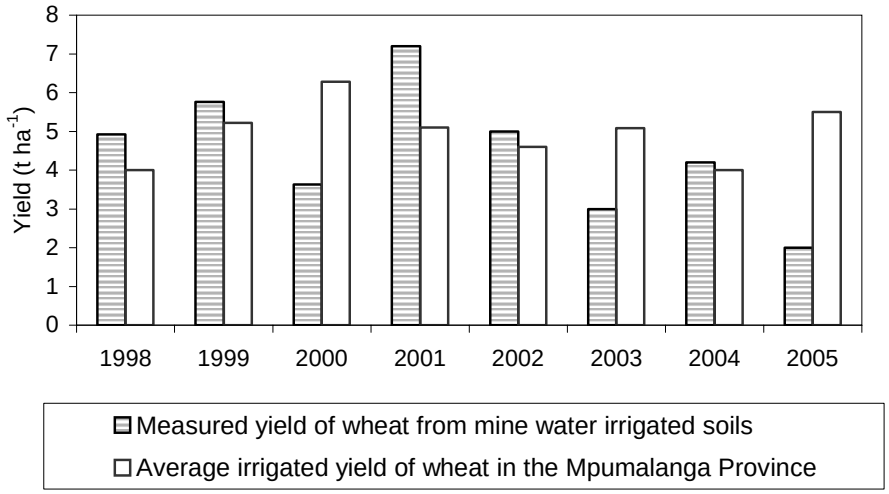


Figure 3.5 Yield of wheat obtained at Pivot Major during the trial period and average irrigated yield for the region

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. The yield of maize obtained from Pivot TWF was compared to average dry land maize yields in the Mpumalanga Province. Maize yields from mine water irrigated soils were often lower than the average dry land yields for the region (Figure 3.6). These low yields are related to the accumulation of salts above the threshold tolerance for the crops 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. In summer, 2004/05 extensive rust was also identified on the maize during in the late maturity stage and yields were very low.

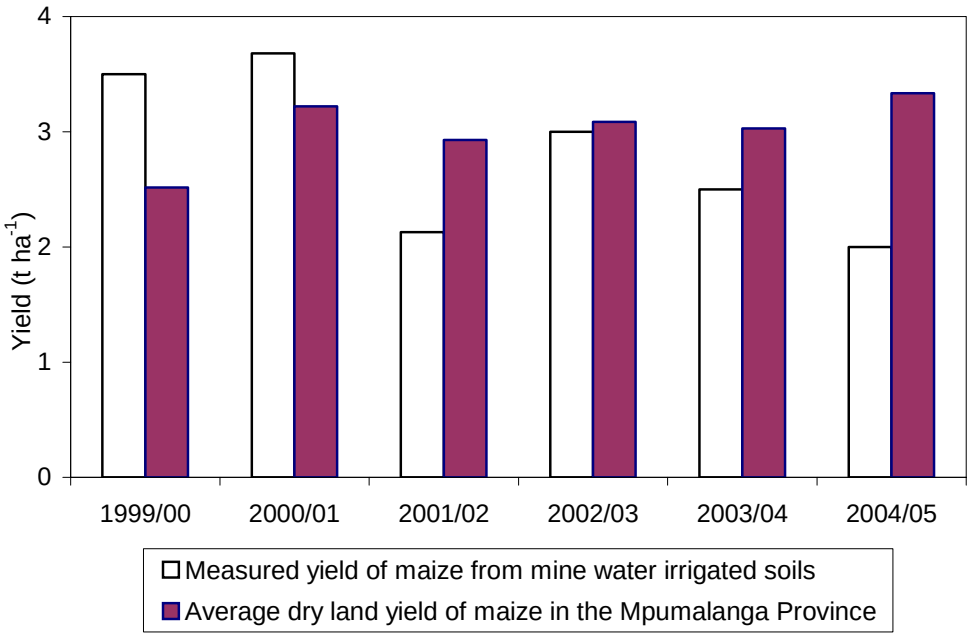


Figure 3.6 Yield of maize obtained at Pivot TWF during the trial period and average dry land yield for the region

The wheat yields obtained from Pivot TWF were also compared to the average irrigated yields for the region. The yields obtained are 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 (Figure 3.7).

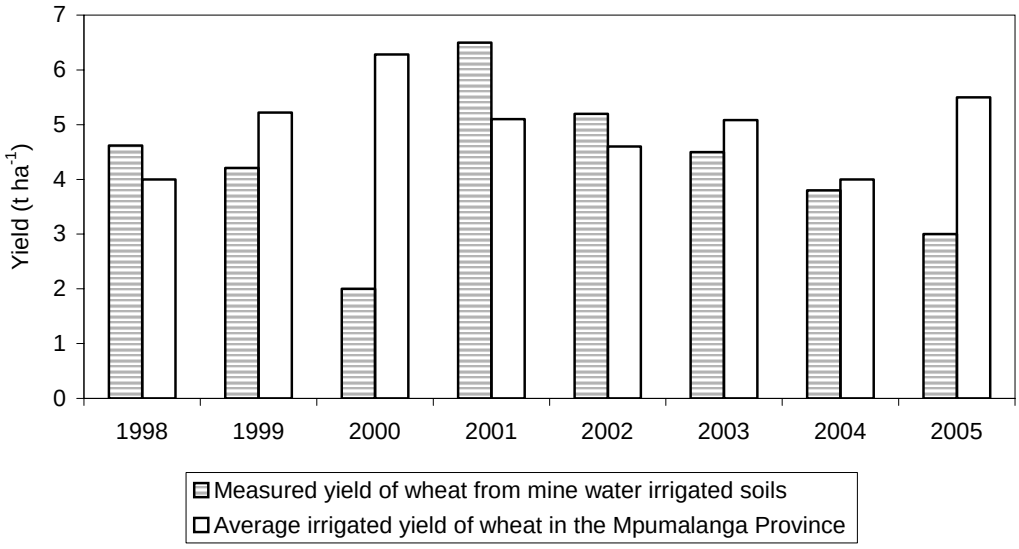


Figure 3.7 Yield of wheat obtained at Pivot TWF during the trial period and average irrigated yield for the region

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 stopped 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. 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.

Certainly, crops can be produced with these 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.

3.1.2 Syferfontein

In Syferfontein annual and perennial pasture crops were grown and the yield obtained was satisfactory for the trial period. The pastures grown and the yields obtained throughout the trial period are indicated in Table 3.2.

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 enable 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. Unfortunately, the mines were irrigating only when they have surplus water.

Since the pastures were harvested to the 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 auxiliary 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).

Table 3.2 Crops, cultivars and yields of planted pastures irrigated with Na_2SO_4 rich mine water at Syferfontein (Oct 2001-March 2004).

Crops and cultivars	Season	Yield (Mg ha^{-1})	Comments
Fescue (*Festuca arundinacea* cv. Iewag)	2001/02	2.8 ± 0.2 2.7 ± 0.5 4.7 ± 0.8	
	2002/03	3.16 ± 0.23 2.61 ± 0.21 2.15 ± 0.11	
	2003/04	4.0 ± 0.45 5.9 ± 0.73 8.5 ± 0.56	
Lucerne (*Medicago sativa* cv. SA Standard) - Fescue (*Festuca arundinacea* cv. Iewag)	2001/02	0.5 ± 0.0 2.2 ± 0.5 5.0 ± 0.9	
	2002/03	1.5 ± 0.12 3.27 ± 0.34 2.07 ± 0.18	
	2003/04	3.4 ± 0.01 2.6 ± 0.20 3.0 ± 0.15	
Fescue (*Festuca arundinacea* cv. Demeter)	2001/02	1.7 ± 0.0 1.1 ± 0.5 4.2 ± 0.3	
	2002/03	1.64 ± 0.12 2.71 ± 0.33 20.7 ± 0.03	
	2003/04	2.19 ± 0.49 3.74 ± 0.64 -	
Eragrostis (*Eragrostis curvula* cv.) - Ryegrass (*Lolium multiflorum* cv. Midmar)	2001/02	0.9 ± 0.1 2.5 ± 0.7 6.8 ± 1.4	
	2002/03	1.72 ± 0.22 - -	Dry period (Dec 02-Feb 03)
	2003/04	- - -	
Kikuyu (*Pennisetum clandestinum*)	2002/03	3.81 ± 0.16 - -	Dry period (Dec 02-Feb 03)
	2003/04	3.89 ± 0.57 - -	

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 (Beletse, 2004). This is likely because Fescue (cv. Iewag) is more tolerant to salinity than the other pastures. According to Tanji (1990), the EC_e threshold of Fescue is 390 mS m^{-1}, while Kikuyu 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 (Beletse, 2004) Figure 3.8.

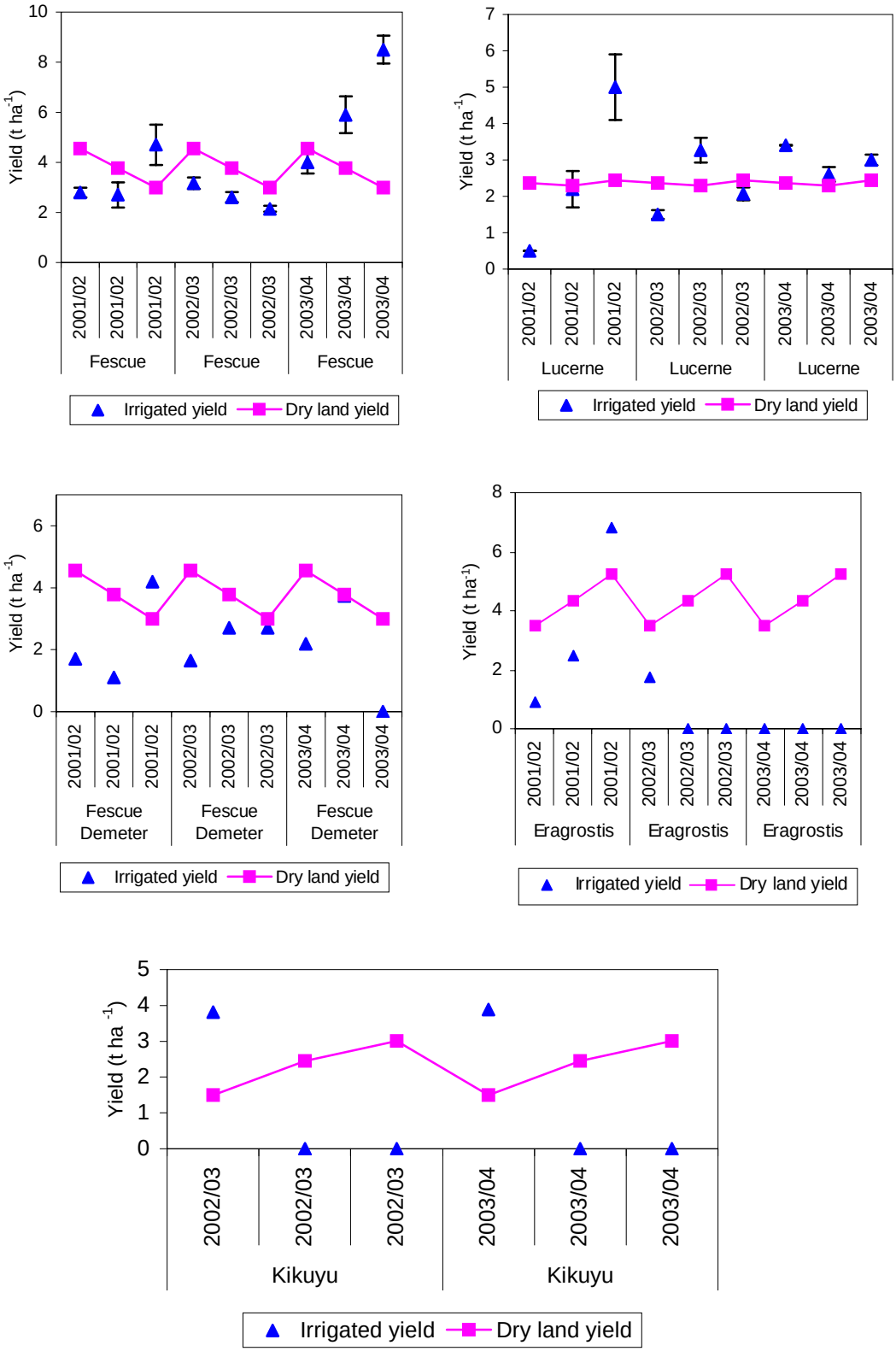


Figure 3.8 Comparison of Na_2SO_4 rich mine effluent and dry land pastures

Although the pastures were all harvested at the same time, the regrowth of Lucerne was observed to be much faster and with higher Nitrogen (N) and Crude Protein (CP) content than the grasses (Beletse, 2004). 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, and that could be due to the EC of the irrigation water, periodic drought and periodic water logging, as Lucerne is adapted to well drained soils.

Figure 3.9 A Herd of cattle grazing on the pastures grown with Na_2SO_4 rich mine effluent (Syferfontein, 2003).

3.1.3 New Vaal

At New Vaal field crops of maize, wheat and soybean, and vegetables like peas, sweetcorn and pumpkin were planted. The yield obtained was 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 is unlined and porous. Map of New Vaal field trial is indicated in Figure 3.10. 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 3.11). 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 report supplied by Gert Pretorius from ACES on the determination of the cause of the problem is presented in Appendix J and the investigation in to this problem by IGS is given in Chapter 5.

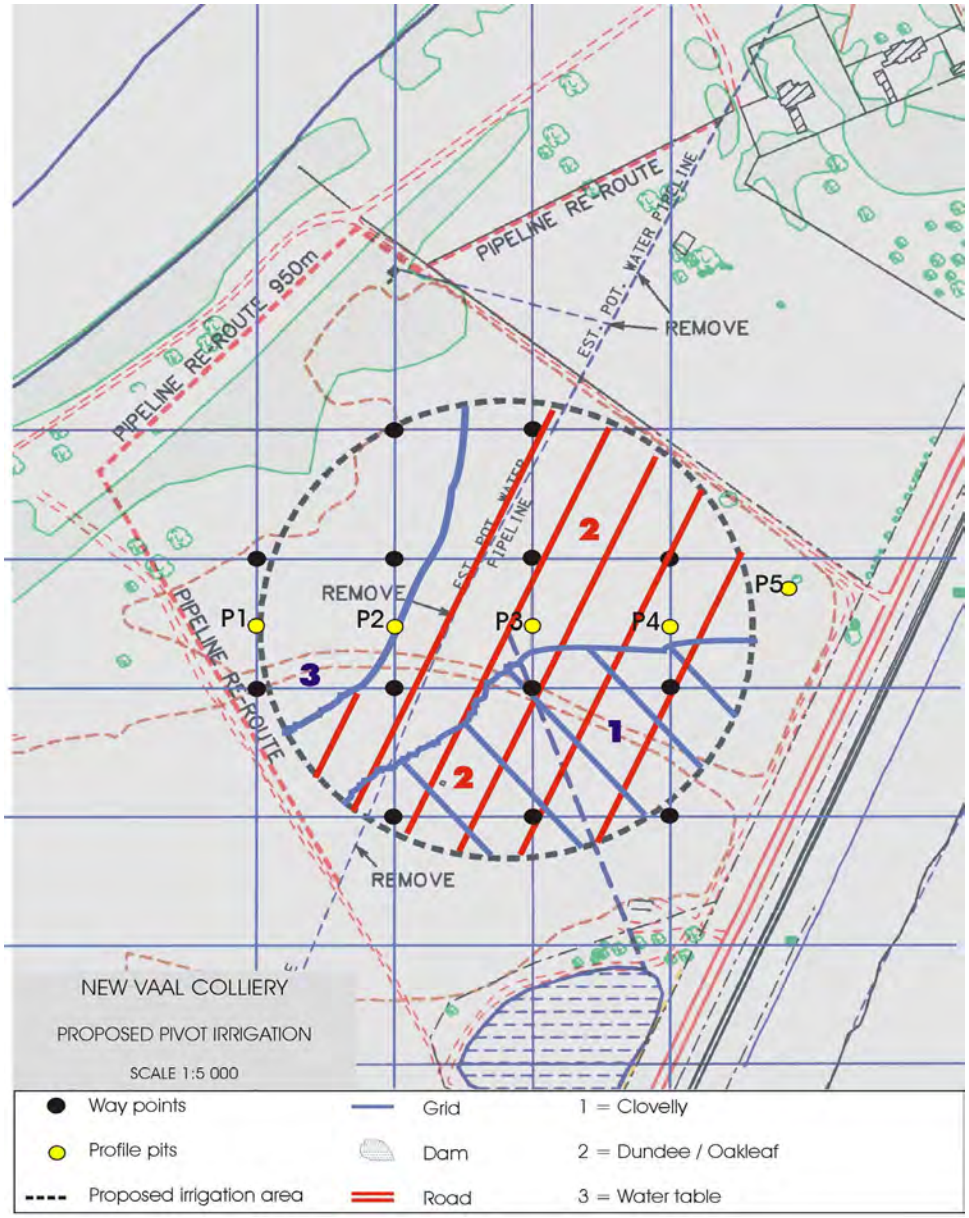


Figure 3.10 Map of New Vaal field trial

The total yield obtained from the crops from 2000 to 2005 is summarized in Table 3.3.

Table 3.3 Crops, cultivars and yields obtained at New Vaal irrigated with gypsiferous mine water.

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, 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 made 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 3.11).

Figure 3.11 Waterlogging at New Vaal during Summer 2003/2004.

During the trial period, larger volumes of water were irrigated during winter season than during summer months, example is in Figure 3.12 for site Major. No symptoms of foliar injury due to centre pivot sprinkler irrigation with Na_2SO_4 and gypsiferous mine water were observed for all crops.

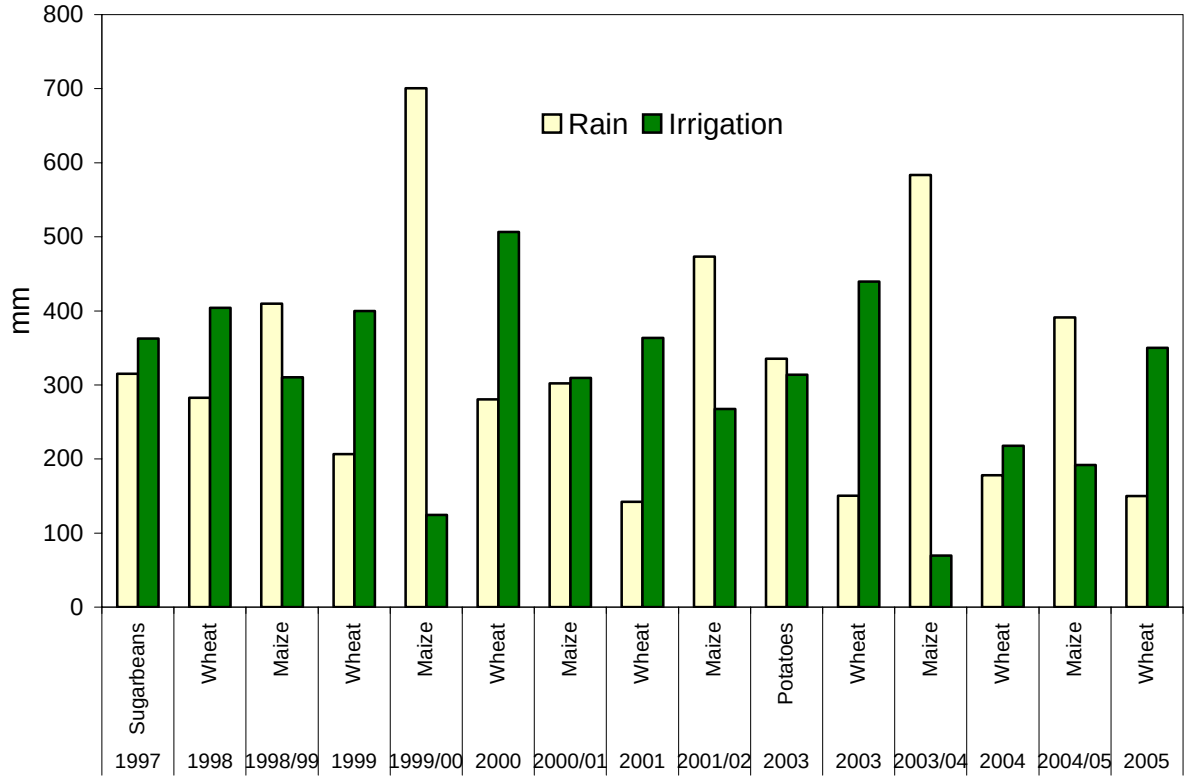


Figure 3.12 Rainfall and irrigation measured in site Major during the 15 seasons crop rotations

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 with irrigated wheat yields 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 is 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 is 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 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 do 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.

3.2 Plant nutrition

Introduction

Plants need essential elements for normal growth and development. Primary nutrients like N, P and K are required in the greatest quantities, secondary elements (Ca, Mg, S) in lesser quantities and micronutrients (Fe, Mn, Zn, Cu, B, Mo, Cl) in very small amounts (Klausner, 1995). Plants get all these nutrients from fertilizer and/or the soil. Three of the elements that plants need-hydrogen, oxygen and carbon-come from water and the atmosphere.

There are different levels of knowledge about functions of essential elements in plants (for more detail see Epstein (1972) and Mengel and Kirkby (1987)). For instance, N is an integral constituent of essential metabolites (amino acids, proteins, nucleotides chlorophyll), P plays a role in physiological processes (energy transfer and membrane integrity), K is important for translocation and stomatal opening, S for protein synthesis and functioning (amino acids, co-enzymes), Ca for membrane maintenance (Calcium pectates), Mg for CO_2 assimilation (as constituent of chlorophyll), Cl for maintenance of electrical neutrality (internal turgor), Cu for lignin synthesis (as a constituent of ascorbic acid oxidase and phenolases), and Zn is essential for certain physiological processes (auxin metabolism and nucleotide synthesis).

These essential elements may also have non-specific roles in plant growth, which may be additional to the specific functions listed. However, the symptoms of deficiency or toxicity, which are most characteristic of a particular nutrient, are those in which one specific function has a much greater requirement than the other functions. For example, it is the impairment of auxin metabolism in Zn-deficient plants that leads to characteristic symptoms of leaf distortion and inter-node shortening (rosetting). Furthermore, deficiencies of S, Fe and Mn all lead to decreased chlorophyll concentrations within the plant. Therefore, it is difficult sometimes to identify the symptom of a particular element, as there are interactions and similarities in effect (Mengel and Kirkby, 1987).

3.2.1 Sufficiency Ranges (SR)

The plant analysis interpretation made in this study uses sufficiency ranges (norms) to interpret the nutrient levels found in plant tissue samples. Excessive levels of nutrients are not always toxic. For example, excess potassium is not harmful unless it is associated with high soluble salts, or creates a significant imbalance with other nutrient concentrations. However, plants are very sensitive to excess levels of micronutrients, which are toxic in most cases. Furthermore, leaf analyses are most reliable when soil water and other stress-related factors are not influencing growth (Reuter, 1986).

In this study plant samples were taken at different stages. The analyses were done for nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulphur (S), zinc (Zn), boron (B), manganese (Mn), iron (Fe), copper (Cu), aluminum (Al) and sodium (Na). The aims of the analyses were to evaluate nutrients in the soil-plant system and to evaluate the effectiveness of fertilizers applied to the gypsiferous water irrigated soils. The results were interpreted by the Sufficiency Range (SR) approach; the SR is defined as the range in concentration that can result in 95 to 100% of maximum yield (Reuter, 1986). The SR given is

related to a particular crop, plant part, and time of sampling. The sufficiency range of the plant analysis results for the irrigation sites is discussed below.

3.2.1.1 Kleinkopjé

In summer 2000/2001, the N contents of maize were below the normal range in the early stages of crop growth. They became fairly high 67 to 74 days after planting and were normal again towards the end of the growing season. K contents on most samples were higher in the early stages and decreased 67 to 69 days after planting, as K was translocated from old leaves to new growth. K increased towards the end of the growing season in all the fields. Cu and Fe were higher at 69 to 74 days after planting for all pivots. The remaining analyses of maize plant material were normal. Zn was also higher towards the end of the season in all pivots.

In winter 2001 at TWF and Major, the N contents of wheat were higher at the tillering stage than the normal range and decreased at the heading stage. Fe and Mn were high throughout the growing season. SO_4 and K were also above the sufficiency range. This could be related to the presence of high SO_4 in the irrigation water and high NPK fertilization.

In summer 2001/2002, N and K were in the normal range for all the sites. SO_4, Fe and Cu were, however, higher than the normal range.

In summer 2002/2003, N, K and SO_4 were above the normal range in maize grown at TWF and Pivot Four. The other cations were within the normal range. The high N and K levels in the tissue were generally due to excessive NPK fertilization. The high SO_4 in the plant tissue was undoubtedly due to the high SO_4 levels in the soil solution coming from the irrigation water.

During winter 2003 wheat season, N, K, SO_4 and Fe were higher 87 days after planting than the normal range, whereas the other nutrients remained below the range until 115 days after planting. This is because plant samples were taken mistakenly from compacted soils that typically restricted root development and exhibited typical nutrient deficiency symptoms. Accumulation of excess SO_4 in the plants was also observed.

In summer 2003/2004, N and K were lower than the normal range. This is due to inadequate N and K fertilization. As a result, older leaves showed necrotic spots and marginal burn. Fe and Zn were higher than the normal range throughout the growing period of maize in all three sites (Major, TWF and Pivot Four). High Fe test results normally indicate soil or dust contamination of the plant.

In summer 2004/2005, N and K were measured below the normal range and marginal leaf burn was also observed during the growing period. SO_4, Fe and Zn, on the other hand, were higher than the normal range. Accumulation of excess SO_4 in the plants could be due to high SO_4 in the irrigation water.

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 was traced in all the pivots in Kleinkopjé, this could be as a result of low K/(Ca + Mg) ratio in the soil. Examples for SO_4, Mg and K are indicated in Figures 3.13, 3.14 and 3.15. The nutrient concentrations within

plants were also not uniform and varied with time through the growing period. However, it did not cause any nutrient disorder in the plants.

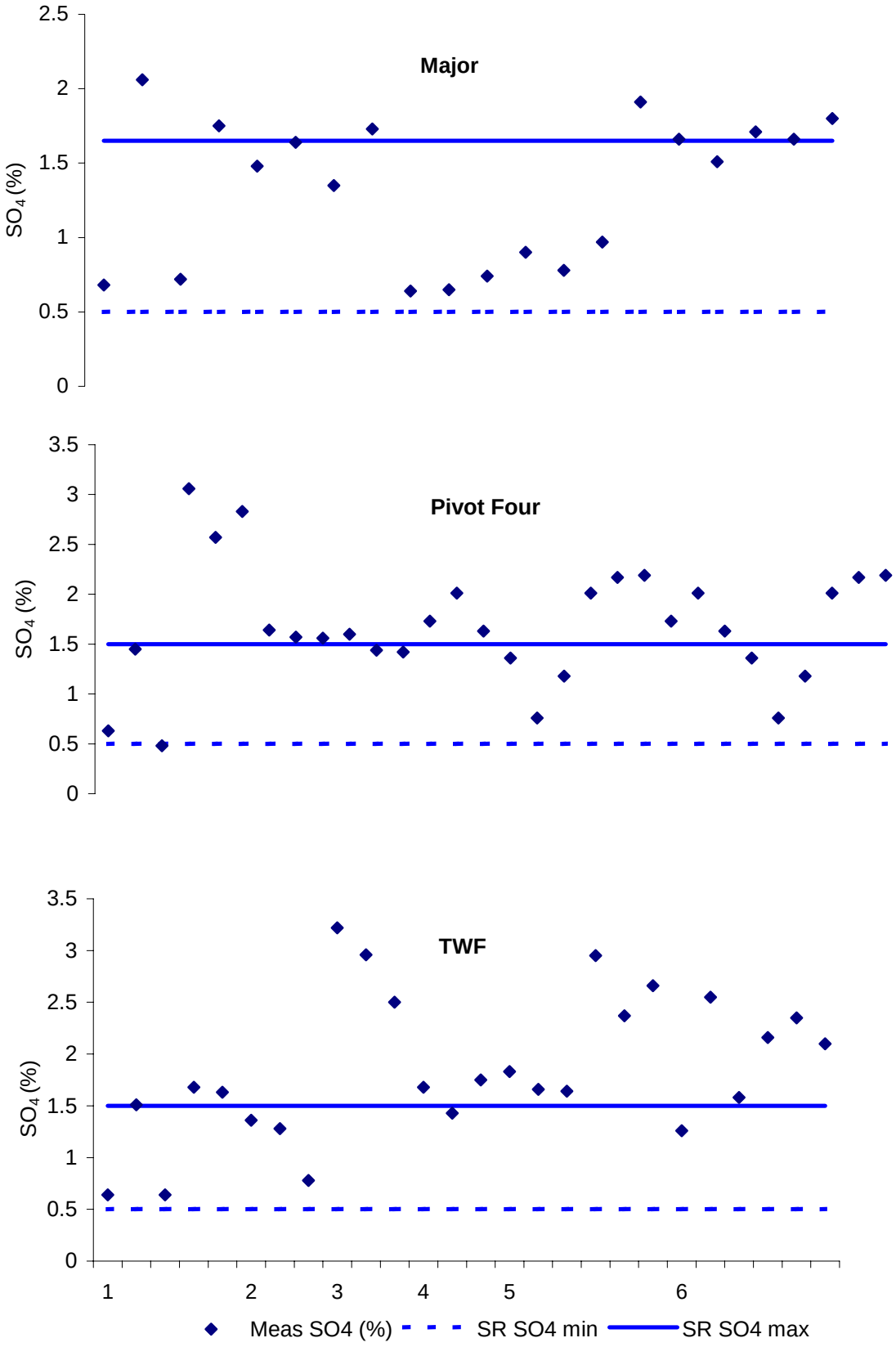


Figure 3.13 SO_4 concentrations in maize leaves compared to SR during the trial period at Kleinkopjé.

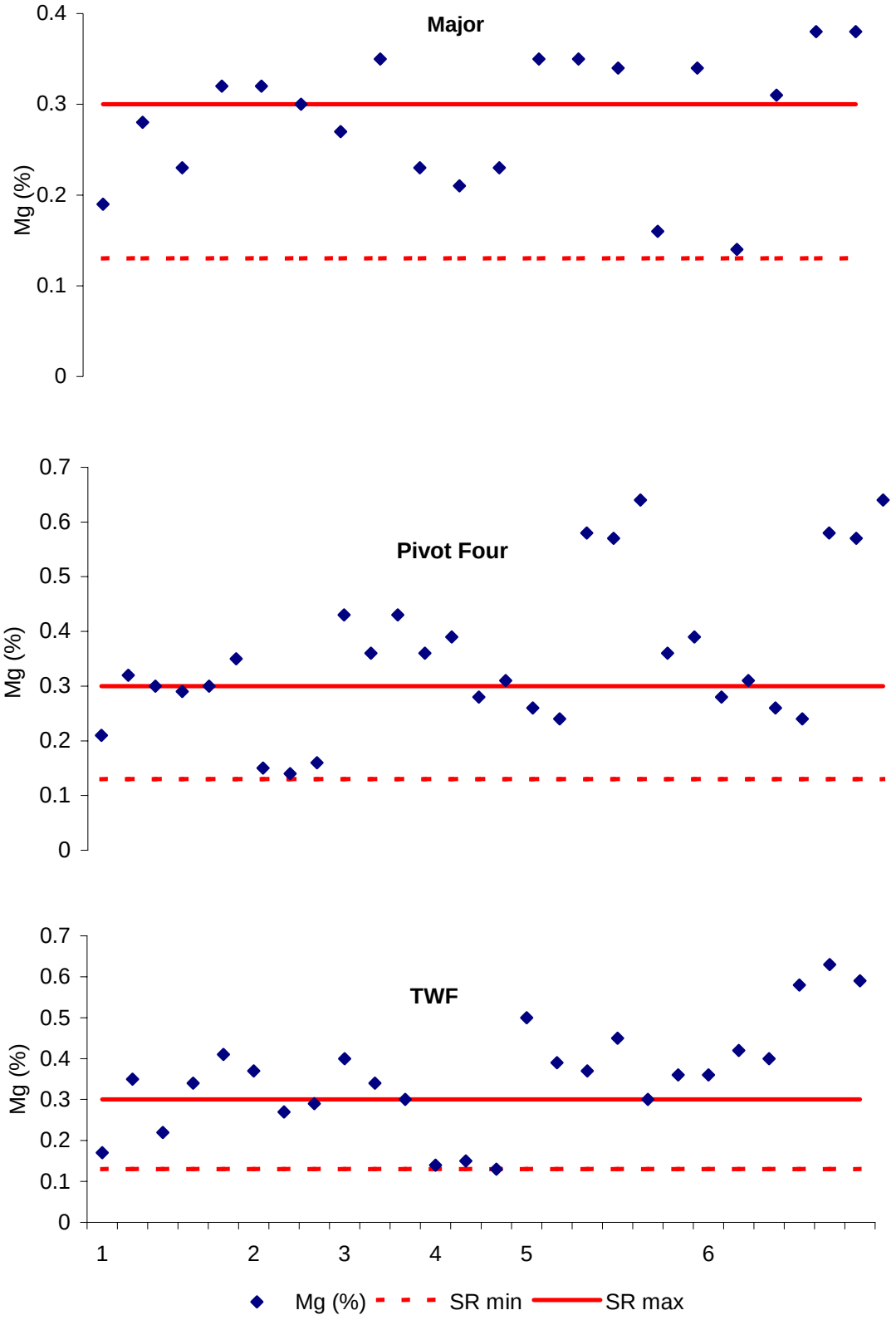


Figure 3.14 Mg concentrations in maize leaves compared to SR during the trial period at Kleinkopjé.

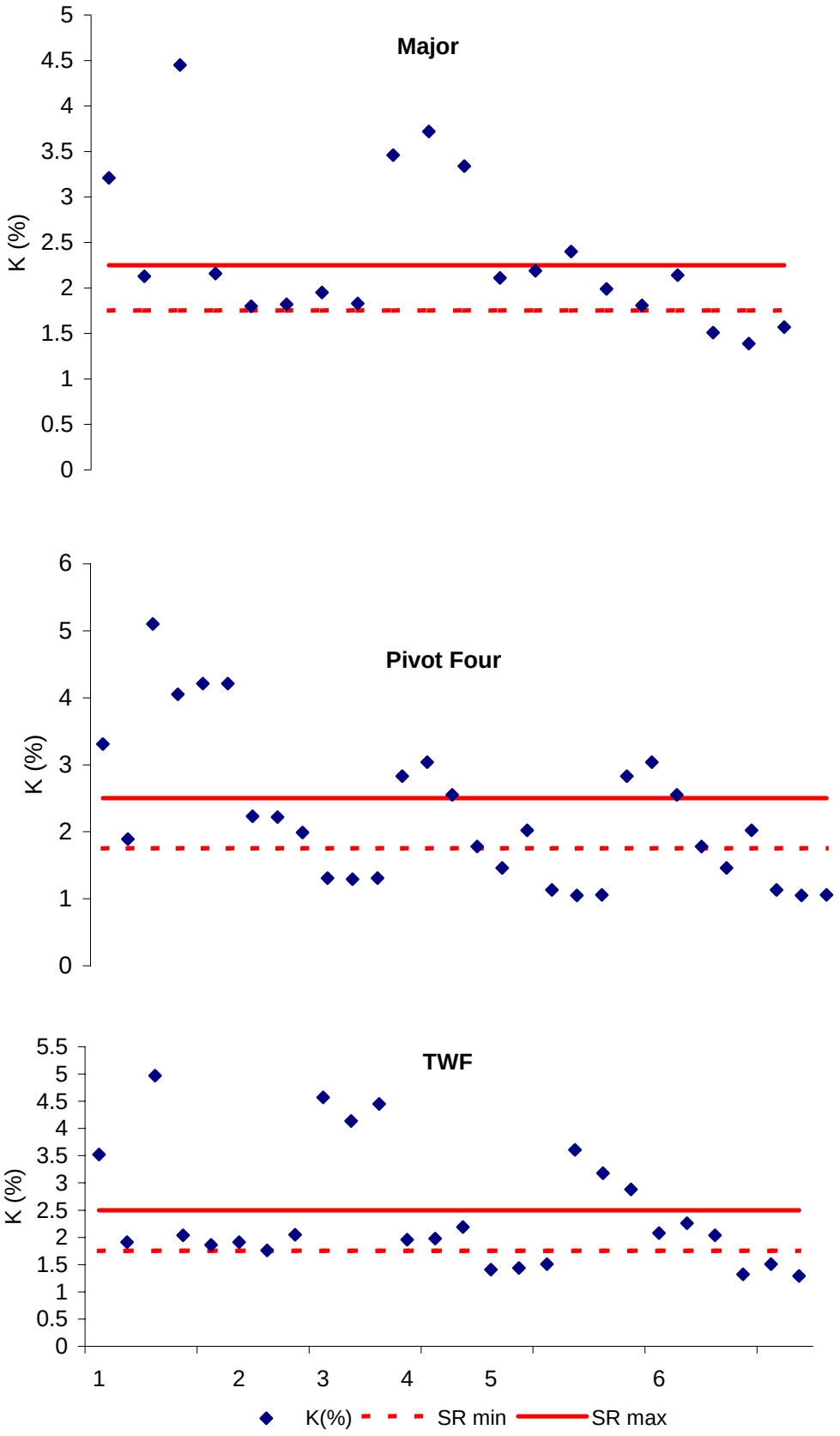


Figure 3.15 K concentrations in maize leaves compared to SR during the trial period at Kleinkopjé.

3.2.1.2 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, 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, to increase 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 increase again by 96 DAP. Fe also was high at 96 DAP. There were no observations of nutrient disorder during the trial period.

Plant analyses results from soybeans at different stages during the growing period are listed in Appendix B. The results of the analysis 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 (Example is indicated for K (%) and Mg (%) in Figures 3.16 and 3.17.) Similarly, the plant analyses results of peas showed no nutritional imbalances for the growing period.

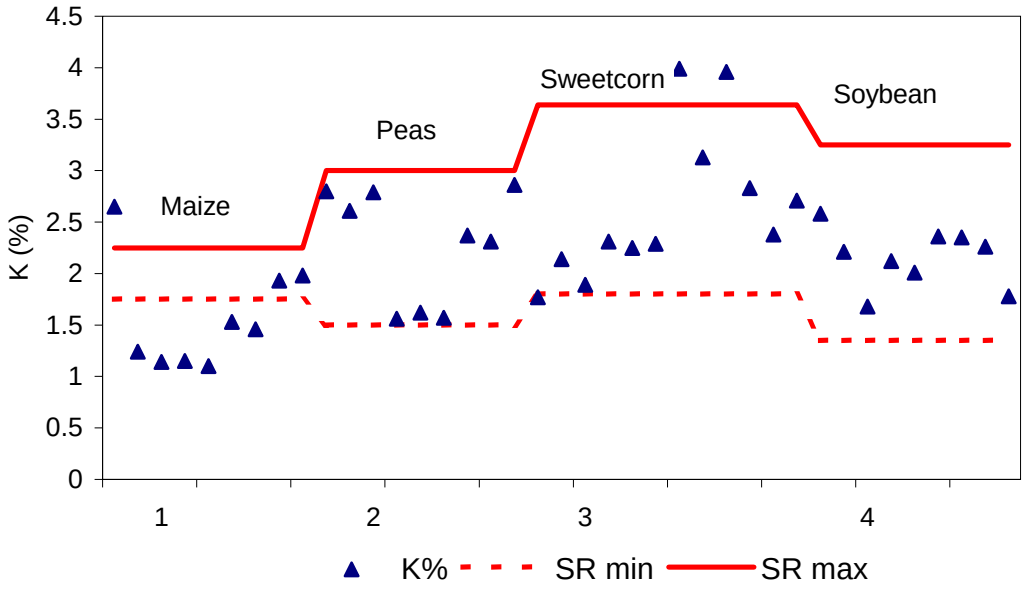


Figure 3.16 K concentrations in different crops compared to SR during the trial period at New Vaal

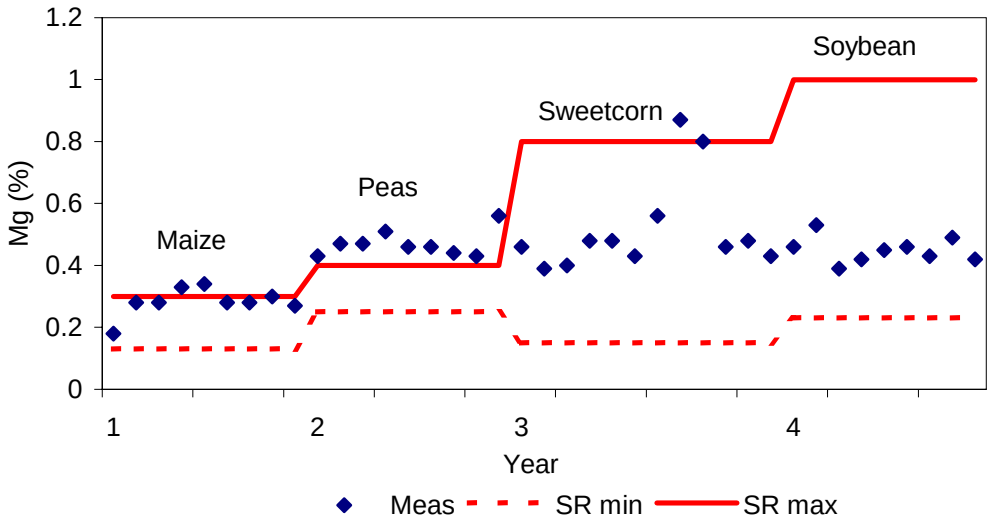


Figure 3.17 Mg concentrations in different crops compared to SR during the trial period at New Vaal

In conclusion, the possibility to incur deficiency and toxicities 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.

3.2.1.3 Syferfontein

The N and Crude Protein contents of the pastures were determined from the plant analysis results for 2002 and 2003. These were compared to the quality of pastures grown under fresh water irrigated conditions cited in South African literature. The quality for fescue and lucerne was in the expected range (Beletse, 2004). As a result, the effect of the quality 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.

3.2.2 Potato nutrition

Calcium is an essential plant macro nutrient for maintaining cell wall stability. In potatoes, calcium related disorders are believed to be the result of limited calcium transport to the tuber. Low tuber calcium concentrations have been associated with internal brown spot of the tuber, which is a physiological disorder associated with the necrosis of the medullary tissue.

In previous investigations, various calcium sources were tested out to supply additional Ca to potato plants, in an attempt to increase Ca concentration in the tubers. Gypsiferous mine wastewater, which contains high levels of Ca, can possibly be used as a source of additional Ca to potatoes, when used for irrigation.

Potato crop response to gypsiferous mine water was investigated in field studies at Kleinkopjé mines. Potatoes were produced in 2 seasons under centre pivot irrigation (2001 on Pivot Four and in 2002 on Pivot Major). Leaf chemical analyses were conducted twice during each of the production seasons to determine the effect of high calcium levels on the uptake of other nutrients. Tissue nutrient concentrations were determined for leaf blades sampled 89 and 130 days after planting (DAP) in 2001, and 86 and 130 DAP in 2002.

In both seasons, no nutrient deficiencies on the leaves were 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 and 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. More detail on the nutritional status of potatoes in this study can be found in Appendix H.

3.2.3 Potassium (K) nutrition

Maize leaf analyses for all pivots, showed a decrease in K levels from the end of summer 2003/04 (Figure 3.15). In the same period, however, ammonium acetate extractable K (K-NH_4Aoc), in the soil increased (Figures 3.19(B) & 3.20(B)). Ca and Mg dominated the cations in the irrigation water. These high concentrations in solution can suppress K uptake and induce K deficiencies (Barber, 1984). NH_4Aoc [K]/[Mg] ratios decreased with time for both Pivot Major and Pivot Four (Figure 3.18 (A & C)). Water-soluble [K]/[Mg] ratio for Pivot Four (Figure 3.18 (D)) fluctuated with time and did not show a clear increasing or decreasing trend. Water-soluble [K]/[Mg] ratio for Pivot Major (Figure 3.18 (B)) at first decreased with time, but increased again in Summer 2004/05. The decrease in K leaf levels, however, coincided with an increase in Mg levels (Figure 3.14), which suggests that Mg suppressed K uptake to some extent. It was difficult to elucidate what role Ca and Mg played in K uptake suppression. [K]/([Mg]+[Ca])-NH_4Aoc (Figure 3.19(A) & Figure 3.20(A)) also generally decreased with time, similar to [K]/[Mg]-NH_4Aoc. The [K]/([Mg]+[Ca])-NH_4Aoc ratio was, however, an order of a magnitude lower than [K]/[Mg]-NH_4Aoc. Gypsum is also extracted with NH_4Aoc, making the use of the [K]/([Mg]+[Ca])-NH_4Aoc ratio, to predict suppression of K caused by competitive uptake of Mg and Ca, questionable in these systems. The water-soluble [K]/([Mg+[Ca]) ratio (Figure 3.19(C) & 3.20(C)), however, was comparable to [K]/([Mg]+[Ca])-NH_4Aoc and Ca concentration in saturated paste extracts was equal to the Mg concentration. It was therefore more likely that K uptake was suppressed by both divalent cations.

The irrigation water contains more Na (40-50 mg ℓ^{-1}) than K (10-15 mg ℓ^{-1}). Pivot Major and Pivot Four showed contrasting pictures when water-soluble NH_4Aoc extractable [K]/[Na] were compared (Figure 3.21). Both water-soluble and NH_4Aoc extractable [K]/[Na] were lower for Pivot Four than for Pivot Major. There was also more Na than K in the 120 cm soil profile of Pivot Major and Pivot Four. [K]/[Na]-NH_4Aoc ratios, however, showed the same trend as ([K]/[Mg]+[Ca])-NH_4Aoc for both Pivots. The ratios increased whilst K levels in the foliage reached their lowest levels. It seems, unlikely that the decrease in K levels in maize leaves from summer 2003/04 to summer 2004/05 was caused by a Na induced K nutritional imbalance in the soil.

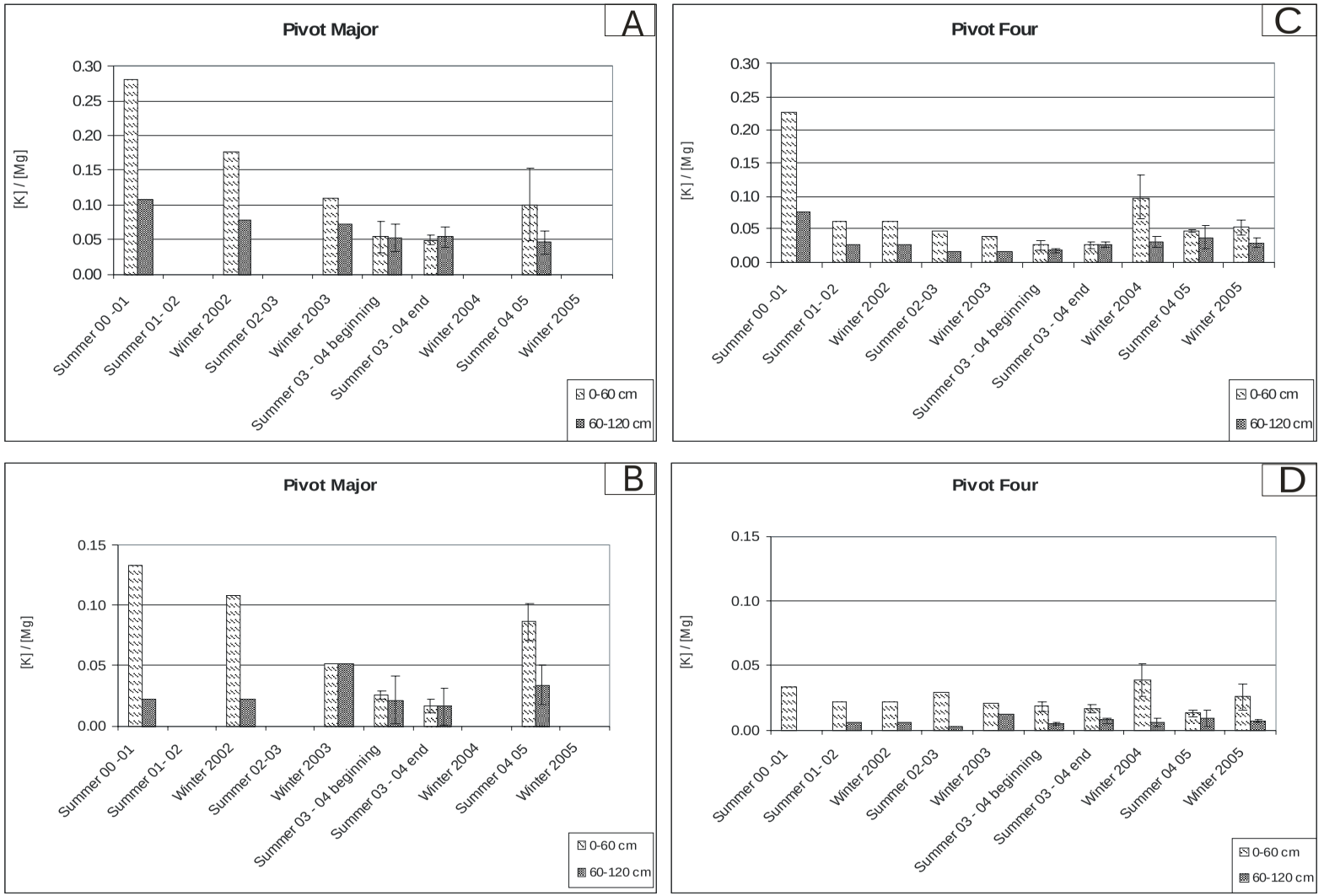


Figure 3.18 Temporal changes in [K]/[Mg]-NH_4Aoc (A) and water-soluble [K]/[Mg] (B) for Pivot Major and [K]/[Mg]-NH_4Aoc (C) and water-soluble [K]/ [Mg] (D) for Pivot Four

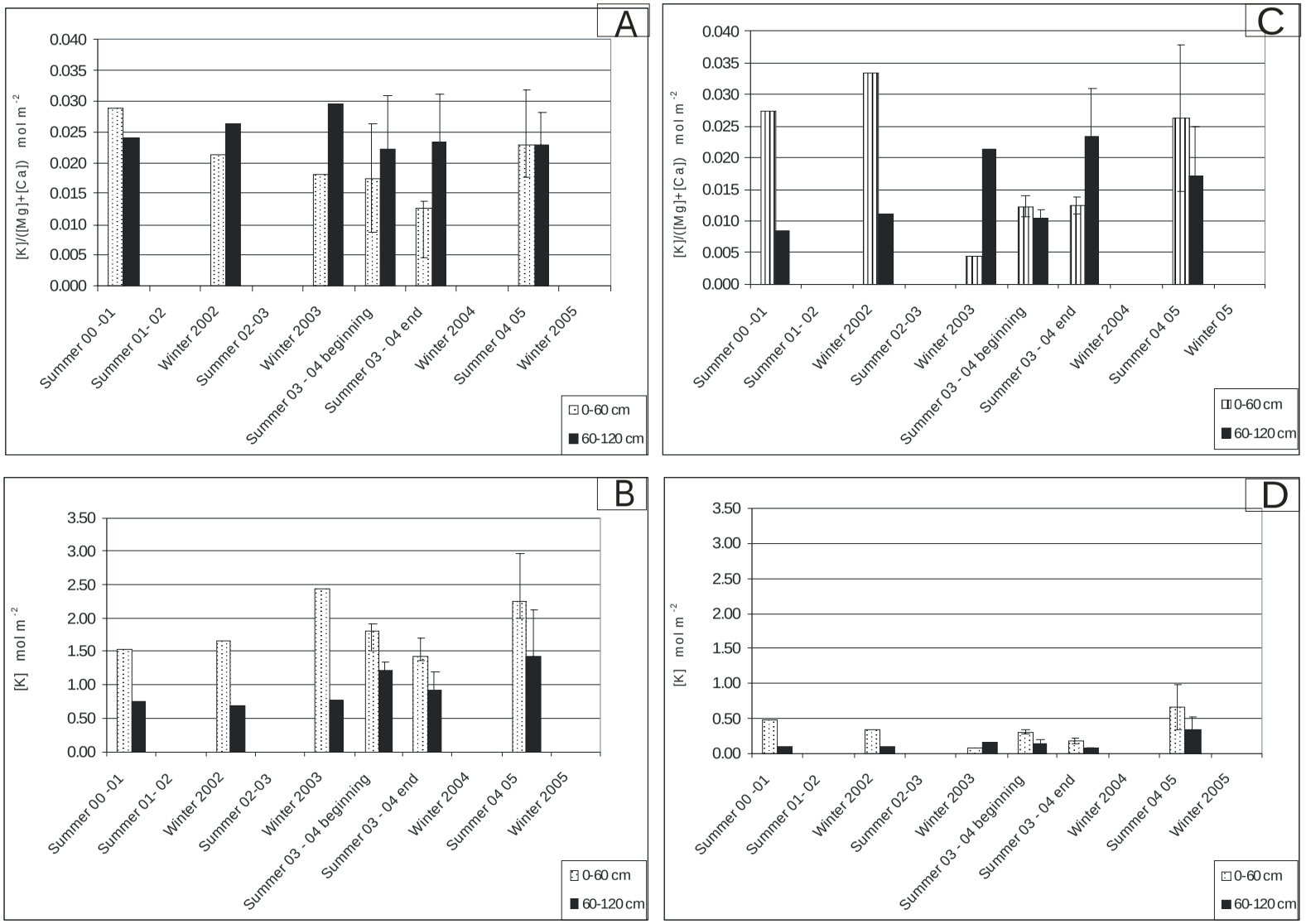


Figure 3.19 Temporal changes in [K]/([Mg+[Ca])-NH_4Aoc (A), K- NH_4Aoc (B), water soluble [K]/([Mg+[Ca]) (C) and water-soluble K (D) for Pivot Major

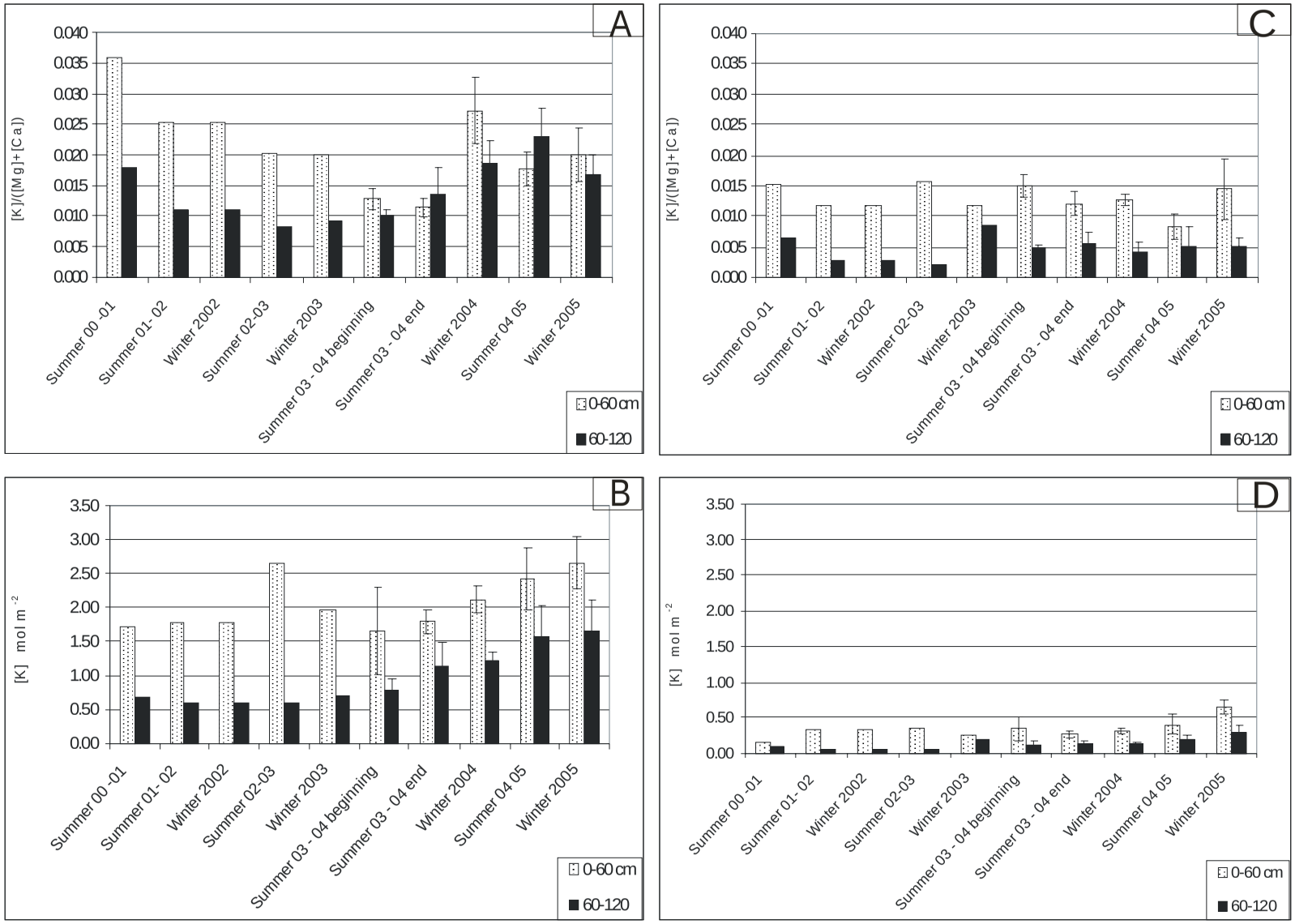


Figure 3.20 Temporal changes in [K]/([Mg+[Ca])-NH_4Aoc (A), K-NH_4Aoc (B), water soluble [K]/([Mg+[Ca]) (C) and water-soluble K (D) for Pivot Four

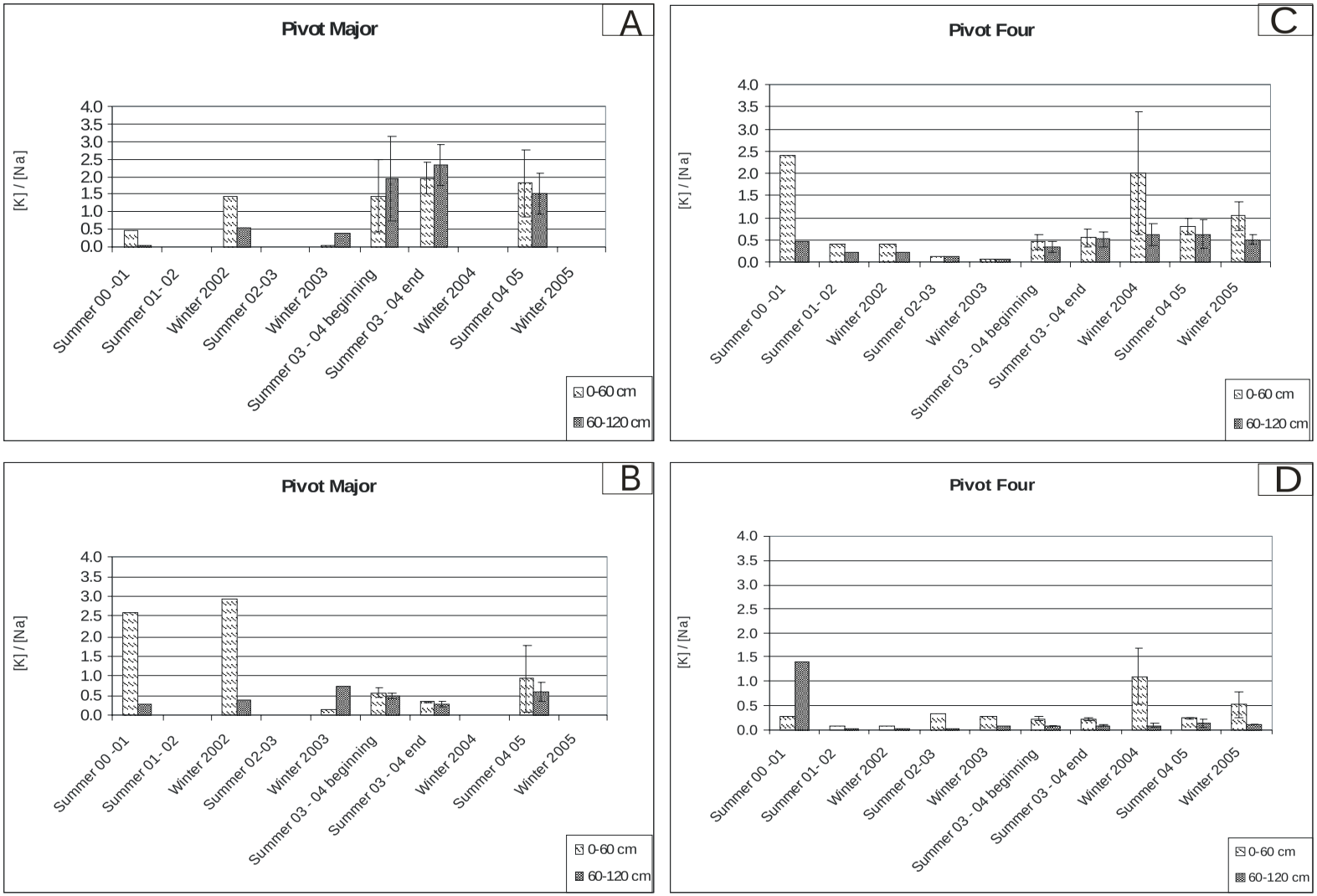


Figure 3.21 Temporal changes in [K]/[Na]-NH_4Aoc (A) and water-soluble [K]/[Na] (B) for Pivot Major and [K]/[Na]-NH_4Aoc (C) and water-soluble [K]/ [Na] (D) for Pivot Four

3.2.4 Interpreting soil test results – fertilizer recommendations

The farmer was advised on several occasions to apply additional Mg, despite the fact that more than a ton ha^{-1} Mg is added to the field each year through irrigation. To our knowledge, the plants did not show any Mg deficiencies to justify this recommendation.

The recommendations were, of course, based on the common practice of using exchangeable cation ratios, e.g. the Ca to Mg ratio, to predict possible Mg or Ca deficiencies. The underlying assumption is that adsorbed cations have low water extractability and soil minerals are sparingly soluble, therefore the source of Ca and Mg to the plants is predominantly in the exchangeable form. However, these pivots are not normal agricultural systems. The irrigated soils contain considerable amounts of soluble salts, and high concentrations of Mg in solution (Table 3.4) as a result of the constant input of Mg through irrigation. Under these conditions, the contribution of Mg in solution to plant nutrition cannot be ignored.

The normal routine soil analytical method to differentiate between exchangeable and soluble Ca is also not applicable to soils that contain gypsum. Gypsum is soluble in ammonium acetate, and therefore the difference between ammonium acetate extractable Ca and Ca concentrations in saturated pastes is **not only exchangeable Ca**. Assuming that this difference is exchangeable Ca will result in an over estimation of “exchangeable Ca” and an over estimation of the Ca:Mg ratio on the exchange complex and erroneous interpretation of the analytical results. This is illustrated in Figure 3.23 from a soil sample taken at Pivot Major in June 2004.

With gypsum-rich soils, all soluble Ca is not removed when preparing a saturated paste. To calculate the 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.

Figures 3.22 and 3.23 show the interference of gypsum on exchangeable Ca determination and over estimation of the exchangeable [Ca]/[Mg] ratio on samples collected from Pivot Major in June 2004. 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. Therefore, according to the guideline norm of Reuter (1986) for this ratio, the canopy would recommend applying Mg, but in actual fact the more reliable indicator of this ratio shows that such an application would not be necessary.

Table 3.4 Saturated paste extracts of selected samples from Pivot Major sampled on 2004/06/25.

Sample number	EC mS m^{-1}	Ca mg ℓ^{-1}	K (mg ℓ^{-1})	Mg (mg ℓ^{-1})	Na (mg ℓ^{-1})	P (mg ℓ^{-1})	S (mg ℓ^{-1})
M 5 (0-30)	276	**583**	14.6	**49**	6.4	0.13	590
M 5 (30-60)	354	**568**	25.2	**204**	20.1	0.058	811
M 5 (60-90)	393	**547**	12.7	**313**	48.2	0.005	903
M 5 (90-120)	302	**341**	6.0	**223**	51.7	0	594
M 11 (0-30)	332	**602**	24.7	**91**	17.9	0.133	737
M 11 (30-60)	384	**548**	18.3	**254**	41.9	0.084	872
M 11 (60-90)	385	**504**	21.0	**302**	50.8	0.011	861
M 11 (90-120)	351	**359**	20.9	**296**	70.7	0.042	744

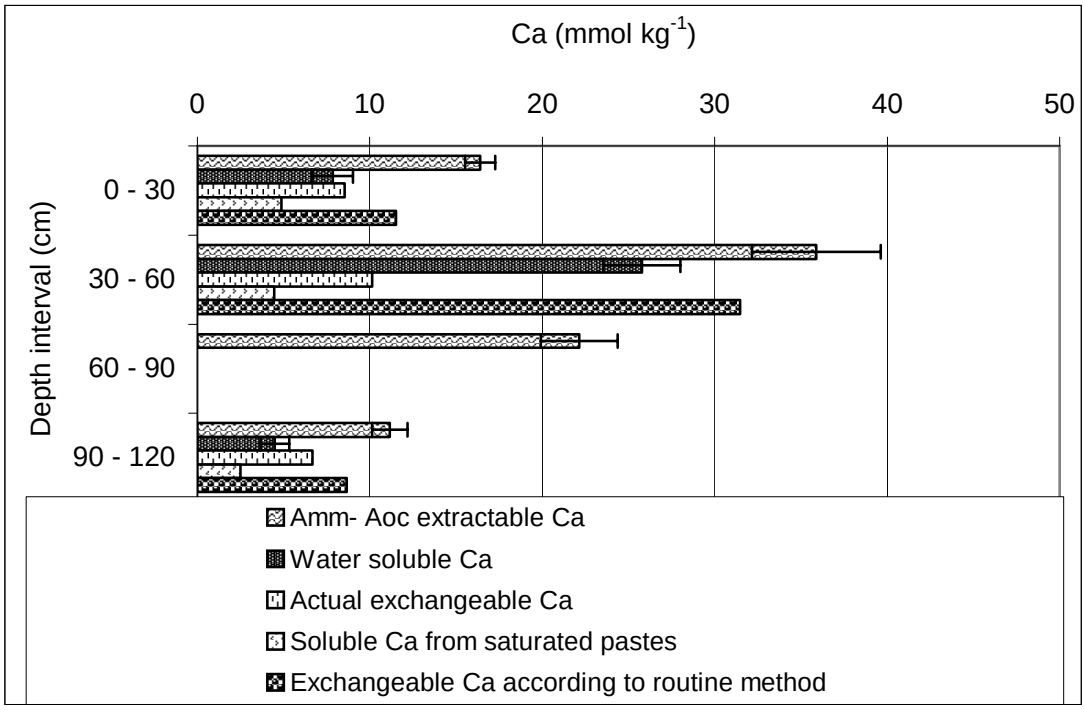


Figure 3.22 Interference of gypsum in the determination of exchangeable Ca using the routine method described above.

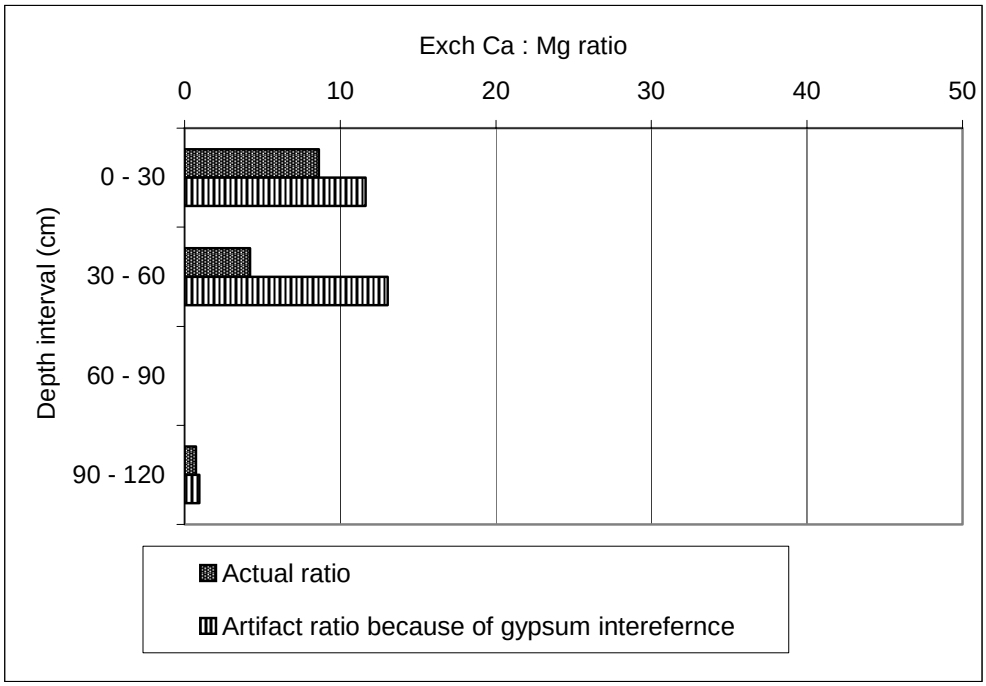


Figure 3.23 Actual Ca:Mg ratio versus artifact Ca: Mg ratio because of gypsum interference

Conclusions

In conclusion, results of plant analysis were useful to diagnose nutrient deficiencies and to reveal imbalances between nutrients that can cause unfavorable 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 becomes 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 overtime. At New Vaal, the results indicated that the nutrient concentrations were found to be within the SR (norms). The possibility to incur deficiency and toxicities 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.

The fertilizer amount applied was also assessed if it has an effect on crop response. The fertilizer was sufficient enough for optimum yield for good quality water irrigated crops. The yields obtained from gypsum-rich water irrigated crops, however, could be promoted more if more fertilizer is applied than the crop requires. In this study the farmer, despite the fact that more than a ton ha^{-1} Mg is added to the field each year through irrigation, applied high Mg containing fertilizer. As a result high Mg was found in the soil solution that suppressed the uptake of K by the plants.

CHAPTER 4

4. SOIL CHEMICAL PROPERTIES

Introduction

In this chapter, the environmental impact of irrigation with Neutralised Acid Mine Drainage (NAMD) on soil chemical properties was assessed. The impact was determined by taking soil samples in different locations in the pivots at the end of each season and along a down-slope transect across the pivots. The aim was to understand the environmental soil chemistry, as Ca, Mg and SO_4 added through irrigation are critical for determining the sustainability of crop production under irrigation with NAMD. The first section, describes the temporal and spatial variation in soil chemical properties in the soil profile. The second part discusses gypsum determination and the role of gypsum precipitation in Ca and SO_4 immobilisation in the irrigated fields.

4.1 Temporal and spatial variation in soil chemical properties

Soil samples were collected at the end of each season to monitor temporal changes in soil chemical properties. The samples were taken at all the pivots throughout the profile depth. Until winter 2003 a single soil sample per depth interval was taken from the pivots for each season. Since the beginning of summer 2003/04 samples were taken randomly at three or four locations at each pivot. Care must therefore be taken when interpreting and comparing soil analysis data from different seasons, especially data earlier than summer 2003/04. Differences could merely be the result of spatial variability.

Soil samples were also collected along a down slope transect across both Pivot Major and Pivot Four on 2004/06/25. The samples were collected every 50 m, starting and ending 100 m outside the pivots (Figures 4.1-4.2) at depth intervals of 30 cm to a depth of 120 cm, or when the limiting layer was reached.

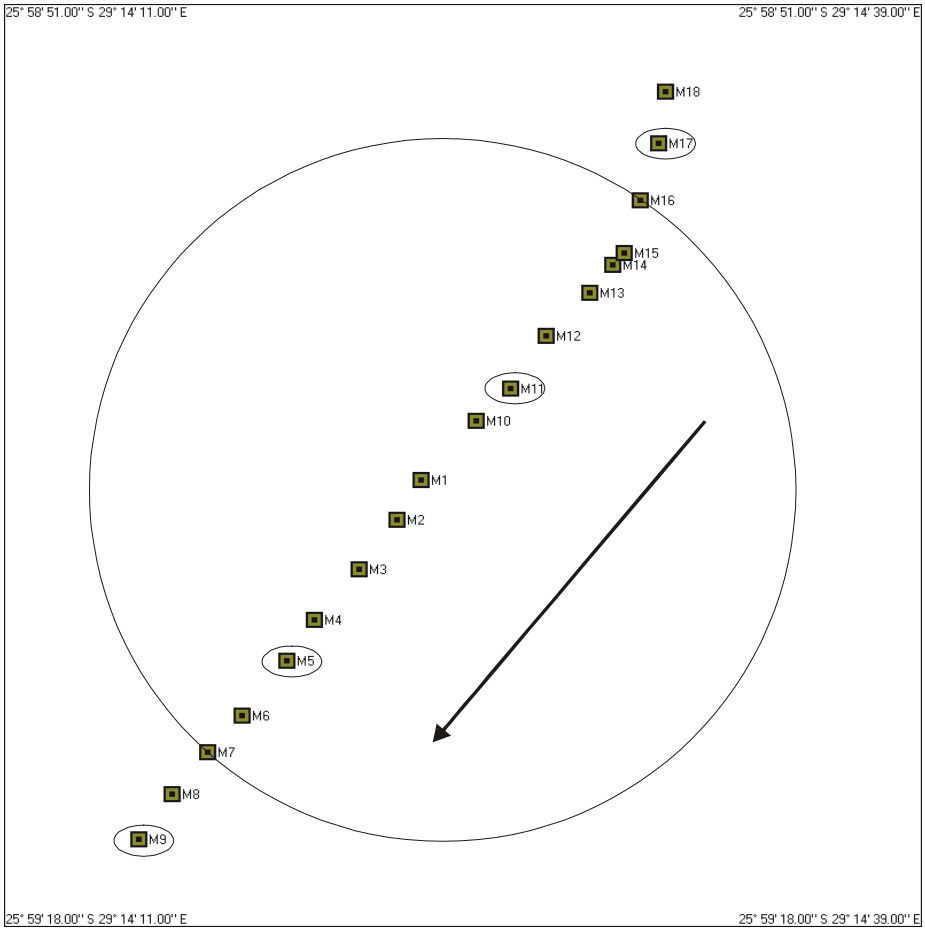


Figure 4.1 Location of sampling points at Pivot Major. Arrow indicates direction of the slope

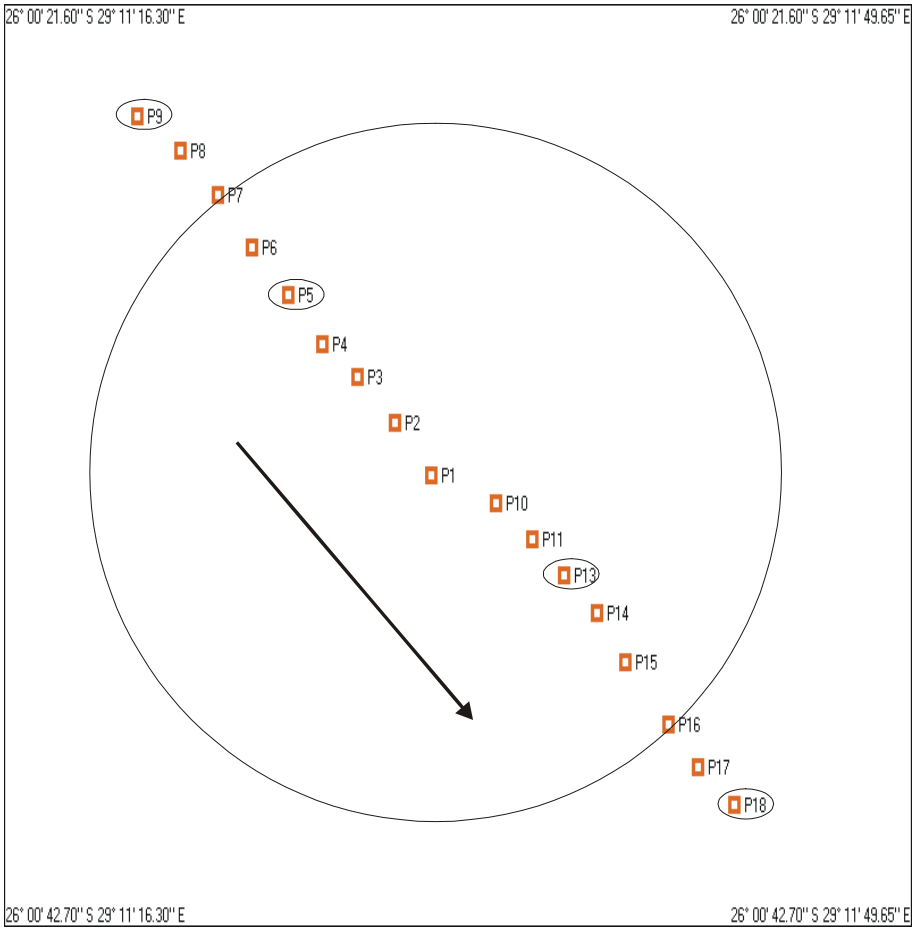


Figure 4.2 Location of sampling points at Pivot Four. Arrow indicates direction of the slope.

Kleinkopjé: soil chemical analyses

The temporal analyses are reported in Appendix C (Tables 1C - 25C in chronological order).

Soil pH: temporal data

The alkalinity as well as the pH of the water from Tweefontein Pan, the irrigation water for Pivot Four, was greater than that of New Vleishaft Dam, the irrigation water for Pivot Major (Figure 4.3 (A & C)). The temporal pH data for New Vleishaft Dam was never higher than 8 and fluctuated between 5 and 7. The temporal pH data for Tweefontein Pan was never lower than 6 and fluctuated between 6 and 8. The alkalinity of the Tweefontein Pan water had no influence on soil pH at Pivot Four (Figure 4.3(D)). 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.

At Pivot Four there was a decreasing trend in the pH of the topsoil until the end of summer 2003/04. A dolomitic lime application of 3 t ha^{-1} in Winter 2004, increased pH of the topsoil in the subsequent summer season. The temporal pH data for Pivot Major did not show an increasing or decreasing trend (Figure 4.3(B)).

Soil pH: transect data

The pH values of each depth interval inside the Pivots in Figure 4.4 were the averages of 12 sampling points for each Pivot and 4 samplings points outside the irrigated areas. The samples were collected along the sampling transect as illustrated in Figures 4.1and 4.2.There was greater spatial variation, in both the 1 *M* KCl pH and deionised water soil pH, for the topsoil (0-60 cm) than for the subsoil (60-90 cm). This is attributed to fertilizer and lime input to the topsoil that was not uniformly distributed and possibly also traces of unreacted fertilizer and lime that find their way into the subsamples used for pH determination. At the time of sampling at Pivot Major the maize had just been harvested and the soil had not been prepared for the winter season and there were no recent inputs of lime or fertilizers. The lime was applied on the day of sampling at Pivot Four. In the lower part of the pivot the lime was already ploughed in. In the upper parts, from P10 to P7, the lime was not yet ploughed in and it was possible to remove most of it from the surface before samples were taken with an auger. The deionised water soil pH for the 90-120 cm depth interval was higher at both Pivot Major and Four compared to the outside samples. The differences in pH were attributed to a combination of the following factors:

- The increase in pH in the subsoil is attributed to the decrease in exchangeable acidity displaced by Ca and Mg
- Possible displacement of hydroxyl groups on metal (oxy)-hydroxide surfaces through inner sphere complexation of SO_4.

Differences in soil suspensions ionic strengths between inside and outside samples, will also influence proton activity and pH. Differences in pH between inside and outside samples can therefore not only be attributed to differences in acidity. Proton activity decreases with increasing ionic strength, and this will translate to an increase in pH. The saturated paste extract ionic strength for the 90 –120 cm of P9, the outside sample (Figure 4.2), was 0.25×10^{-2} compared to 6.48×10^{-2} for the sample depth interval of P11 (Figure 4.2). The proton activity coefficient was 0.84 for the 90 –120 cm layer of P11 compared to 0.95 for P9. The pH of a 10^{-5} *M* proton solution with an ionic strength of 0.25×10^{-2} would be about 5.0 (5.02) and the pH in a solution with an ionic strength of 6.48×10^{-2} would be 5.1 (5.08). Therefore, any consistent difference <0.1 in the deionised water soil pH between inside and outside samples, could possibly be an ionic strength effect.

The ionic strength differences are less between inside and outside samples for 1 *M* KCl pH, and pH differences cannot therefore be attributed to the ionic strength effect. Campbell (2001) reported a decrease in exchangeable acidity inside the pivots when compared to outside reference samples. The results for Pivot Major support these findings. H^+ and Al^{3+} were either displaced and removed from the soil profile, or in the case of Al^{3+}, was immobilised in a form that is not exchangeable, e.g. surface precipitation of hydroxysulphate solid phases. Simulations with PHREEQC showed in undiluted NAMD, the stability of alunite ($KAl_3(SO_4)_2(OH)_6$) is extended to

more alkaline conditions and is thermodynamically more stable than gibbsite up to a pH values approximately 6. At Pivot Four it was just the opposite, the 1 *M* KCl pH values for inside samples were lower than for outside, and increased with soil depth for both pivots. The results show that exchangeable acidity is greater for inside samples than for outside samples. H^+ and Al^{3+} are in forms that are readily displaced by, or soluble in 1 *M* KCl. The source of H^+ and Al^{3+} in the 90-120 cm depth may be displaced H^+ and Al^{3+} from the topsoil, which has been transported to the subsoil.

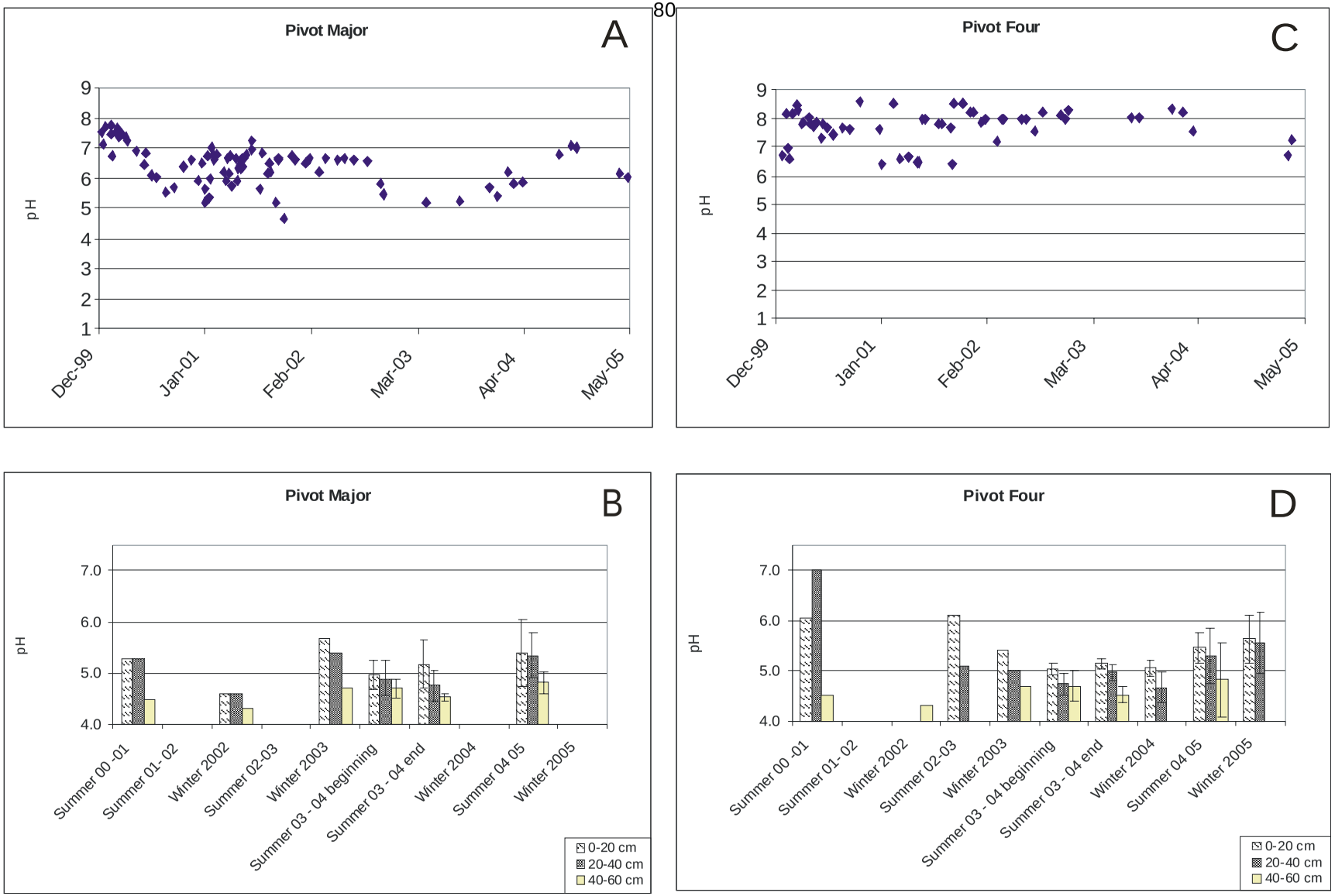


Figure 4.3 Temporal change in irrigation water pH for Pivot Major (A) and Pivot Four (C) and topsoil pH for Pivot Major (B) and Pivot Four (D).

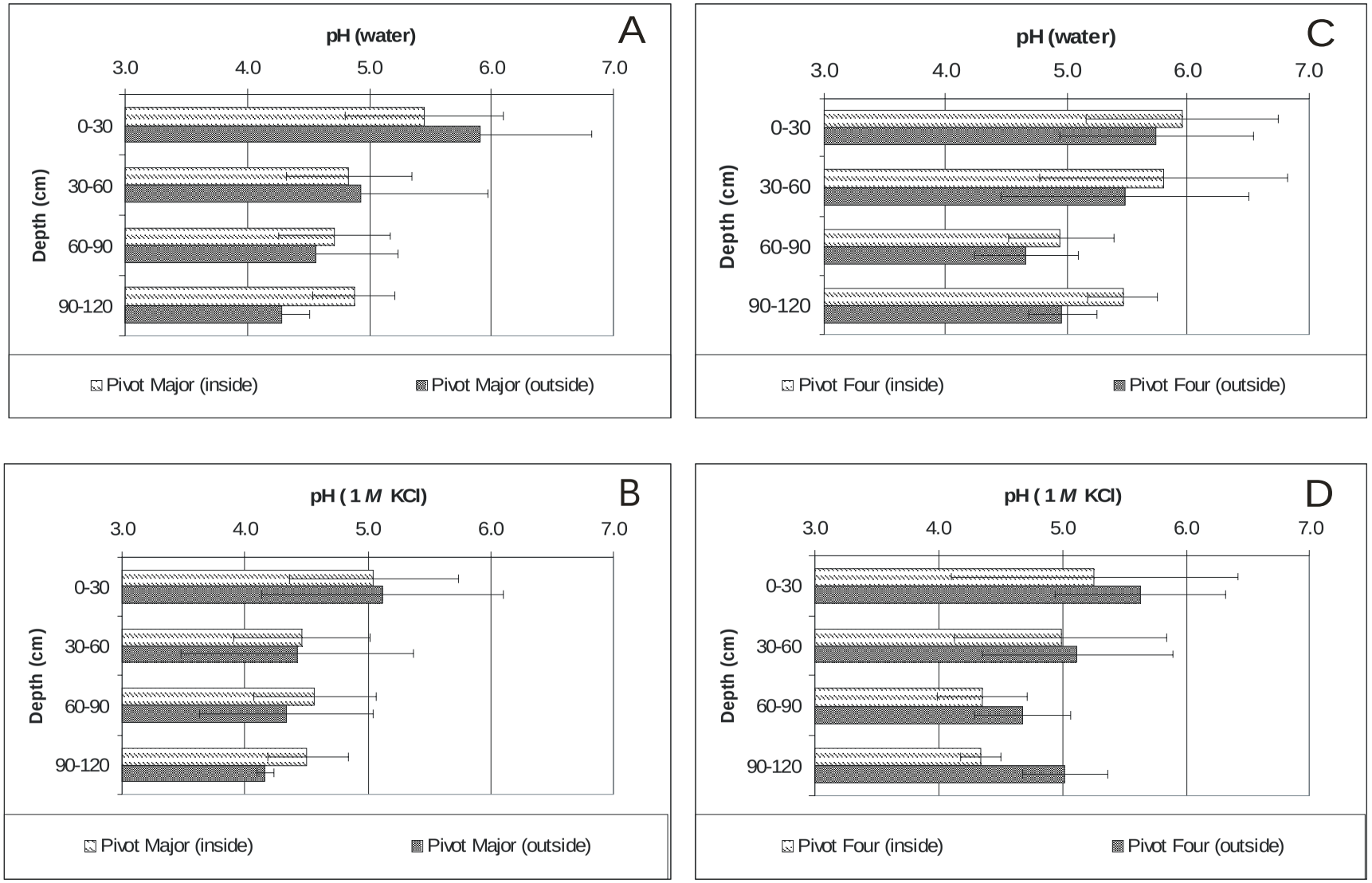


Figure 4.4. Change in deionised water pH (A) and 1 *M* KCl pH (B) for Pivot Major as a function of depth and change in deionised water pH (C) and 1 *M* KCl pH (D) as a function of depth for Pivot Four.

Soil salinity

Salinisation of the irrigated soils influences sustainable crop production negatively. It was, therefore, important to quantify salinisation on both a temporal and spatial basis to determine whether successive years of irrigation resulted in a build up of salts, or whether salinity remains relatively at certain levels. The water quality of New Vleishaft Dam stayed relatively constant. The average water EC for New Vleishaft Dam was 316 mS m^{-1}, and over the past 8 years the EC deviated only 13% from the average (Figure 2.15). From 1998 to 2001, the EC of the irrigation water at Tweefontein dam was similar to that of New Vleishaft Dam. Since 2001, however, the EC gradually increased to 500 mS m^{-1} in 2005. This deterioration of the water quality was the result of increasing Ca, Mg and SO_4 concentration in the water.

EC_e: Temporal data

The saturated paste electrical conductivity *(*EC_e) increased in the root zone over time at both Pivot Major and Pivot Four (Figure 4.5 (A & C)). EC_e in the root zone at Pivot Four, reached a maximum at the beginning of summer 2003/04. Thereafter, EC_e showed seasonal fluctuations increasing in the winter and subsequently decreasing again in the summer. At Pivot Major the EC_e did, on average, not exceed 400 mS m^{-1} in the rootzone. The EC_e in the root zone, at Pivot Four, exceeded 400 mS m^{-1} in the beginning of summer 2003/04. This was attributed to the deterioration of the water quality that Pivot Four receives. According to Maas and Hoffman (1977), at these levels of EC_e no yield reduction is expected for wheat but a yield reduction of 15% is estimated in maize.

ECe: Transect data

Salinity increased throughout the soil profile at both Pivot Major and Pivot Four (Table 4.1). At Pivot Four, the 90 – 120 depth interval had the highest EC_e whilst at Pivot Major the highest EC_e was found in the 60 – 90 depth interval. The EC_e value indicates a deeper movement of salts in the soils of Pivot Four than in Pivot Major. At depths greater than 60 cm the EC_e was higher at Pivot Four than at Major and exceeded 400 mS m^{-1}.

Table 4.1 Average EC_e of two locations inside and two outside Pivot Major and Pivot Four. (The locations are encircled in Figures 4.1 and 4.2). Sampling date 2004/05/25

Site	Depth interval (cm)	Soil saturated paste extract (EC_e)(mS m^{-1}) Inside	Outside
Major	0 – 30	304 ± 40	85 ± 1
	30 - 60	369 ± 21	58 ± 5
	60 - 90	389 ± 6	35 ± 0
	90 - 120	327 ± 35	60 ± 12
Pivot Four	0 – 30	312 ± 7	24 ± 10
	30 - 60	313 ± 40	18 ± 3
	60 - 90	408 ± 54	20 ± 2
	90 - 120	443 ± 88	20 ± 5

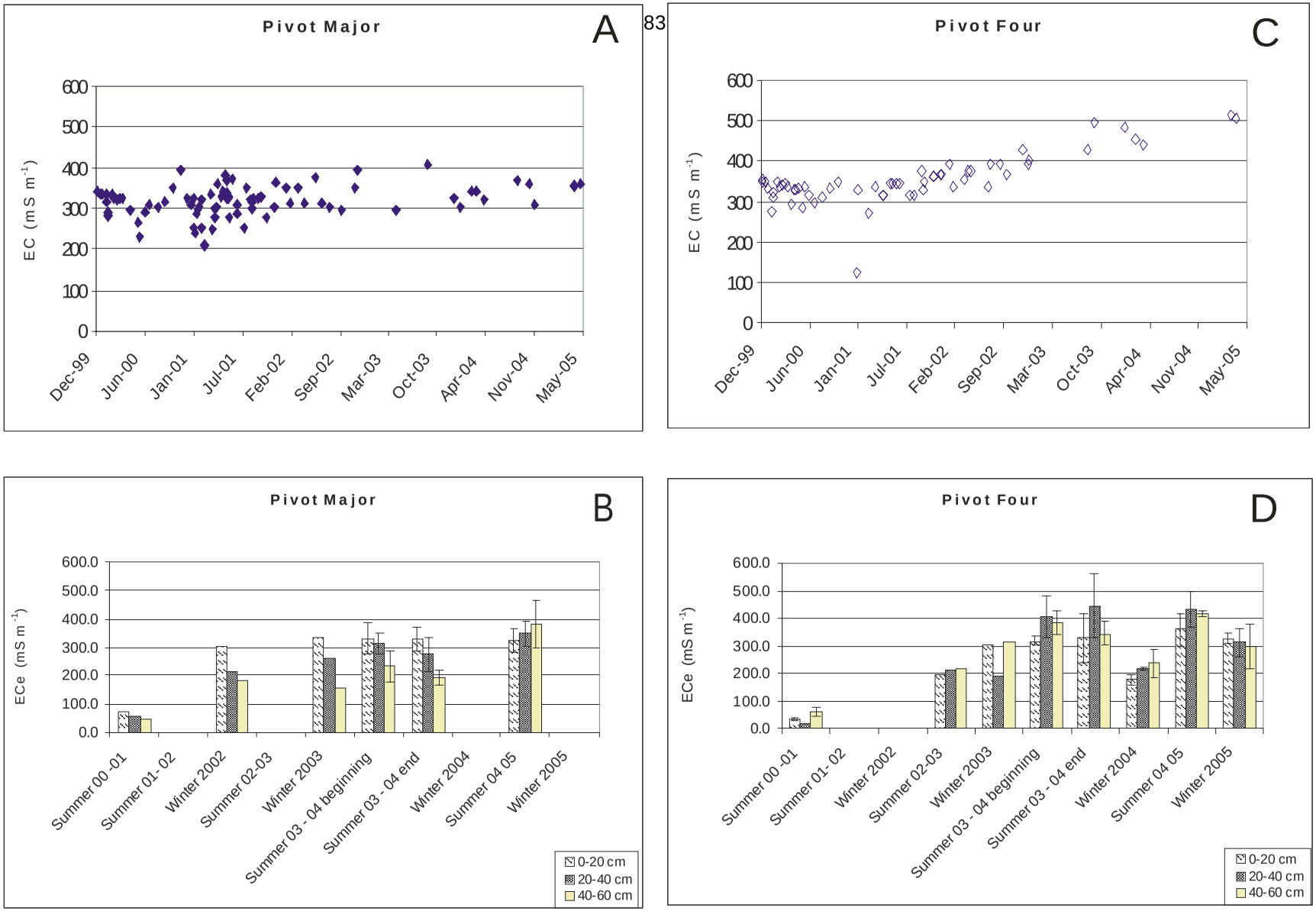


Figure 4.5 Temporal changes in irrigation water EC (A) and EC_e (B) for Pivot Major and temporal changes in irrigation water EC (C) and EC_e (D) for Pivot Four

Ca, Mg and S: transect data

The transect data show that Ca, Mg and S increased at Pivot Major and Pivot Four compared to samples collected outside these pivots (Figures 4.6 & 4.7). However, the distribution patterns of these three dominant ions in the irrigation water differ. At Pivot Major and Pivot Four, Mg increased down the soil profile and the distribution patterns indicate that Mg is the most mobile ion of the three dominant ions in the irrigation water. Mg forms only evaporate minerals, therefore Mg salt precipitation is not an effective immobilisation mechanism. The higher mobility of Mg in the soil is also attributed to preferential adsorption of Ca by negatively charge surfaces, resulting in the exclusion of Mg from the exchange complex in the topsoil. The mass transfer of Ca down the soil profile is the lowest of the three dominant ions. There was a definite accumulation of Ca in the top 60 cm. This is attributed to gypsum precipitation and Ca adsorption. S did not show a definite increasing or decreasing trend as a function of depth, and was more evenly distributed in the soil profile compared to Ca and Mg. The distribution patterns of S and Ca were similar at the two down slope sampling locations, M5 and P13, at Pivot Major and Pivot Four. The large difference between S and Ca in the top 30 cm of P13 was attributed to the liming that took place. The lime was applied on the day of sampling at Pivot Four. In the lower part of the pivot the lime was already ploughed in. In the upper parts, from P10 to P7, the lime was not yet ploughed in and it was possible to remove most of it from the surface before samples were taken with an auger.

More SO_4 is added through irrigation than Ca and Mg, which could explain the higher S concentrations in the soil profile when the S concentrations of the outside samples are subtracted. 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} ($10^{5.05}$ mol 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} ($10^{4.80}$ mol ha^{-1} a^{-1}). Mg added would be 0.97 t ha^{-1} a^{-1} ($10^{4.60}$ mol ha^{-1} a^{-1}) based on a solution concentration of 193 mg ℓ^{-1}.

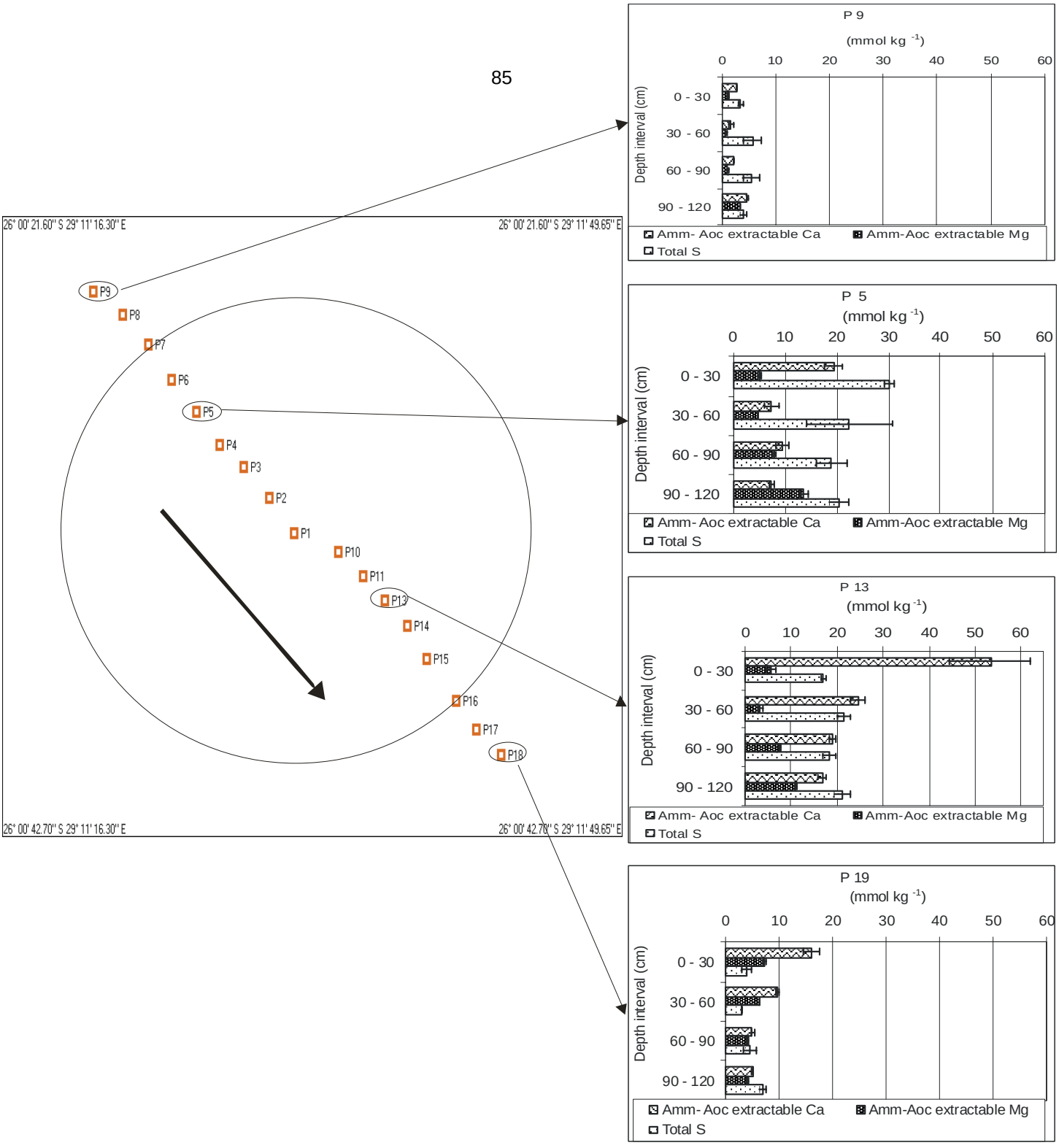


Figure 4.6 Spatial distribution of Ca, Mg and S inside and outside Pivot Four

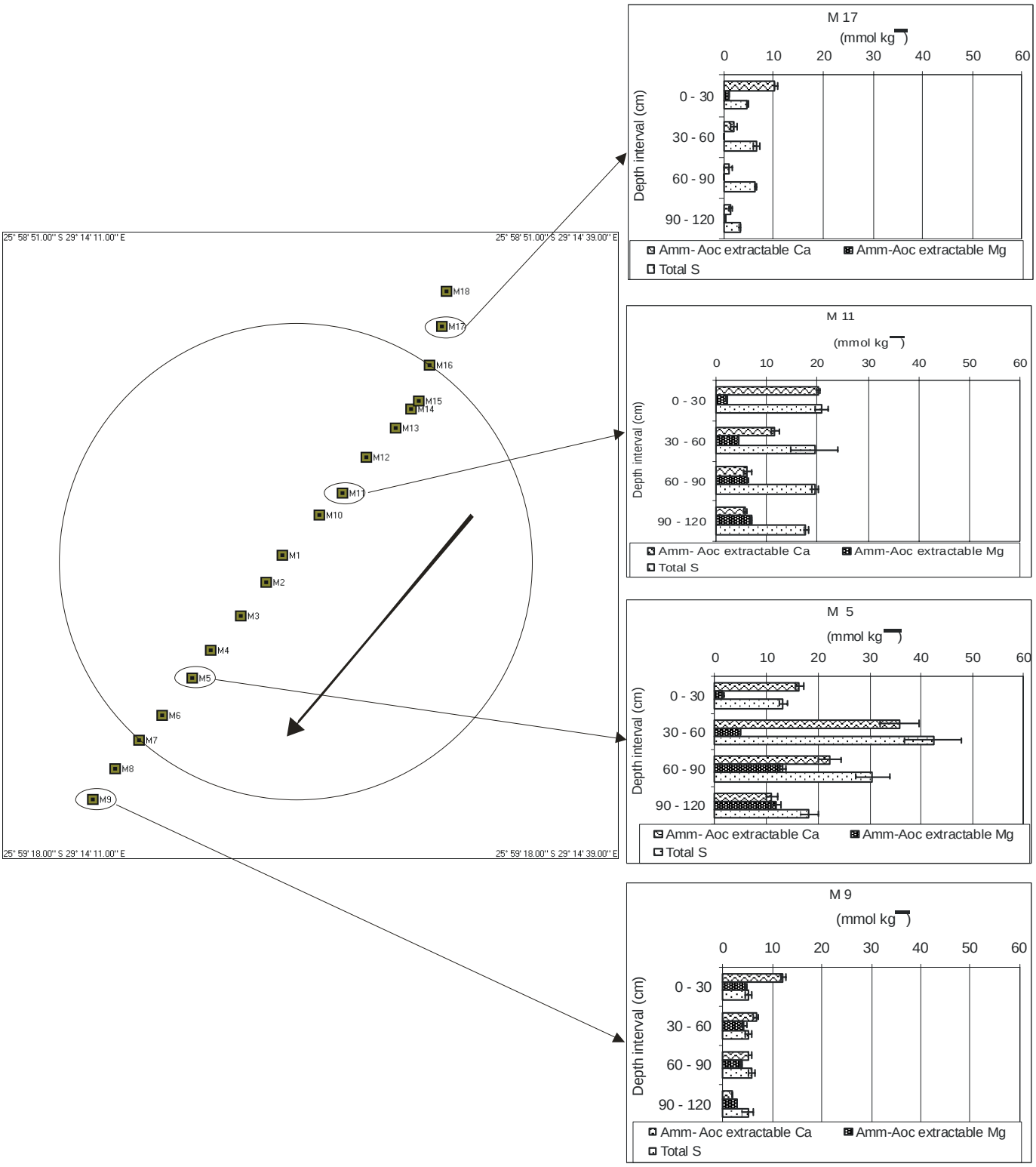


Figure 4.7 Spatial distribution of Ca, Mg and S inside and outside Pivot Major *Temporal data*

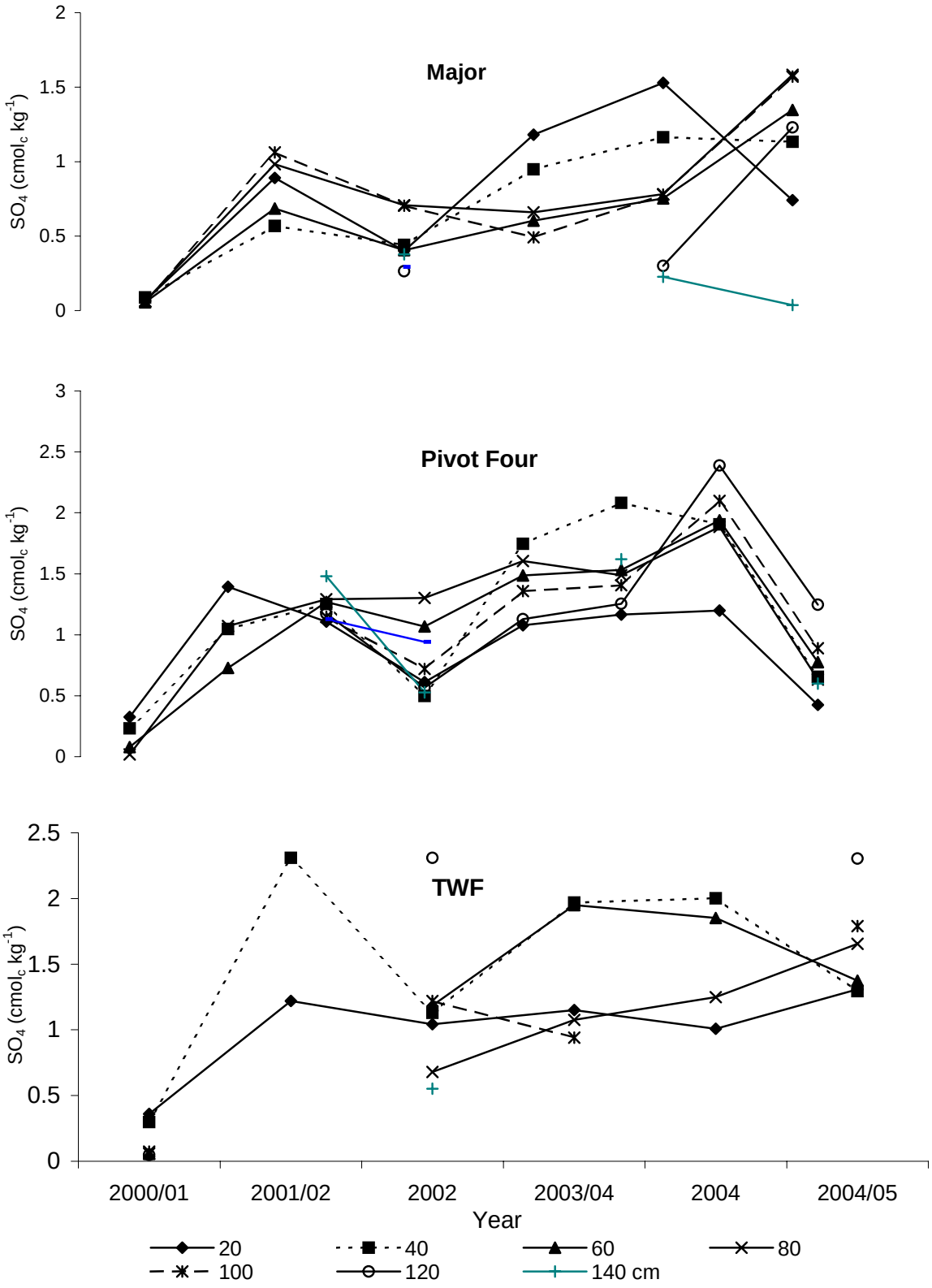


Figure 4.8 Temporal variation of soluble SO_4 measured at Kleinkopjé

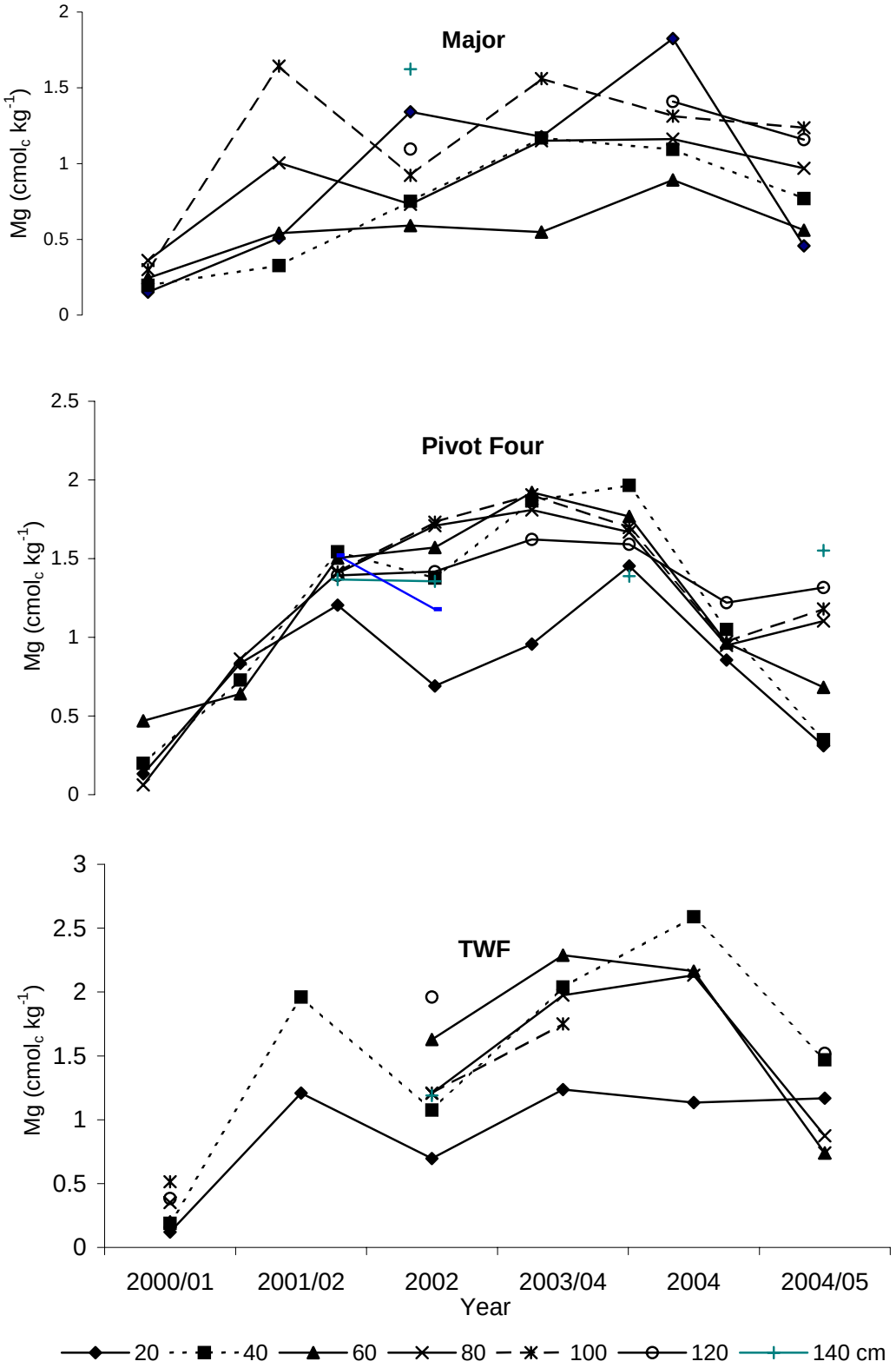


Figure 4.9 Temporal variation of exchangeable Mg measured of Kleinkopjé

Temporal soluble SO_4 and exchangeable Mg concentrations fluctuated (Figures 4.8-4.9). However for both soluble SO_4 and exchangeable Mg, 2005 values were higher than 2000 values

New Vaal: Soil chemical analyses

pH

At New Vaal, the pH of the soil was in a range between 4 and 7.5 (Figure 4.10). The pH increased during the summer season of 2003/04. This is due to unusual increase in alkalinity of the irrigation water, the low buffer capacity and relatively high hydraulic conductivity of the sandy soil, and resulted in a drastic increase in soil pH up to a depth of 1.4 m. In this season, interveinal chlorosis, distortion of new growth and short internodes were observed. These symptoms are indications of unavailability of micronutrients that were effected by the increase in pH of the soil. The spike in pH observed in 2003/04 was associated with a drastic increase in soluble and exchangeable Na (Appendix C, Figure C8). However, the clay content of the irrigated soil is less than 5% and the fact that both the pH and Na^+ were able to move to depths of 2 m in the soil profile during the season shows that clay dispersion that might have occurred did not significantly influenced the hydraulic conductivity of the soil.

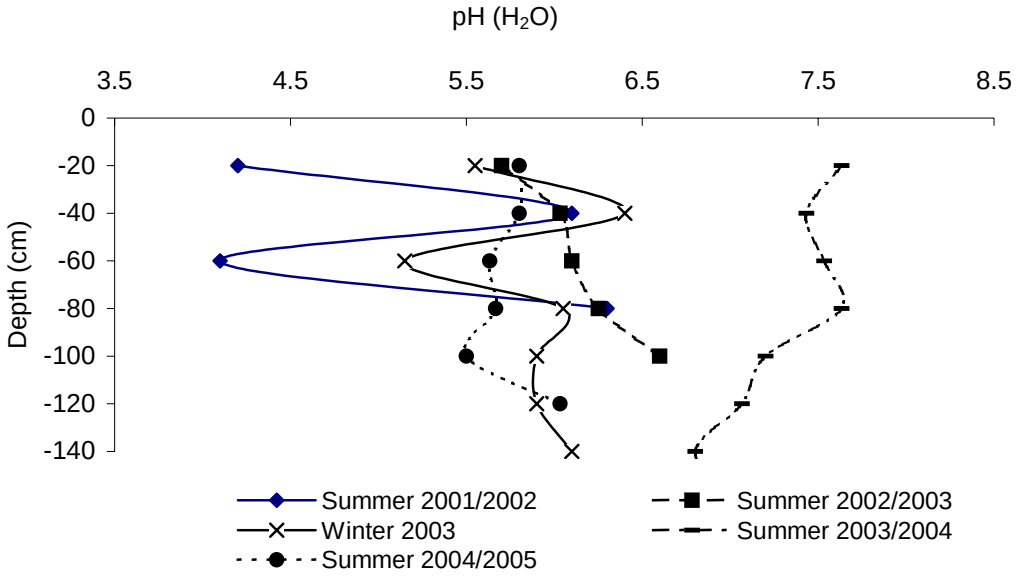


Figure 4.10 pH (H_2O) of soil at New Vaal during the trial period

Salinity

Irrigation water quality fluctuated in the beginning of 2001, associated with fluxes of poor water quality. For example, at the end of January 2001, the EC of ceramic cup soil solution extracts at 1.4 m was 36 mS m^{-1} (Appendix D, Table D8). On 19 February 2001, the EC of ceramic cup soil solution extracts at 1.4 m was 312 mS m^{-1} and sulphate concentrations increased from 63.3 mg l^{-1} to 1600 mg l^{-1}. On 29 February 2001, the EC was 33 mS m^{-1}. The sudden increase and decrease in EC in a month, illustrates the fast mass transfer of salts in these sandy soils. In May 2001 (Appendix D, Table D9), another flux of poor water quality occurred through the soil profile.

However, with time, the water quality deteriorated and since August 2003 the EC of ceramic cup soil solution extracts and WFDs was generally higher than 200 mS m^{-1} (Appendix D, Table D10 -12) and dominated by Na and SO_4.

4.2 Gypsum

Whether gypsum is present or not in the irrigated fields has been a point of debate since the project started. Campbell (2001) concluded that gypsum was not present at Pivot Major and Pivot Four. This conclusion was based on the apparent under saturation of saturated pastes with respect to gypsum. However, the strict convention of saturation indices that $\log\frac{IAP}{K_{sp}} < 0$ means that a solution is undersaturated with respect to a certain solid phase can often not be applied in environmental chemistry (Bohn & Bohn, 1986). Most solubility products in the literature are those of minerals in their standard state: pure and well crystalline. Minerals in the soil are not pure end member phases and are often poorly or micro crystalline (Essington, 2004). Over or undersaturation of a soil solution could simply mean the mineral under investigation is not in its standard state. According to Bohn & Bohn, (1986) a $\log\frac{IAP}{K_{sp}}$ ratio between -1 and 1 can be considered confirmation that the soil solution is saturated with respect to the specific mineral. A ratio lower than -1 indicates that the solution is either undersaturated with respect to the pure mineral, or could indicate that the solid phase is a minor constituent of another solid. Differences within that range can be attributed to uncertainty in IAP measurements, as well as uncertainties in reported K_{sp} values in the literature. In the case of gypsum, four different K_{sp}s were obtained. The standard state K_{sp} for gypsum is reported to be $10^{-4.58}$ by Nordstrom et al. (1990), $10^{-4.64}$ according to Lindsay (1979), $10^{-4.62}$ is reported by Essington (2004) and the default K_{sp} for gypsum in the Minteq. v.4 database file is $10^{-4.61}$. SWB uses Robbins (1998) model.

In this study, the four solubility products obtained from the literature were introduced into PHREEQC, and the saturation of the soil solutions with respect to gypsum, was evaluated using all of the above reported solubility products. A saturation range, based on the inherent uncertainty of the true standard state K_{sp} of gypsum, is therefore obtained (Table 4.2), rather than a single saturation value or index based on an arbitrarily chosen K_{sp} or default K_{sp} in a database file. Using the K_{sp} reported by Nordstrom et al. (1990) in saturation index calculations therefore give the upper limit of the saturation range and the K_{sp} reported by Lindsay (1979) give the lower limit of the saturation range. The minerals kaolinite, goethite, hematite, gibbsite and quarts have been identified by X-ray diffraction in the soils of Pivot Major and Pivot Four (Campbell, 2001). To obtain ion activity- and solution speciation approximations as close as possible to that in the soil solution, above mentioned solid phases were introduced in PHREEQC and equilibrated with the saturated pastes.

Table 4.2 Gypsum saturation indices $\left(log \frac{IAP}{K_{sp}} \right)$ of different depth intervals for selected locations inside Pivot Major and Pivot Four. Sampling date 2004/06/25.

Pivot	Location	Depth interval (cm)	$\log \frac{IAP}{K_{sp}}$				
			a	**b**	**c**	**d**	**Mean**
Major	***M 5***	0 - 30	- 0.01	0.00	0.02	- 0.04	**- 0.01**
		30 - 60	0.02	0.03	0.05	- 0.01	**0.02**
		60 - 90	0.03	0.04	0.06	0.00	**0.03**
		90 - 120	- 0.25	- 0.24	- 0.22	- 0.28	**- 0.25**
	M 11	0 - 30	0.04	0.05	0.07	0.01	**0.04**
		30 - 60	0.01	0.02	0.04	- 0.02	**0.01**
		60 - 90	- 0.04	- 0.03	- 0.01	- 0.07	**- 0.03**
		90 - 120	- 0.20	- 0.19	- 0.17	- 0.23	**- 0.19**
Pivot 4	**P 5**	0 - 30	- 0.06	- 0.05	- 0.03	- 0.09	**- 0.05**
		30 - 60	- 0.01	0.00	0.02	- 0.04	**- 0.01**
		60 - 90	0.03	0.04	0.06	0.00	**0.03**
		90 - 120	- 0.06	- 0.05	- 0.03	- 0.09	**- 0.06**
	P 13	0 - 30	- 0.02	- 0.01	0.01	- 0.05	**- 0.02**
		30 - 60	- 0.07	- 0.06	- 0.04	- 0.10	**- 0.07**
		60 - 90	0.04	0.05	0.07	0.01	**0.04**
		90 - 120	- 0.09	- 0.08	-0.06	- 0.12	**- 0.09**

a) Ksp reported in Essington (2004)

b) Default Ksp in the Minteq. v.4 database file

c) Ksp reported by Nordstrom et al. (1990)

d) Ksp reported in Lindsay (1979)

On average, the saturation range of all the depth intervals at Pivot Major were between –0.25 and 0.04. At M5, the saturation range of the 30-60 and 60-90 cm depth intervals were >0, while at M11, the saturation range of the 0-30 and 30-60 cm depth interval was >0. On average, the saturation range of all the depth intervals at Pivot Four were narrower than at Pivot Major, between –0.09 and 0.04. The depth intervals at P5 and P13 were the only layers where the saturation range was >0. Although the lowest limit of the saturation range differs between the two pivots, the highest oversaturation for both pivots never exceeded 0.07. Overall for both pivots, it was notable that, with the exception of the 90-120 cm depth intervals of M5 and M11, the lower limit of the saturation range of all the depth intervals was >– 0.1. Even the 90-120 cm depth intervals of M5 and M11 fall within the range of –1 to 1 suggested by Bohn & Bohn, (1986) and were relatively high compared to the undersaturation of the outside reference points (Figures 4.11 and 4.12).

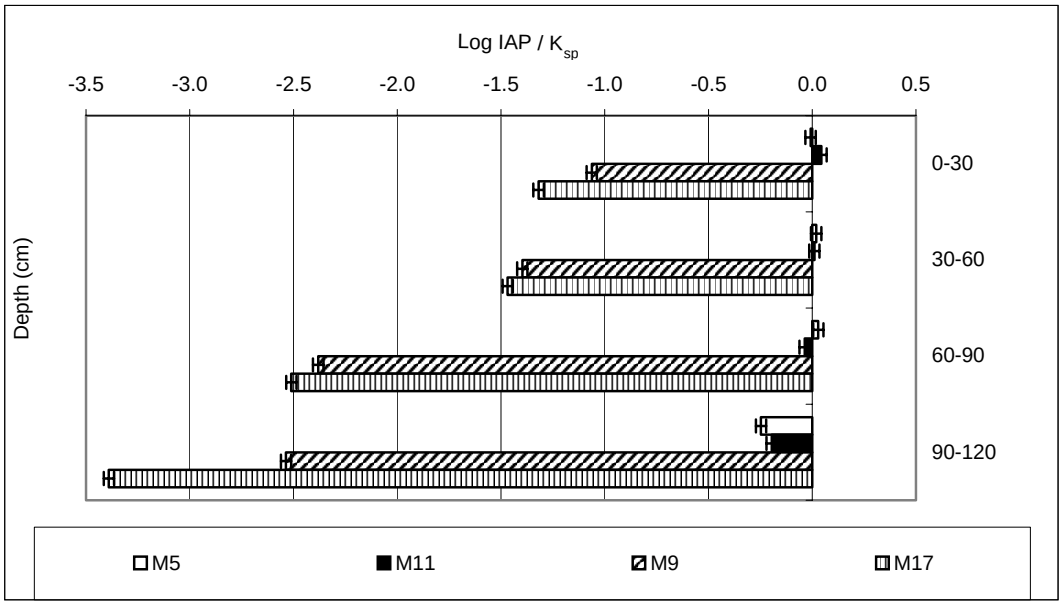


Figure 4.11 Comparison between average saturation indices, based on the solubility products obtained from the literature, inside and outside Pivot Major.

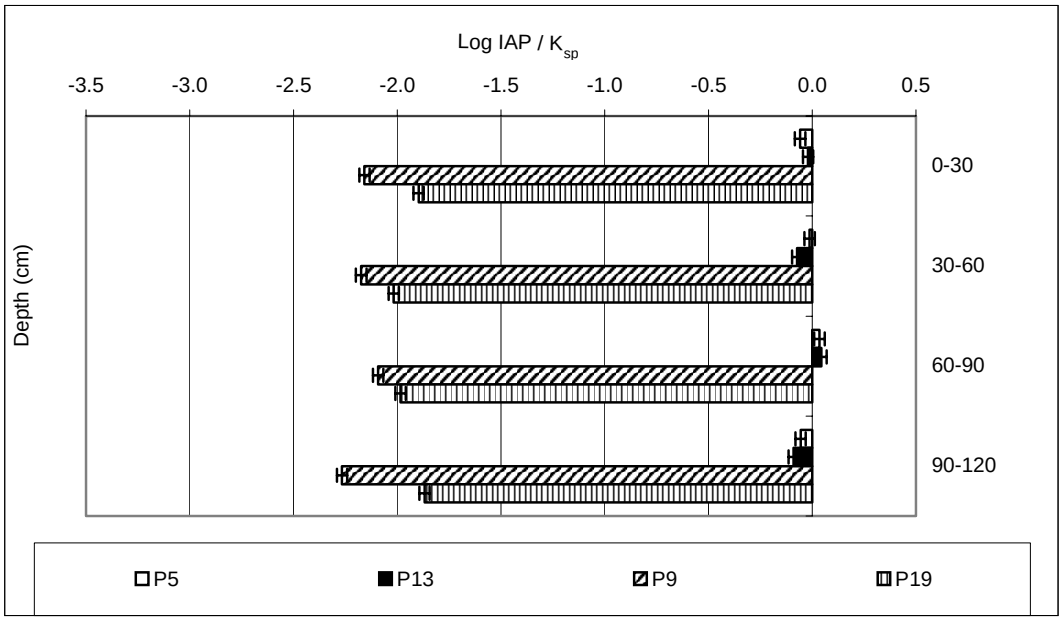


Figure 4.12 Comparison between average saturation indices, based on the solubility products obtained from the literature, inside and outside Pivot Four.

The saturation ranges for the soils of Pivot Major and Pivot Four are similar to those reported by Steinwand & Richardson (1989) and Carter & Inskeep (1988). Steinwand & Richardson (1989) collected equilibrium solutions of gypsiferous soils at wetland margins with passive extractors. The saturation indices reported by Steinwand & Richardson (1989) never exceeded 0.1 and the lowest value was -0.13. Carter & Inskeep (1988) obtained equilibrium solutions from saturated paste extracts of various soil horizons containing gypsum of different origin: pedogenic, allogenic

and/or parent material gypsum. The reported Ca, Mg, K and Na saturated paste extracts concentrations of the different horizons of one soil profile, Acme-2, was introduced in PHREEQC and chemical speciation and IAP was recalculated and evaluated against the same K_{sp} value of $10^{-4.64}$ used by Carter & Inskeep (1988). Slightly lower IAPs were obtained than those reported by Carter & Inskeep (1988) and the saturation indices ranged from -0.05 to 0.09. In this study and those of Steinwand & Richardson (1989) and Carter & Inskeep (1988), the saturation indices of gypsum were all close to zero, which indicates that in the different soil environments, gypsum was close to its standard state and the saturation range of gypsum in soils is narrower than the general range suggested by Bohn & Bohn (1986) for soil minerals.

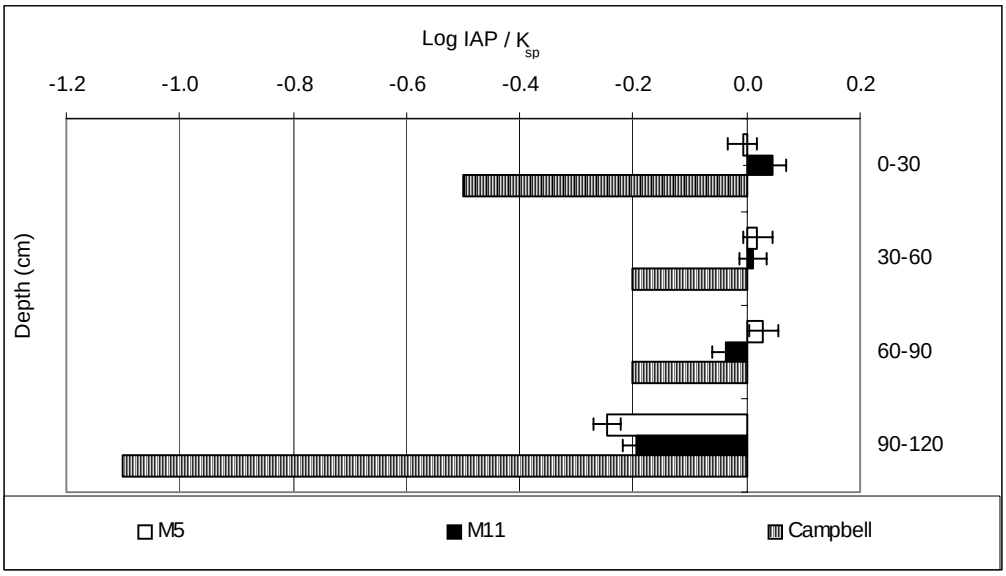


Figure 4.13 Comparison of saturation indices of samples collected in 2004/06/25 compared to that obtained by Campbell (2001) for Pivot Major.

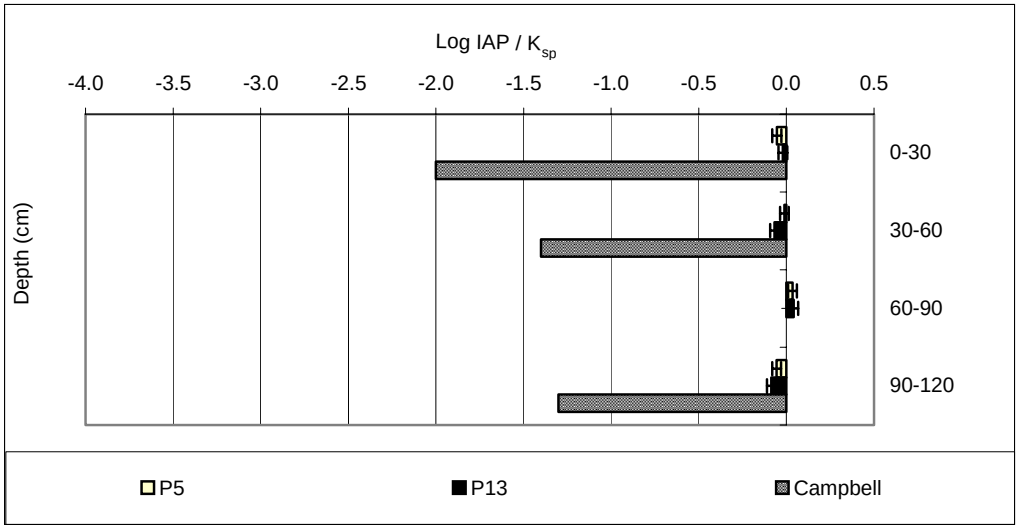


Figure 4.14 Comparison of saturation indices of samples collected in 2004/06/25 compared to that obtained by Campbell (2001) for Pivot Four.

The soil solution saturation with respect to gypsum did increase since mid June 2000 when the samples were collected by Campbell (Figure 4.13 & Figure 4.14). This result shows that gypsum did accumulate in the soils over the past four years to the extent that the solutions became saturated with gypsum. However, at the time Campbell (2001) collected soil samples at Pivot Four, the solutions were indeed undersaturated with respect to gypsum and were outside the proposed range of –1 to 1 proposed by Bohn & Bohn, (1986).

Saturated paste extracts are generally accepted as an approximation of the soil solution composition, ion activity and solution speciation. However, as pointed out by Campbell (2001), the gravimetric water content of the samples collected is generally far from that of a saturated paste extract. The difference in field gravimetric water content and that of saturated pastes is illustrated in Figure 4.15. Increasing the gravimetric water content of P5 for example, from the field gravimetric water content to that of the saturated paste was equivalent to making up 233 cm^{-3} of water in a volumetric flask to 1000 cm^{-3}. This increase in the water content will definitely result in the dissolution of gypsum and an underestimation of the solid phase gypsum. Calculations with PHREEQC showed that this volume increase could result in the dissolution of approximately 10.1 mmol l^{-1} for P5, using the default K_{sp} for gypsum in the Minteq. v.4 database file ($10^{-4.61}$). The concentration of the soil solutions to field soil water levels increased the gypsum saturation from 0.00 to 0.64. The saturation index for the 90-120 depth interval of M5 increased from -0.25 to 0.20.

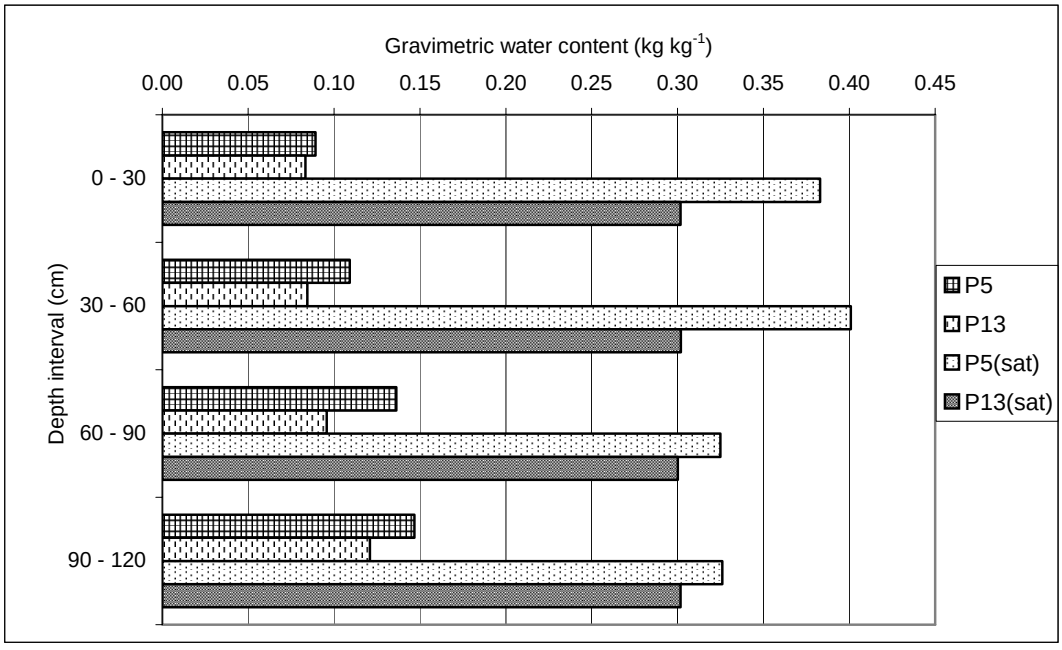


Figure 4.15 Field gravimetric water content of P5 and P13 compared to gravimetric water content of the saturated pastes of the same samples.

4.2.1 Gypsum quantification

Initially gypsum quantification of the irrigated soils was based on the difference between total extractable- Ca and SO_4 and a certain Ca and SO_4 sorption capacity. This was based on the

assumption that a finite sorption capacity must be filled before gypsum precipitation will occur. However, this approach was abandoned because the determination of the sorption capacity of Ca and SO_4 in the laboratory, and extrapolation of it to the field, is questionable for various reasons:
The sorption capacity of a soil is a function of pH, ionic strength and ion composition of the soil solution (Rietra et al, 1999 & Peak et al, 2001). The experimentally obtained sorption capacity is therefore a conditional sorption capacity, and not necessary correct for all conditions. The sorption capacity is therefore not a constant and finite capacity that must be filled. Concentration of the soil solution through drying and dilution as a result of rain will influence this sorption capacity. The solution, which the soil is equilibrated with, should be similar to the water quality of the irrigation water, which means soil samples should be equilibrated with NAMD. According to Ford, Scheinost & Sparks, (2001), surface precipitation can occur in the double layer despite the fact that the bulk solution is undersaturated with respect to the pure mineral. The NAMD is saturated with respect to gypsum and what it basically comes down to is that it is impossible to determine whether the decrease in Ca and SO_4 in solution after equilibration was the result of precipitation or adsorption.

The logical option was to determine the sorption capacities in a more dilute solution to minimise the risk of surface precipitation, and to linearly extrapolate this value to that of a theoretical sorption capacity in undiluted NAMD. The result would have been a theoretically extrapolated (not determined) value based on the unproven assumption that the Ca and SO_4 sorption capacities increase linearly with ionic strength. This makes it impossible to validate the Ca and SO_4 sorption capacities, and therefore the quantified Ca and SO_4 sorption capacities or a fraction of the values could simply be an experimental artefact.

A thermodynamically more sound and analytically easier approach, was therefore chosen in the end. The saturation range, as discussed previously, was determined for the saturated paste extracts. **If the saturation range indicated that the solution was saturated with respect to gypsum water extractable Ca was taken as gypsum**. Using water-extractable S to calculate gypsum generally resulted in higher values (Figure 4.16). The reason for this was that overall S input in these systems was always higher than Ca inputs. This resulted in higher saturated paste S concentrations, water-soluble S than Ca. More exchangeable S than Ca will be removed with water because distilled water, in equilibrium with atmospheric CO_2, at a pH of 5.5, has approximately 10^{-4} *M* HCO_3. HCO_3 is a conjugated base of a weak acid, and will therefore displace electrostatically adsorbed SO_4. Less of an error is made when water extractable Ca is used to calculate gypsum, because the water extractability of exchangeable Ca is lower than that of SO_4.

Assuming, gypsum precipitation to be the dominant mechanism of S and Ca immobilisation at Pivot Four, resulted in an underestimation of the total S and Ca immobilised in the soil profile. Figure 4.17 shows that at both Pivot Major and Pivot Four more than 50% of the Ca immobilised in the soil was exchangeable. Total Ca immobilised in the soil profile at Pivot Major was 23.9 mol m^{-2}, of which 11.4 mol m^{-2} was gypsum. At Pivot Four, total Ca immobilised was 25.9 mol m^{-2}, of which 10.9 mol m^{-2} was gypsum. The amount of gypsum precipitated at Pivot Major was equivalent to 19.6 tons ha^{-1} and that at Pivot Four to 18.9 tons ha^{-1}.

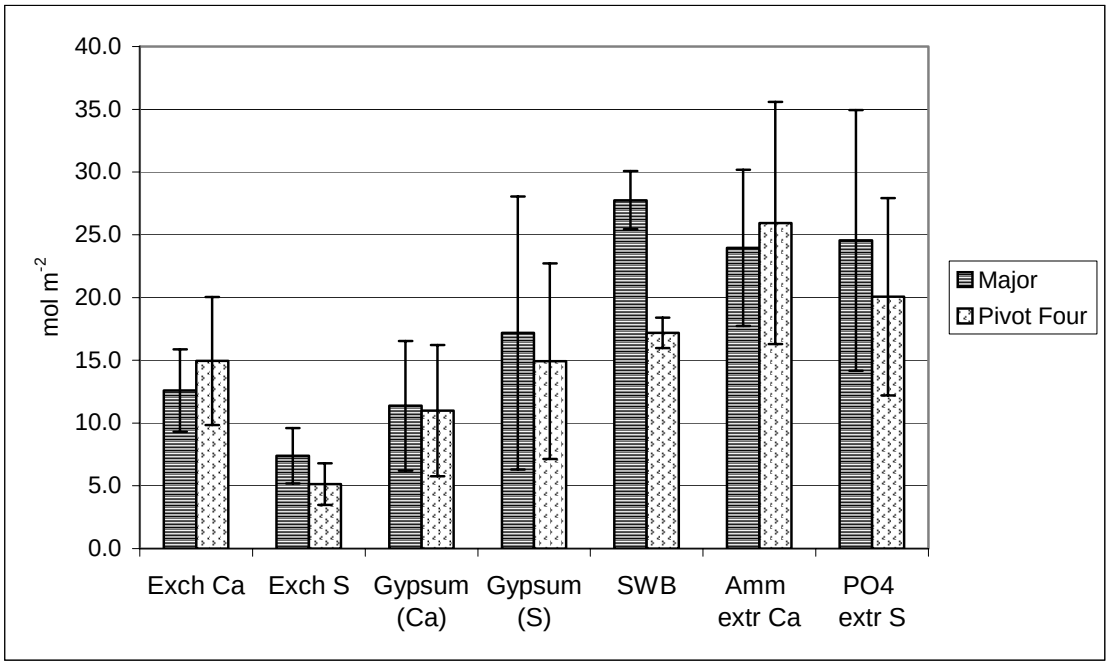


Figure 4.16 Comparison between SWB simulations and the extractable Ca and S gypsum and exchangeable Ca and S in the 1.2 m soil profile at Pivot Major and Pivot Four. Error bars indicate the range of extracted values of the samples collected along transects inside Pivot Major and Pivot Four.

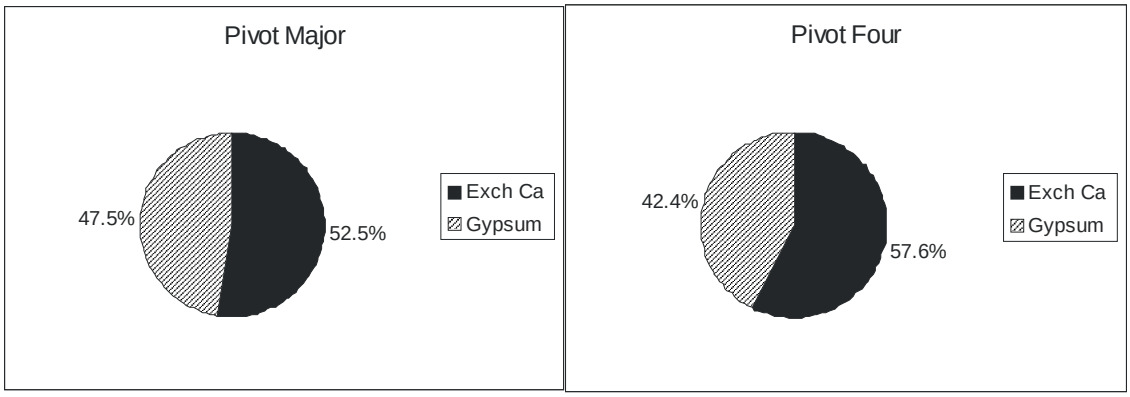


Figure 4.17 Averaged percentage exchangeable Ca and gypsum in the soil profile at Pivot Major and Pivot Four.

Conclusions

Both temporal and the transect EC_e data showed an increase in salinity over time. Average EC_e at both Pivot Major and Pivot Four increased to between 300 and 400 mS m^{-1}. Pivot Four was more saline than Pivot Major, and this was caused by the increase in salinity of the water of Tweefontein Pan. There was also an increased in salinity at New Vaal. This was also the result of deteriorating water quality. Based on the 1 *M* KCl pH values, the exchangeable acidity at Pivot Four is greater than outside the pivot. The opposite is true for Pivot Major.

There is thermodynamic proof, in the form of calculated Ca and SO_4 activities, that gypsum is present in the soils irrigated with NAMD. The saturation ranges were similar to that reported in literature for natural gypsiferous soils. Gypsum accumulated in the soils over the past four year to the extent that the solutions became saturated with gypsum. The amount of gypsum precipitated at Pivot Major was equivalent to 19.6 tons ha^{-1} and that at Pivot Four to 18.9 tons ha^{-1}.

Assuming that gypsum precipitation is the dominant mechanism of S and Ca immobilisation at Pivot Four resulted in an underestimation of the total S and Ca immobilised in the soil profile. At both Pivots Major and Four more than 50% of the Ca immobilised in the soil was exchangeable Ca.

CHAPTER 5

5. GROUNDWATER MONITORING

Introduction

The Institute for Groundwater Studies at the University of the Free State was appointed to establish and undertake groundwater monitoring at the New Vaal, Syferfontein and Kleinkopjé Collieries, to ascertain the effect of the irrigation with mine water on groundwater.

These investigations included:

- Water level measurements and interpretation.
- Multi-parameter chemical profiling of the water quality in the boreholes.
- Sampling and chemical analyses of water in the boreholes. The standards used in all interpretations are the SABS 241 Drinking Water Standards.
- Interpretation of results and recommended actions.

Positioning and chemical profiling of the water quality in the monitoring boreholes

Boreholes were drilled so that groundwater levels and qualities could be monitored every 2 to 6 months in pivots Major and Four (Kleinkopjé Colliery). Boreholes were not needed at field TWF (Kleinkopjé Colliery), which is on rehabilitated land. In pivot Major six of the 10 boreholes were monitored regularly for water levels, but only five are used for hydrochemical profiling and water quality. The other boreholes have been damaged and are inaccessible as far as the samplers and probes are concerned. In pivot Four six boreholes were monitored regularly for water levels, profiling and water quality. The surface slope through the irrigation area is to the north at an average gradient of 1:30. Boreholes were sited in such a way that any groundwater migration from the pivot would be intercepted by these boreholes. The borehole siting took the dyke positions and flow directions into account.

In New Vaal five monitoring boreholes were drilled. These five boreholes were sited according to expected water flow. Boreholes NVPV1 and NVPV2 were placed in order to gain background values. Boreholes NVPV3 and NVPV4 were located at the expected down-gradient side of the pivot, in order to gain any irrigation water information, while Borehole NVPV5 was located in the centre of the pivot to gain further water quality information on its expected path to the river. The boreholes were all drilled to a depth of approximately 26 m. This depth was based on the on-site drilling, ensuring that the borehole was drilled approximately 10m into the geology below the alluvial system. Five boreholes were monitored initially, but since 2004 PV1 PV2 and PV3 became blocked, possibly because of the sandy nature of the area.

In Syferfontein, the surface slope through the irrigation area is to the north at an average gradient of 1:30. Boreholes were sited in such a way that any groundwater migration from the pivot would be intercepted by these boreholes. The borehole siting took the dyke positions and flow directions into account. Borehole OBH3 was intended to monitor background water quality. The remaining boreholes are situated in the northeastern corner of the pivot adjacent to the test quadrant being

researched by the University of Pretoria. An existing borehole, REGM-86, is also close enough to serve as a monitoring borehole and has therefore been included in the monitoring system. Trenches were dug in 2001 to prevent the runoff water from the pivot area entering the boreholes from surface, thereby skewing the interpretation of results.

5.1 Kleinkopjé

Two pivots were monitored at Kleinkopjé, namely Pivots Major and Four. Pivot Tweefontein was on a rehabilitated profile, and monitoring was felt to be of little value for such a highly impacted site.

5.1.1 Water levels

Figure 5.2 illustrates the ground water levels at Pivot Major. The water levels, as expected at an irrigation scheme, are very shallow.

- The time variation of the water levels indicates that the water levels fluctuate in correspondence to the seasons. Typically, the water level drops during the mid- to late winter months, and then recovers again during mid- to late summer.
- The rise in the water level during the early months of 2005 is due to high rainfall and, to a lesser degree, incorrect irrigation practises. Flooding was so great in this period that some of the boreholes (PV1BH-5, 6 and on occasion 7) could not be sampled at times.

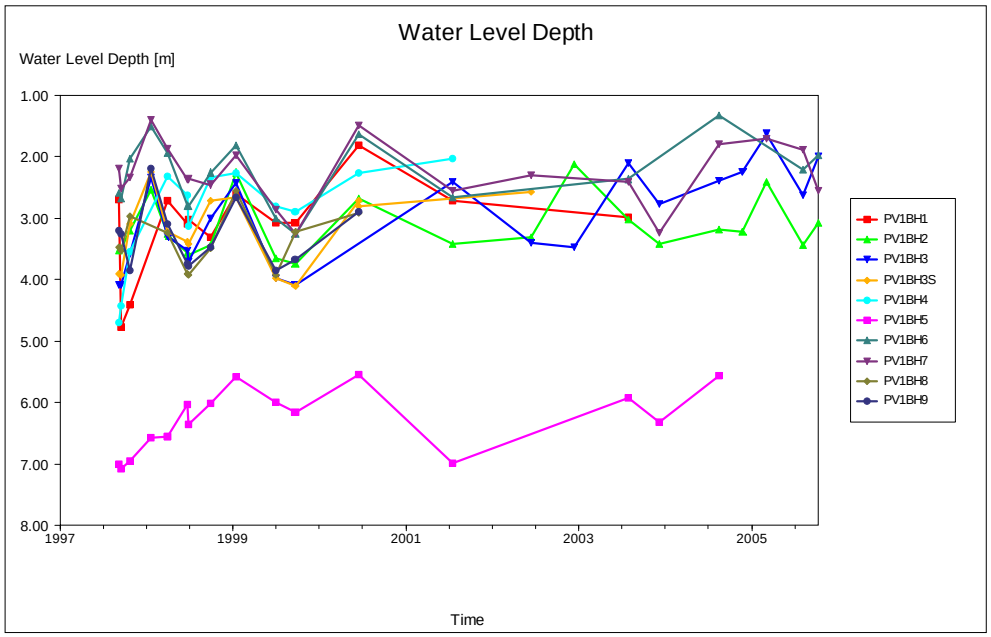


Figure 5.1 Water levels at Pivot Major.

Figure 5.2 illustrates the ground water levels at Pivot Four.

- Since the middle of 2002 there is a constant drop in the water levels. However, during the latter part of 2004 there was a rise in water levels due to very high rainfall. During the latter part of 2005 the water levels dropped again.
- Borehole PV4BH-2 has been destroyed since early 2005.

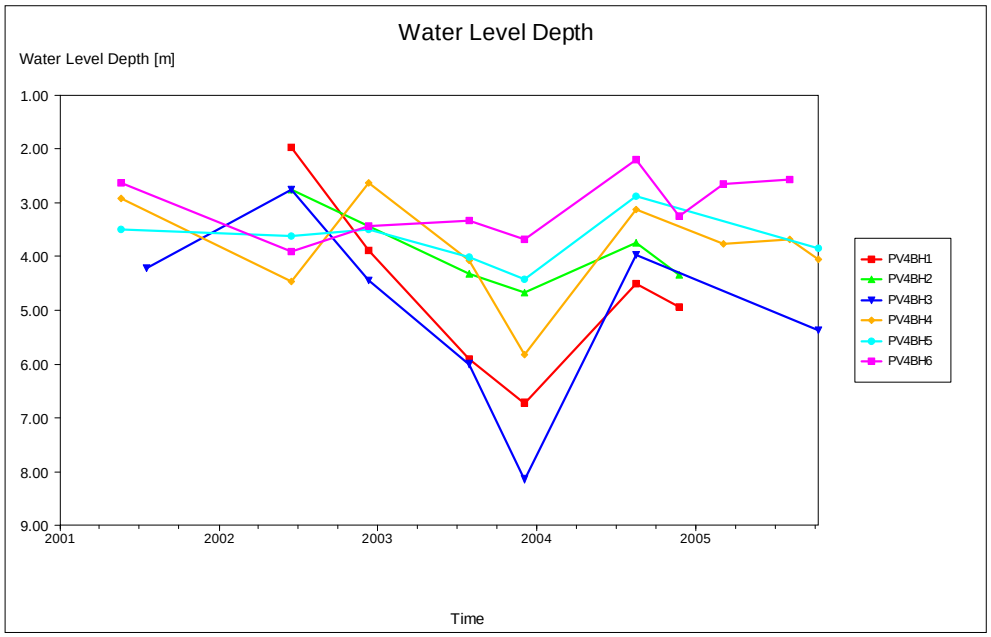


Figure 5.2 Water levels at Pivot Four

5.1.2 Groundwater quality

Multi-parameter profiling

Pivot Major.

In-situ measurements of water qualities were done at five localities at Pivot Major. The profiling graphs are presented in the Appendix I**.**

- There is a slight increase in EC in the down-gradient boreholes BH5 and BH2 at 10 m, which may be the result of the rock composition at that depth.
- There is no variation in any parameters in the higher lying boreholes BH6 and BH7.

Pivot Four.

In-situ measurements of water qualities were done at six localities at Pivot Four. The profiling graphs are also presented in the Appendix I.

- No significant variations occur with depth in any of the boreholes.
- EC values are very low.

Groundwater quality analysis

Pivot Major

The analysis of the sampling done during November 2005 is illustrated in Table 5.1.

Table 5.1 Water quality of the groundwater - Pivot Major (November 2005).

Site map	PH	EC (mS m^{-1})	Ca mg ℓ^{-1}	Mg mg ℓ^{-1}	Na mg ℓ^{-1}	K mg ℓ^{-1}	PAI mg ℓ^{-1}	MAI mg ℓ^{-1}
PV1BH2	5.69	73.5	51.5	36.2	30.4	9.2	0	13.6
PV1BH3	6.45	3.6	0.6	0.2	7.8	2.0	0	15.4
PV1BH6	6.43	5.36	1.5	0.8	7.4	2.1	0	18
PV1BH7	6.42	6.25	3.6	1.5	7.9	6.5	0	17.5
Site Name	F mg ℓ^{-1}	Cl mg ℓ^{-1}	NO_2(N) mg ℓ^{-1}	Br mg ℓ^{-1}	NO_3(N) mg ℓ^{-1}	PO_4 mg ℓ^{-1}	SO_4 mg ℓ^{-1}	B mg ℓ^{-1}
PV1BH2	<0.01	41.1	0	0.1	25.46	<0.01	197.0	<0.04
PV1BH3	<0.01	1	0		0.64	<0.01	1.2	0.04
PV1BH6	<0.01	1.5	0	0.02	1.52	<0.01	0.9	0.04
PV1BH7	<0.01	4.8	0	0.06	3.07	<0.01	1.8	0.04

- According to these analyses, the water quality of all the boreholes sampled inside the pivot area is within Class 0 and Class 1, i.e. ideal to acceptable water, except for Nitrate in PV1BH2, which falls in Class III (not allowable).

- The overall water quality trend of all the boreholes is sideways (Figure 5.3), indicating that over the period of irrigation, water quality has not deteriorated within the underlying aquifer. The only exception is PV1BH2, where a rise in salinity is evident

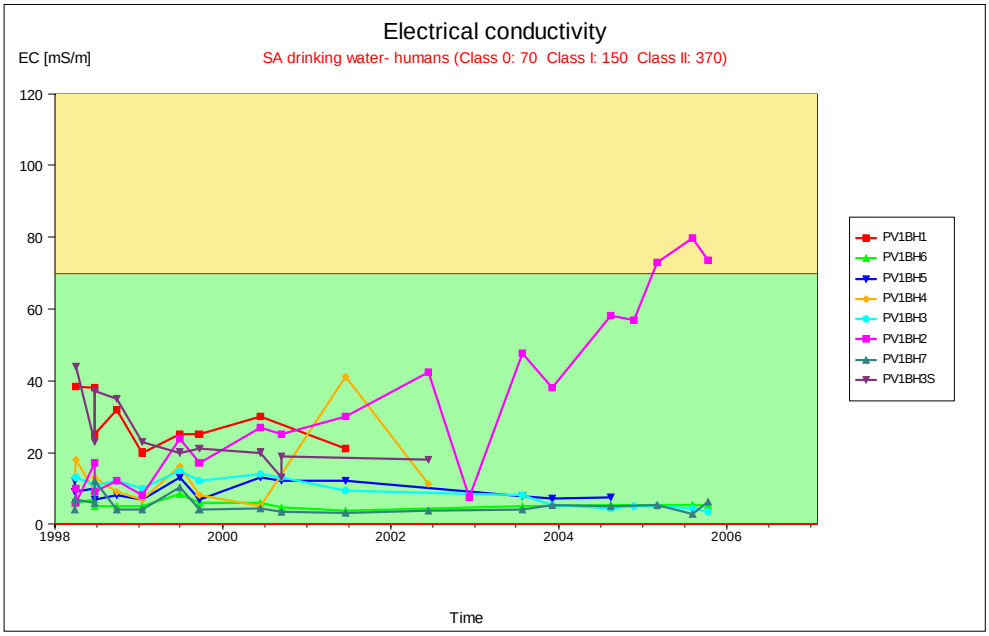


Figure 5.3 Time graph of the Electrical Conductivity at Pivot Major.

- Most of the groundwater constituents have not shown an increase over time, as illustrated in the time graph of calcium, sulphate and nitrate in Figure 5.4.. This indicates that these macro constituents are not reaching the groundwater. The exception is PV1BH-2, which deteriorated drastically in water quality since 2003. As this borehole is down gradient of the expected flow direction, this vast increase in dissolved solids is an indication of localised degradation in groundwater quality. The water is probably being transported from elsewhere in the pivot area by the bedding-plane fracture situated approximately 10 m towards PV1BH-2. This situation must be closely monitored to minimise regional impacts.

- The steep increase in nitrate in PV1BH2 since 2001 correlates with the increase in dissolved solids. The values are currently an order higher than in the other boreholes. As this borehole is down gradient of the expected flow direction this increase in nitrate is cause for concern. The nitrate is not specific to mine water irrigation and local increases in nitrate are common to irrigation where fertilizer is applied.

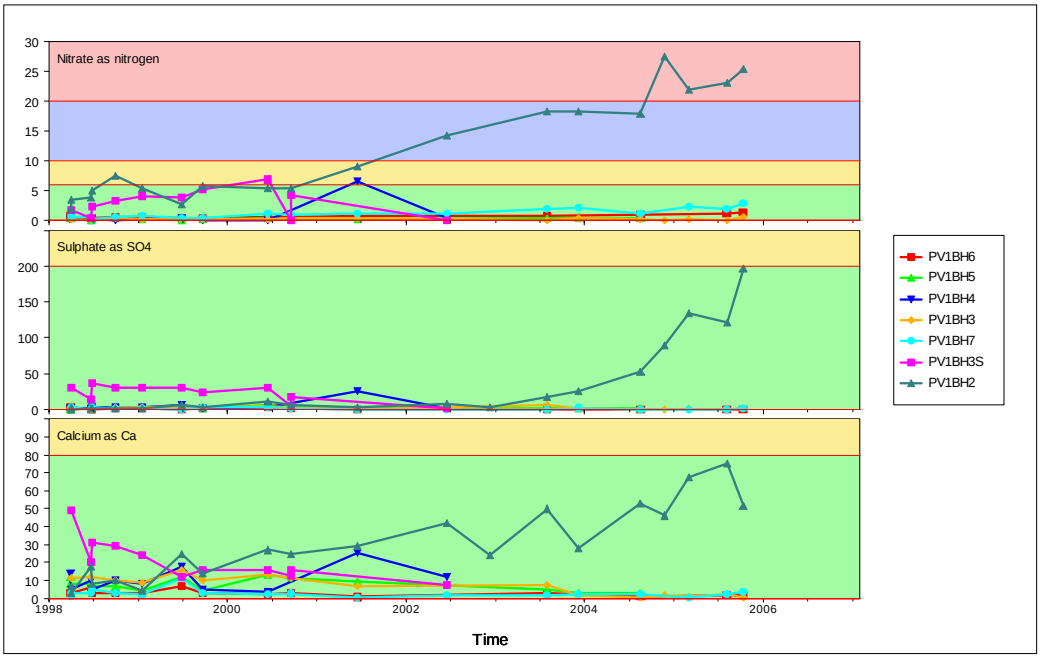


Figure 5.4 Time graph of the calcium, sulphate and nitrate at Pivot Major.

Pivot Four.

The analysis of the sampling done during November 2004 is illustrated in Table 5.2. According to this analysis, the water quality of all the boreholes sampled is within Class 0 and Class 1, i.e. ideal to acceptable water, except for PV4BH2, which has a nitrate content that falls in Class II.

Table 5.2 Water quality of the groundwater - Pivot Four (November 2004).

Site name	pH	EC (mS m^{-1})	Ca mg ℓ^{-1}	Mg mg ℓ^{-1}	Na mg ℓ^{-1}	K mg ℓ^{-1}	PAI mg ℓ^{-1}	MAI mg ℓ^{-1}
PV4BH1	5.16	13.7	5.8	5.0	4.3	7.14	0	2
PV4BH2	6.89	73.5	49.9	43.6	36.8	5.41	0	95
PV4BH3	5.2	6.6	1.8	1.4	4.8	2.04	0	1
PV4BH4	5.25	5.1	1.6	1.0	5.2	0.83	0	1
PV4BH6	5.11	9.16	3.5	2.4	7.7	2.10	0	3
Site Name	F mg ℓ^{-1}	Cl mg ℓ^{-1}	NO_2(N) mg ℓ^{-1}	Br mg ℓ^{-1}	NO_3(N) mg ℓ^{-1}	PO_4 mg ℓ^{-1}	SO_4 mg ℓ^{-1}	NH_4 mg ℓ^{-1}
PV4BH1	<0.01	4.2	<0.01	<0.04	13.75	<0.1	0.4	<0.1
PV4BH2	0.03	50.3	<0.01	<0.12	0.04	<0.1	240	<0.1
PV4BH3	<0.01	4.9	<0.01	<0.04	2.46	<0.1	4.0	<0.1
PV4BH4	<0.01	5.3	<0.01	<0.04	2.66	<0.1	4.1	<0.1
PV4BH6	0.01	4.1	<0.01	<0.04	9.28	<0.1	0.4	<0.1

- The overall water quality trend of all the boreholes indicates relative stability, indicating that over the period of irrigation, water quality has not deteriorated within the underlying aquifer (Figure 5.5). The increase in the EC in PV4BH2 during 2004 is the result of a broken down pivot that caused water logging. The borehole is down gradient and water infiltrated via the broken casing into the borehole. The EC should return to the original values over time (there was already a slight improvement with the next sampling run). Unfortunately this borehole has been destroyed, and cannot be monitored currently.

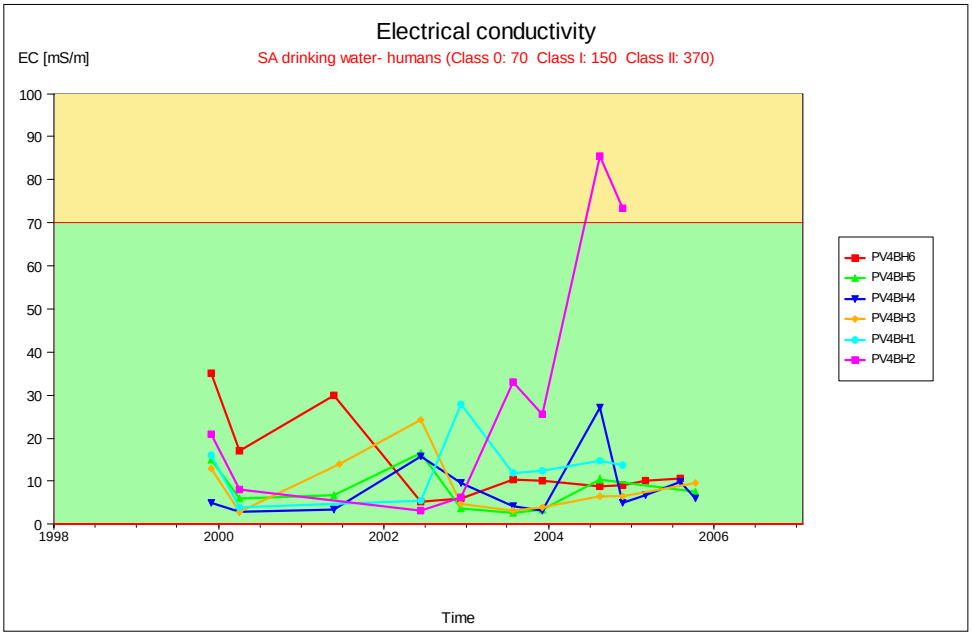


Figure 5.5 Time graph of EC - Pivot Four boreholes.

- In Figure 5.6, Stiff Diagrams of the analysis at Pivot Four reveal that sodium is the dominant cation, and chloride the dominant anion in the groundwater. There is very little evidence of the irrigation water quality (Ca, Mg and SO_4). This excludes PV4BH2, which has been influenced by run-off into the borehole.

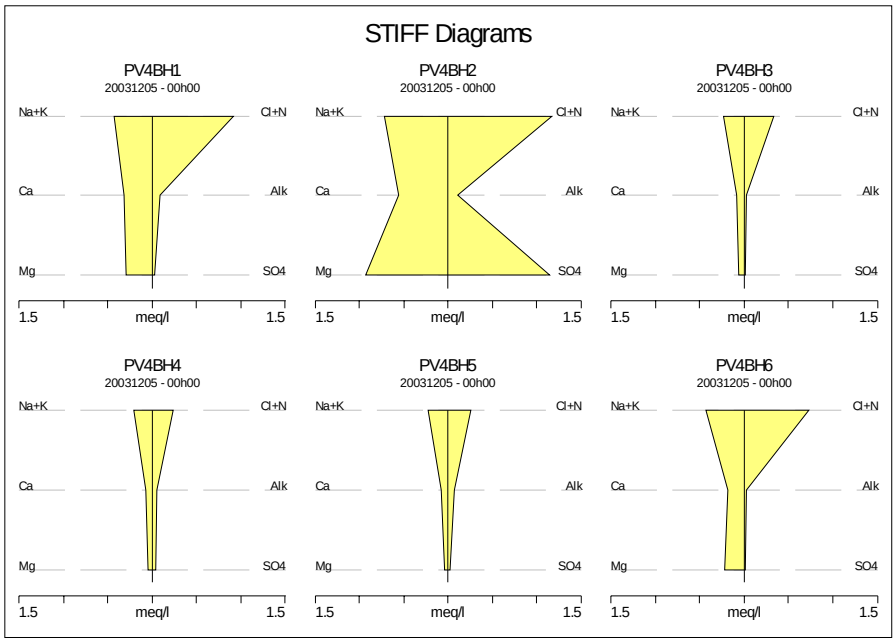


Figure 5.6 A Stiff Diagram illustrating a plot of the concentrations of the major ions at Kleinkopjé, Pivot Four

Conclusions

It is important to consider reasons that the irrigation water is not represented in the groundwater. The hydraulic and attenuation factors preventing the salts in the mine water used for irrigation from being mobilised down the soil profile and into the aquifer would be important considerations in this process. The soil composition and associated sorption and hydraulic properties may be informative. Details of the soil analysis are presented in Chapter 2.

Three core boreholes were also drilled at each of the pivots, two inside the pivot areas and one outside for background values. The core samples were analysed at the IGS laboratory for the major cations and anions. Figures 5.7 and 5.8 show the leaching of water-soluble constituents for two cores inside the pivot areas.

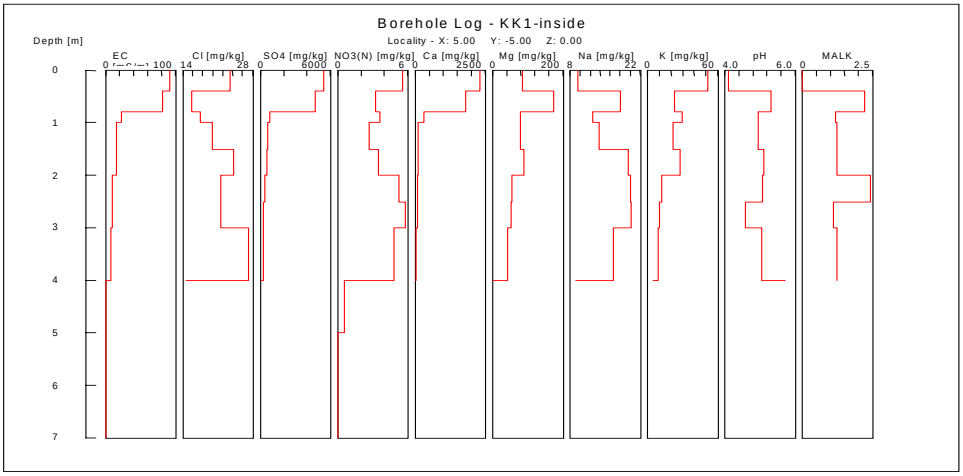


Figure 5.7 Soil leaching analyses over depth within Pivot Major.

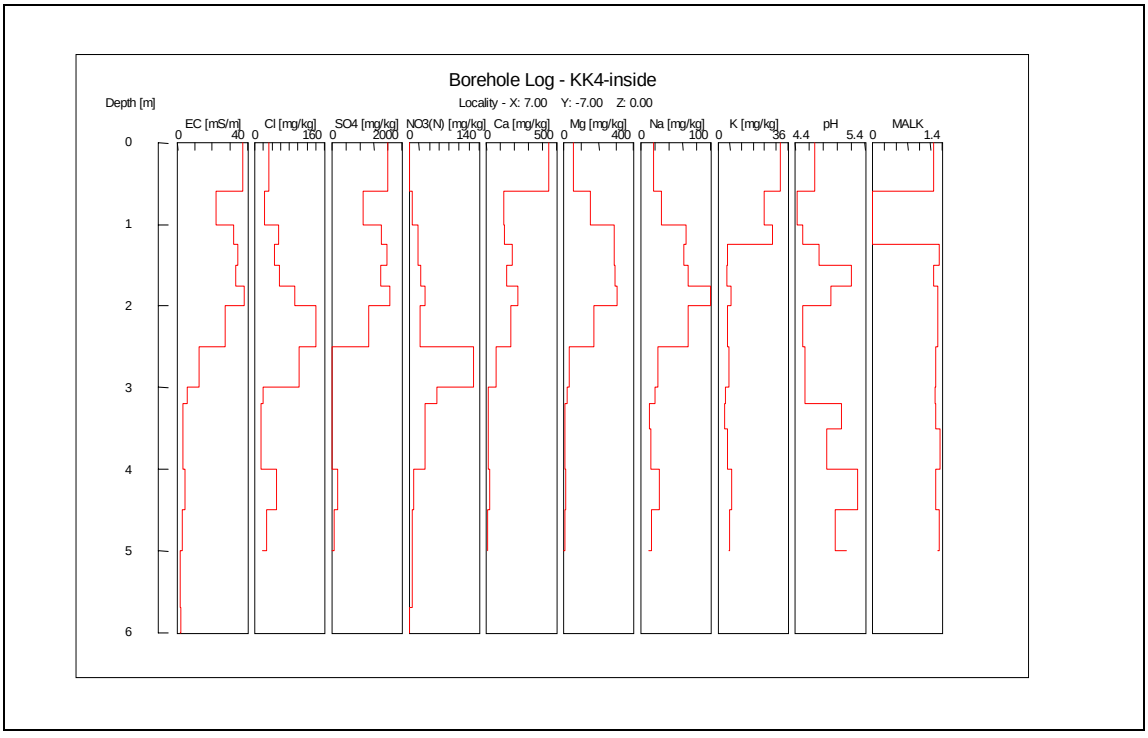


Figure 5.8 Soil leaching analyses over depth within Pivot Four.

From these figures it is clear that there is currently a build up of salts in the soils above and within the clayey layers, and that a limited proportion of the associated salts move through into the groundwater. Regarding the water composition, sodium is the dominant cation, while bicarbonate represents the dominant anion at Pivot Major and chloride at Pivot Four.

5.2 New Vaal Colliery

Five boreholes were monitored initially, but since 2004, PV1 PV2 and PV3 became blocked, possibly because of the sandy nature of the area.

5.2.1 Water levels

Figure 5.9 illustrates the groundwater levels at the New Vaal Pivot. The water levels are a little deeper than most other irrigation schemes. It was originally thought that this could be attributed to the high conductivity in the soils, resulting in rapid drainage towards the river. It appears, however, to be related to a clay layer at 2.4-4 m that prevents most of the irrigation water from migrating downwards.

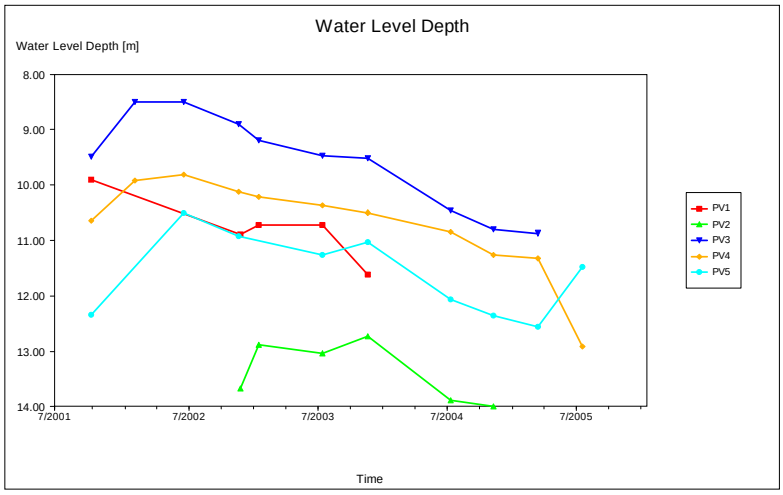


Figure 5.9 Water levels at New Vaal Pivot.

The water levels at New Vaal pivot have varied very little over time, although a general decline is evident. The slight variations in water levels can be attributed to seasonal variation and associated rainfall. Over the course of the irrigation period at New Vaal, areas of water logging were experienced, and reasons for this were investigated.
The water levels are relatively deep and different activities were undertaken to determine why:

1. Two trenches were dug inside the pivot area, and inspected. Water seepage was very shallow, and occurred at approximately 2.4 m below surface.

   The distinctive geological layers were selected, sampled and a determination of soil properties in terms of relative clay, sand and silt content was done at the Glen Agricultural College. The results are shown in Chapter 2, and confirm the existence of a clay layer below 2.4 m, which is also a reason for the water logging which occurs at this pivot.

2. Three auger boreholes were drilled at the pivot, one inside the pivot area and one outside for background values. Another one was drilled between the irrigation dam and the pivot

to determine the leaching properties from the dam towards the pivot, and to determine the influence of the dam on the water logging problems. The auger samples were analysed at the IGS laboratory for the major cations and anions. Figure 5.10 shows the leaching of water-soluble constituents for the auger hole inside the pivot, with a high concentration of constituents in the clay layer.

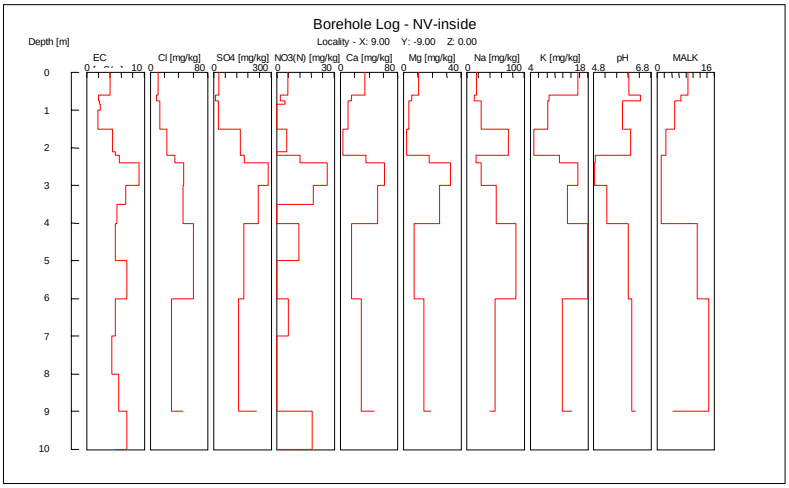


Figure 5.10 Soil leaching analyses profile inside the New Vaal Pivot.

3. Two piezometers were installed near to PV5 to study the influence of the clay layer on the irrigation waters.

Table 5.3 Chemical analysis of water in piezometers.

PH	**EC (mS m^{-1})**	**Ca mg ℓ$^{-1}$**	**Mg mg ℓ$^{-1}$**	**Na mg ℓ$^{-1}$**	**K mg ℓ$^{-1}$**	**PAI mg ℓ$^{-1}$**	**MAI mg ℓ$^{-1}$**
8.3	232	118.5	33.5	407.6	20.5	4	140
F mg ℓ$^{-1}$	**Cl mg ℓ$^{-1}$**	**NO_2(N) mg ℓ$^{-1}$**	**Br mg ℓ$^{-1}$**	**NO_3(N) mg ℓ$^{-1}$**	**PO_4 mg ℓ$^{-1}$**	**SO_4 mg ℓ$^{-1}$**	**B mg ℓ$^{-1}$**
0.8	126	0.0	0.4	7.9		968	1.32

Chemical profiles of EC in PV5 (near the centre of the pivot), and the piezometer adjacent to PV5, also show vast differences in water quality (Table 5.4). The very high EC values in the piezometer, compared to the boreholes, also indicate that water does not migrate easily downwards below the clay layer at 2.4 m.

Table 5.4 EC profile.

Depth	PV5	Piezo
1.47	-	148.7
2	-	242.2
12.78	17.3	
13.5	17.9	
14	37.3	
15	39.7	
20	37.9	
25	37.9	
28.5	35.9	

Conclusion: There is a significant clay layer below 2.4 m in the pivot area and slightly deeper towards the dam. This layer impedes downward migration of water and associated salts, which gives rise to the deeper water levels, levels that are uncommonly deep for an irrigation site. The installed shallow piezometers support these findings, since the water quality measured in them showed elevated concentrations, consistent with mine water that could not migrate downwards (Table 5.4).

5.2.2 Groundwater quality

Multi-parameter profiling

- The water quality in the groundwater was profiled with a multi-parameter probe. Multi-parameter logs ensure that water qualities are measured as they are, *in-situ*, without disturbing the water column in the boreholes through sampling. Without such probing, sampling would be less precise and associated with greater uncertainty with regards to water quality variation.

In-situ measurements of water qualities were done at five localities in and around the pivot area at New Vaal. One such profile is illustrated in Figure 5.11. The other profiles are illustrated in the Appendix I.

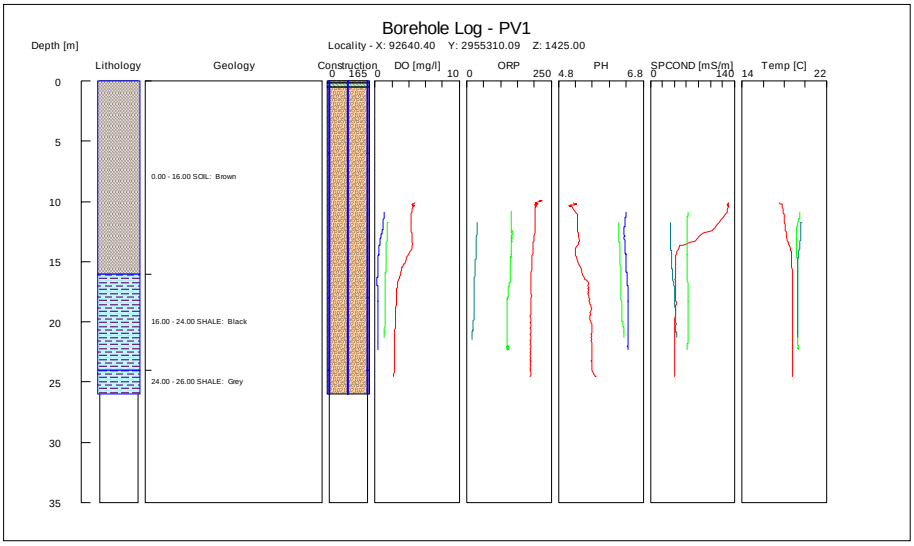


Figure 5.11 Multi-parameter profiling of PV1.

- PV1 is a background value with typical unpolluted aquifer parameters. The EC is low (46 mS m^{-1}) and the pH neutral.
- The measured values indicate clearly that the groundwater flow paths from the pivot do not intersect borehole PV4, as this borehole is not impacted by the irrigation. A more westerly flow direction from the pivot towards the Vaal River is expected.
- PV5 is situated in the centre of the pivot. The measured values indicate clearly that the mine water used for irrigation has not impacted significantly on the water quality of the aquifer yet.
- The EC values in boreholes PV2 (above 300 mS m^{-1}) and PV3 are elevated (90-120 mS m^{-1}) compared to the previous three boreholes. These increases were influenced by spillage of water from the irrigation dam.

Groundwater quality analysis

According to the analysis of the sampling done, the water quality of all the boreholes sampled, excluding PV2, is mostly within Class 0 and Class 1, i.e. ideal to acceptable water. PV2 is totally different water to the rest. This is because the water originates from overflow from the dam. Unfortunately this borehole is now blocked and cannot be sampled any longer. Regarding the 2005 sampling (Table 5.5), it is clear that the water in the shallow piezometers, above the clay layer, is highly mineralised when compared to the deeper “aquifer” below the clay.

Table 5.5 Water quality of the groundwater at the New Vaal Pivot (March 2005).

Site name	**pH**	**EC (mS $m^{-1)}$**	**Ca mg ℓ^{-1}**	**Mg mg ℓ^{-1}**	**Na mg ℓ^{-1}**	**K mg ℓ^{-1}**	**PAI mg ℓ^{-1}**
PV3	6.99	105	76.6	31.1	95.7	4.52	0
PV4	7.34	20.4	15.4	6.7	10.8	1.65	0
PV5	6.64	32.1	26.0	10.7	17.7	2.58	0
Short piezo	7.64	223	141.7	50.1	290.2	22.52	0
Solid piezo	7.74	255	114.9	59.7	422.1	5.52	0
Site Name	**MAI mg ℓ^{-1}**	**Cl mg ℓ^{-1}**	**NO_2(N) mg ℓ^{-1}**	**Br mg ℓ^{-1}**	**NO_3(N) mg ℓ^{-1}**	**SO_4 mg ℓ^{-1}**	**NH_4 mg ℓ^{-1}**
PV3	83.0	125.0	-1.00	0.54	0.06	271	0.16
PV4	43.6	7.5	0.03	-1.00	1.11	34	0.23
PV5	16.6	41.4	-1.00	0.18	0.13	75	0.26
Short piezo	163.0	78.9	0.06	-1.00	27.6	745	0.19
Solid piezo	226.0	98.0	0.71	0.43	6.17	896	0.17

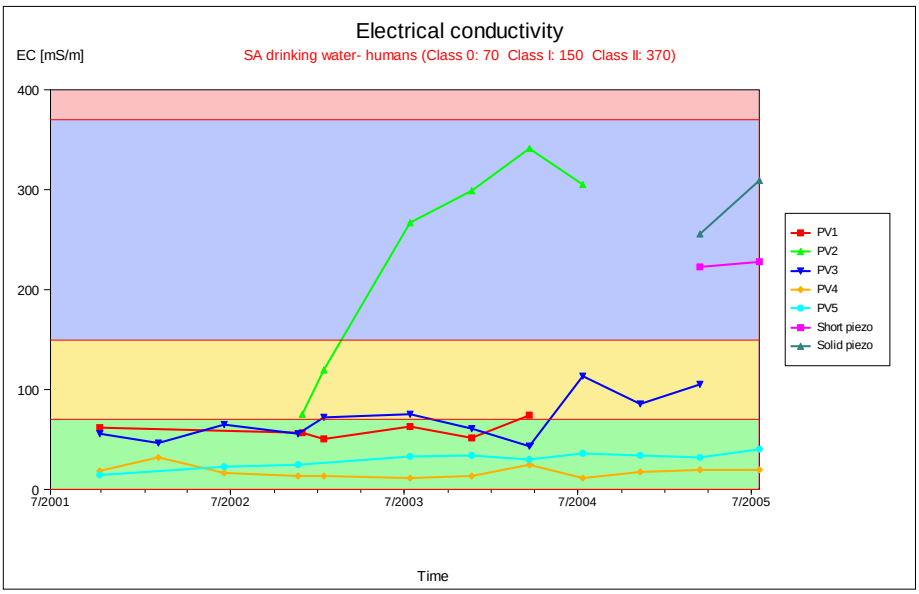


Figure 5.12 Time graph of the Electrical Conductivity at New Vaal Pivot.

- The electrical conductivity of all the boreholes except PV2 is ideal, as illustrated in Figure 5.12. The piezometer holes, however, show elevated values, indicating leachate from the irrigation to the shallow subsurface. This also indicates that over time, the water quality has not yet deteriorated significantly within the underlying aquifer because of irrigation. The reason may be because of dilution due to the high lateral flow of water through the sandy layers above the clay layer and high natural recharge in the sands. The clay layer discussed previously also limits downward migration and therefore only gradual deterioration in water quality of the aquifer occurs from slow leakage through this layer.

However, it is insightful to zoom in to Borehole PV5 in the pivot area as far as trends are concerned (Figure 5.13).

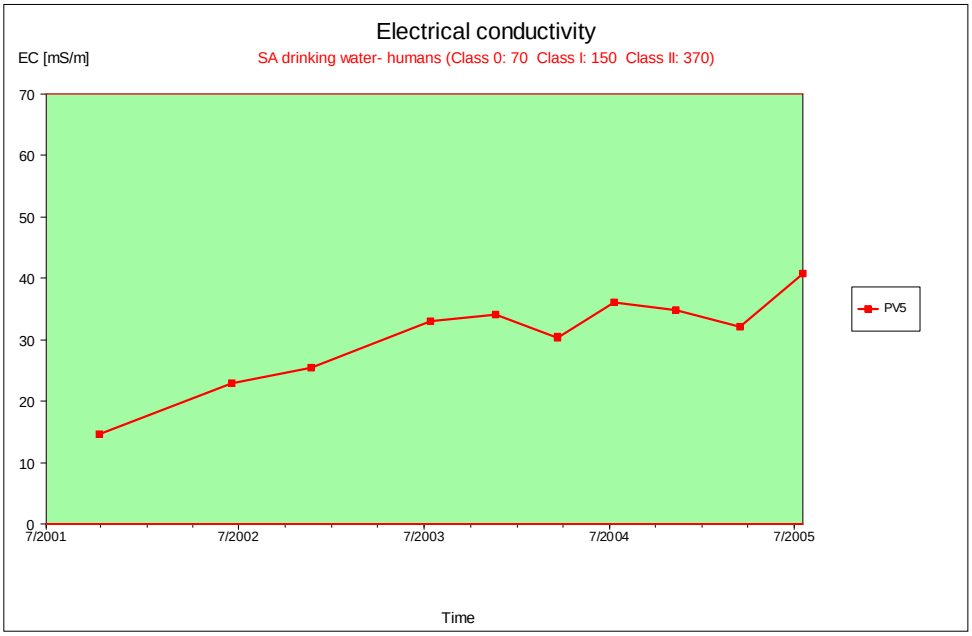


Figure 5.13 PV5 electrical conductivity trend since monitoring began.

Although the water quality in this borehole is excellent, the results from the analysis show that there is a steady and consistent rise in the electrical conductivity. This indicates that the irrigation water is slowly leaching through the clay layers and starting to influence the groundwater quality directly below the pivot. The trend in this borehole is cause for some concern and future phases would have had to investigate this further if irrigation was to continue. At the current rate of increase, irrigation will start to cause marked deterioration to values beyond the trigger values for this site within a few years.

Conclusions

- The water levels at New Vaal pivot have varied very little over time, with some decreases evident. The water levels are deeper than most other irrigation schemes, and can be attributed to the high conductivity of the soils above the clay layers, resulting in faster drainage towards the river, and the lack of vertical migration from the irrigation area itself.
- The overall water quality trend in the deeper aquifer is generally stable, except for PV2, which is influenced by the irrigation dam.
- PV5 within the pivot area, is showing signs of consistent water quality degradation, with increases in most of the constituents.
- The irrigation water has, as yet, shown a minimal impact on the groundwater. This implies very slow movement of the constituents in the irrigation water, and that they are caught up between the surface and the aquifer in the clay layer. The amount leaching through from the pivots is small enough to be easily diluted by the regional groundwater flow.

5.3 Syferfontein Colliery

Monitoring on a quarterly basis was performed until August 2004, when a conveyor constructed through part of the site, destroyed most of the monitoring holes. New boreholes, OBH6 shallow and deep, OBH 7 and OBH 8 were then constructed. Irrigation also halted until October 2005, because of the construction of the conveyor. Subsequently, a half circle was re-commissioned.

5.3.1 Water levels

Figure 5.14 illustrates the groundwater levels at the Syferfontein Pivot. The water levels, as expected at an irrigation scheme, are very shallow (3-5 m below surface).

- All the water levels except OBH3 show a similar downward trend.
- The construction of the run-off trenches will also play a part in the lower water levels.

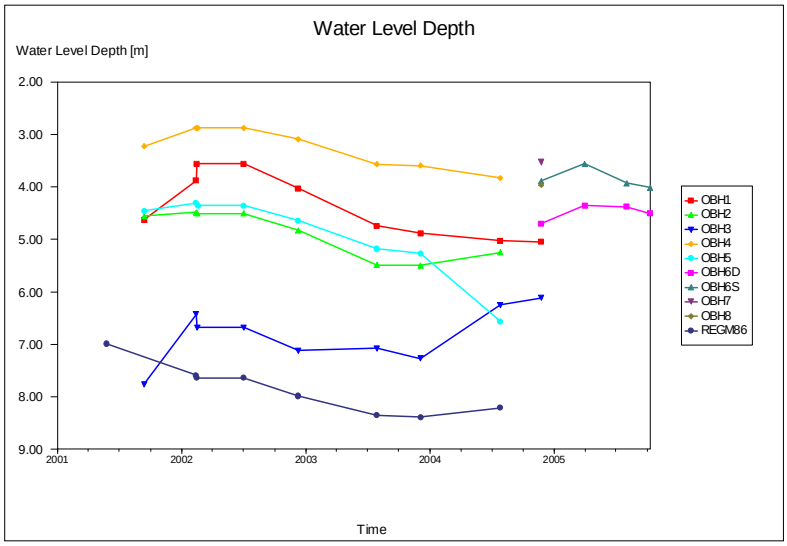


Figure 5.14 Groundwater levels for the Syferfontein pivot.

Of importance is the fact that the irrigation activities do not appear to have significantly affected the observed water levels, since these are at or below the levels measured when the boreholes were drilled in 2001.The dykes running though the area appear to be more important in delineating zones of different water levels. It is important to note, however, that the two boreholes with deeper water levels are the up-gradient borehole OBH3 and REGM 86, which could both be considered to be less likely to be influenced by irrigation.

5.3.2 Groundwater quality

Multi-parameter Profiling

In-situ measurements of water qualities were done at six localities in and around the pivot area at Syferfontein. The profiling graphs are presented in the Appendix I**.** As an example, the *in situ* characterization of OBH1 is shown below in Figure 5.15.

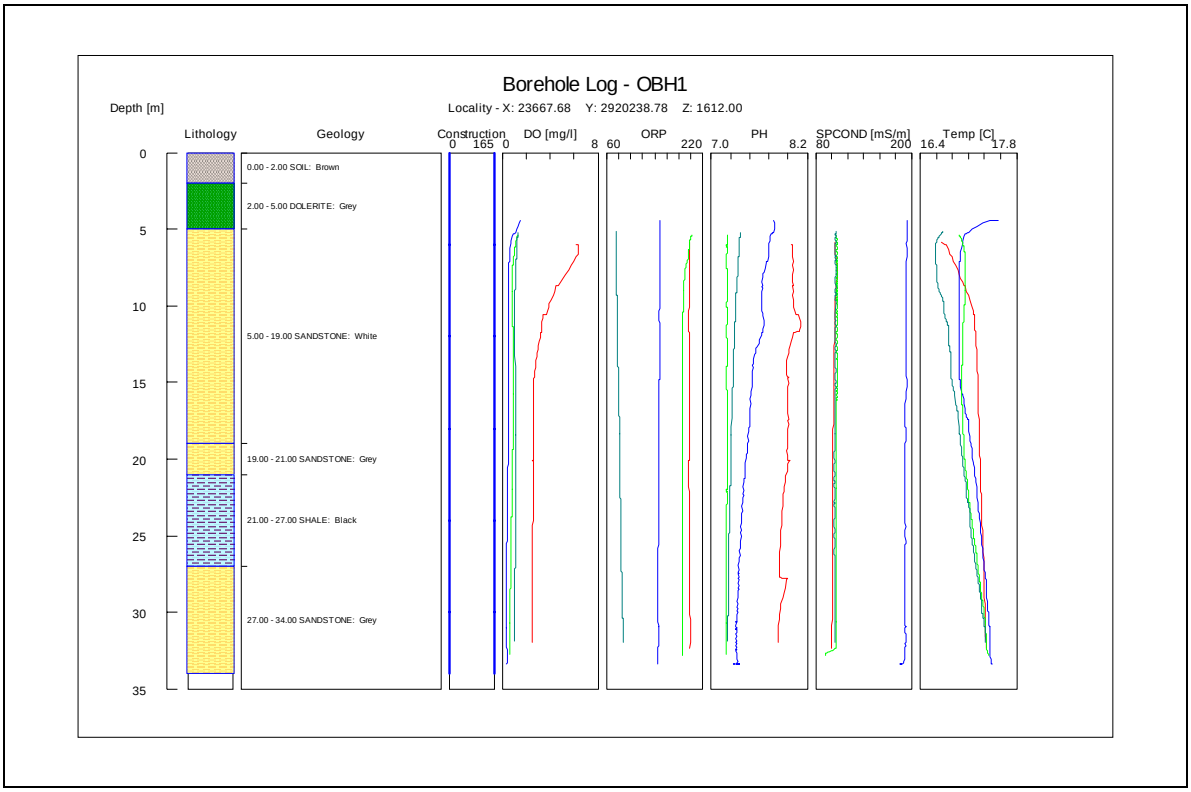


Figure 5.15 Multi-parameter profiling of OBH1.

From Figure 5.15 it can be seen that there is very little variation in the different parameters with depth. Temperature increases slightly with depth. Dissolved oxygen shows the expected decrease with depth, as oxygen diffusion decreases with depth. The distinct shift in specific conductivity and pH in OBH1 during February 2002 (blue line) was the result of run-off water entering the borehole. The profiling compares favourably to the time graph of Electrical Conductivity (Figure 5.16), and indicates a two-year period before the water quality returned back to normal, after the cut-off trenches were constructed.

Groundwater quality analysis

The analysis of the sampling done during December 2003 (the last time sampling was possible) is illustrated in Table 5.6. According to this analysis, the water quality of all the boreholes sampled is within Class 0 and Class 1, i.e. ideal to acceptable water, except for Nitrate, which falls in Class II.

Table 5.6 Water quality of the groundwater at the Syferfontein Pivot.

Site name	**pH**	**EC (mS m $^{-1}$)**	**Ca mg ℓ^{-1}**	**Mg mg ℓ^{-1}**	**Na mg ℓ^{-1}**	**K mg ℓ^{-1}**	**PAI mg ℓ^{-1}**	**MAI mg ℓ^{-1}**	**Cl mg ℓ^{-1}**
OBH1	7.83	102	79.5	51.3	62.1	1.63	8.11	341	102.5
OBH2	8.03	116	72.4	41.9	137.2	1.01	4.1	349	78.9
OBH3	8.02	84	75.5	64.2	33.4	1.91	11.5	325	9.8
OBH4	7.91	75	55.7	39.8	51.4	2.75	8.5	366	10.1
OBH5	8.29	97	73.5	48.9	67.2	1.97	1.4	356	42.3
REGM86	7.91	94	74.7	49.9	75.9	2.29	12.6	339	22.9
Site Name	**SO_4 mg ℓ^{-1}**	**NO_3(N) mg ℓ^{-1}**	**F mg ℓ^{-1}**	**NO_2(N) mg ℓ^{-1}**	**PO_4 mg ℓ^{-1}**	**Br mg ℓ^{-1}**	**Al mg ℓ^{-1}**	**Fe mg ℓ^{-1}**	**Mn mg ℓ^{-1}**
OBH1	16.00	1.72	0.16	<0.012	<0.012	0.24	0.003	0.030	0.004
OBH2	138.71	16.61	0.31	<0.012	<0.012	0.67	0.003	0.028	0.013
OBH3	129.80	3.74	0.32	<0.012	<0.012	<1	0.008	0.082	0.012
OBH4	6.19	0.04	0.15	<0.012	<0.012	0.11	0.006	0.023	0.023
OBH5	39.05	9.67	0.12	<0.012	<0.012	0.52	0.006	0.023	0.023
REGM86	92.20	12.76	0.15	<0.012	<0.012	0.61	0.004	0.007	0.006
Site Name	**Ag mg ℓ^{-1}**	**As mg ℓ^{-1}**	**B mg ℓ^{-1}**	**Ba mg ℓ^{-1}**	**Cr mg ℓ^{-1}**	**Cd mg ℓ^{-1}**	**Co mg ℓ^{-1}**	**Li mg ℓ^{-1}**	**Cu mg ℓ^{-1}**
OBH1	0.0	0.0	<0.04	0.154	0.0	0.0	0.0	0.022	0.025
OBH2	0.0	0.0	<0.04	0.107	0.0	0.0	0.0	0.014	0.026
OBH3	0.0	0.0	<0.04	0.020	0.0	0.0	0.0	0.010	0.032
OBH4	0.0	0.0	<0.04	0.188	0.0	0.0	0.0	0.040	0.028
OBH5	0.0	0.0	<0.04	0.078	0.0	0.0	0.0	0.026	0.030
REGM86	0.0	0.0	<0.04	0.112	0.0	0.0	0.0	0.028	0.023
Site Name	**Mo mg ℓ^{-1}**	Ni **mg ℓ^{-1}**	**Pb mg ℓ^{-1}**	**Sb mg ℓ^{-1}**	**Se mg ℓ^{-1}**	**Sr mg ℓ^{-1}**	**V mg ℓ^{-1}**	**Zn mg ℓ^{-1}**	**SAR mg ℓ^{-1}**
OBH1	0.0	0.0	0.0	0.0	0.003	0.491	0.000	0.007	1.335
OBH2	0.0	0.0	0.0	0.0	0.002	0.382	0.000	0.013	3.177
OBH3	0.0	0.0	0.0	0.0	0.003	0.463	0.013	0.015	0.683
OBH4	0.0	0.0	0.0	0.0	0.002	0.757	0.000	0.011	1.284
OBH5	0.0	0.0	0.0	0.0	0.003	0.439	0.000	0.012	1.490
REGM86	0.0	0.0	0.0	0.0	0.003	0.523	0.016	0.020	1.667

- The electrical conductivity of all the boreholes are allowable, as illustrated in Figure 5.16. The exception is OBH6S, the shallow borehole inside the pivot area. The deeper one (OBH6D) shows no variation from the other boreholes. During 2005, only the area where these two boreholes are situated was irrigated, in order to continue some degree of monitoring.

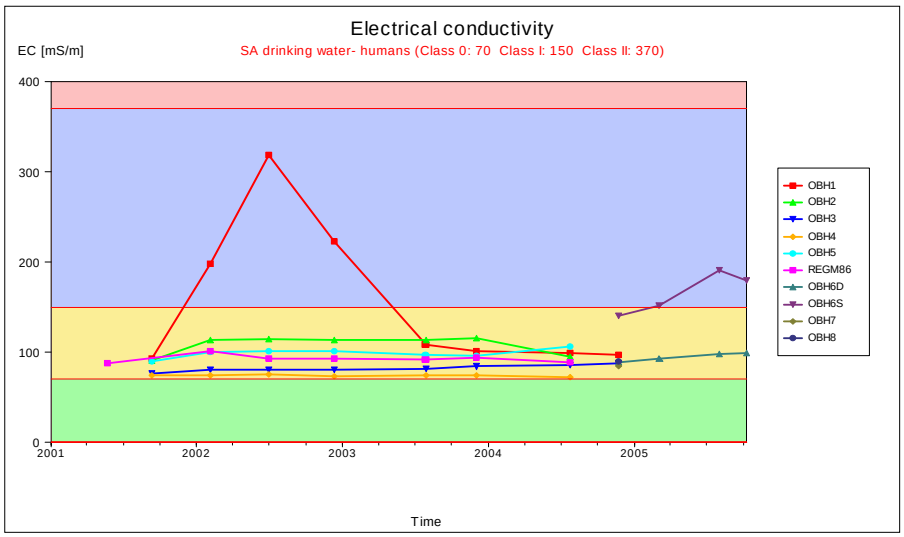


Figure 5.16 Time graph of the Electrical Conductivity at Syferfontein Pivot.

- OBH1 shows a vast improvement since the construction of the run-off trenches and is currently similar to the water quality in the other boreholes.
- The overall water quality trend of all the boreholes is sideways, indicating that over the period of irrigation water quality has not deteriorated within the underlying aquifer.
- In order to determine why the aquifer below and adjacent to the pivot area is not impacted, soil tests were performed.
- Core drilling was done at various sites inside and outside the irrigation area. From the cores, distinctive geological layers were selected, and determination of soil properties in terms of relative clay, sand and silt content, were done at Glen Agricultural College. The results are shown in Chapter 2, and it is clear that this heavy swelling clay soil of the Arcadia form varies in thickness from 300 to 900 mm and lies on weathered dolerite saprolite. Infiltration in such soils can be very low.
- Leaching tests were also performed with deionised water through the cores drilled inside and outside the pivot area. The leaching analyses on these samples can be graphically represented (Figures 5.17 and 5.18) to show the layers where there is enrichment in soluble salts. From these it is clear that the shallow portions under the irrigated area have far higher values than the lower layers and those outside of the pivot. The clays in the shallow zones appear to prevent migration and attenuate the salts strongly in the upper portions.

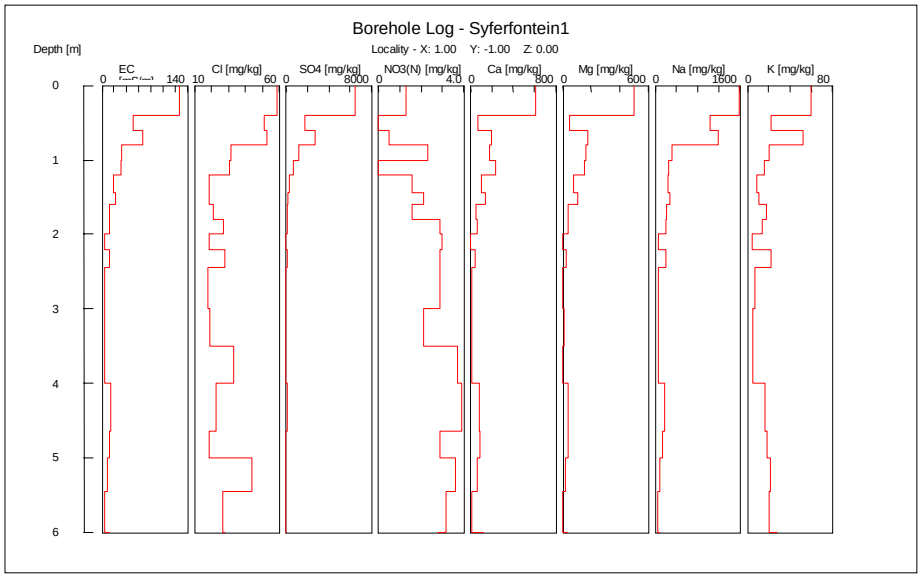


Figure 5.17 Soil leaching analyses within the pivot area

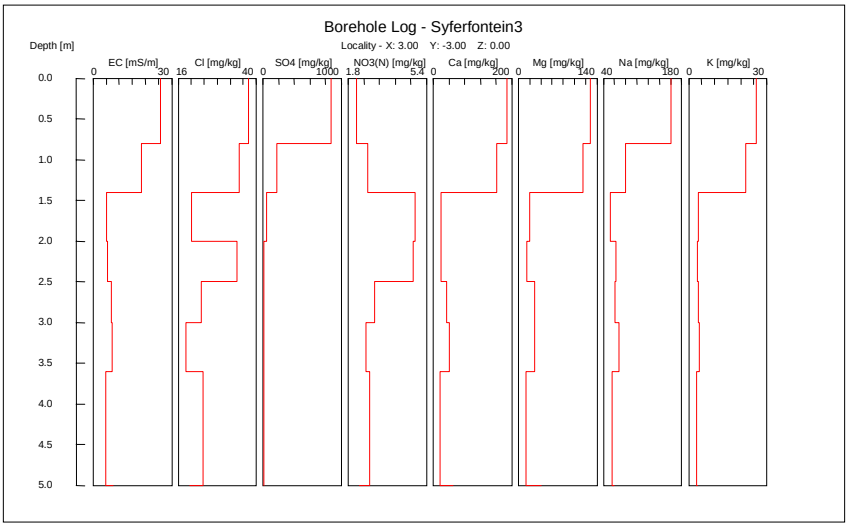


Figure 5.18 Soil leaching analyses outside the pivot area

- The nitrate profile in Figure 5.17 is noteworthy since it suggests that this is relatively mobile compared to the other parameters. Redox induced changes and root uptake will have to be considered too. The nitrate is also present in the groundwater, as illustrated in the time graph in Figure 5.19. The values have not increased dramatically over the monitoring period.

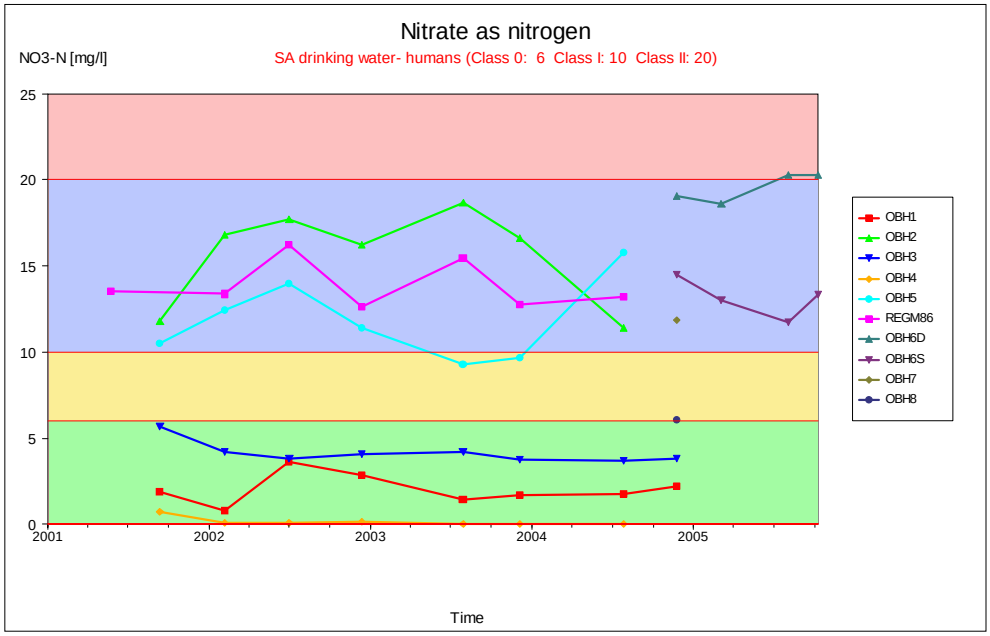


Figure 5.19 Time graph of nitrate in the monitoring boreholes.

Conclusions

- All the water levels show a similar downward trend. The construction of the run-off trenches may also play part in the lower water levels.
- Since the construction of the run-off trenches, the water quality of OBH1 returned to the same quality as that of the other boreholes at Syferfontein Pivot.
- The overall water quality trend is generally sideways, with a very small decrease in calcium and magnesium.
- The quality of the irrigation water is sodium sulphate rich, and that of the groundwater calcium/magnesium bicarbonate. The water quality of the up-gradient borehole OBH3, is also the same as that of the down-gradient boreholes. This means that the irrigation water has, as yet, not impacted on the groundwater, despite the fact that irrigation started nearly 5 years ago. This is illustrated by the sodium and sulphate values in Figure 5.20. This implies very slow movement of the constituents in the irrigation water, and that they are caught up between the surface and the aquifer. The amount leaching through from the pivots is small enough to be easily diluted by the regional groundwater flow.
- The larger concentrations of nitrate are due the agricultural activity at the pivot. Of concern is the fact that the relatively mobile constituents are able to move through the soil profile into the groundwater and cause groundwater degradation. This has not been significant over the almost five years of operation and monitoring.

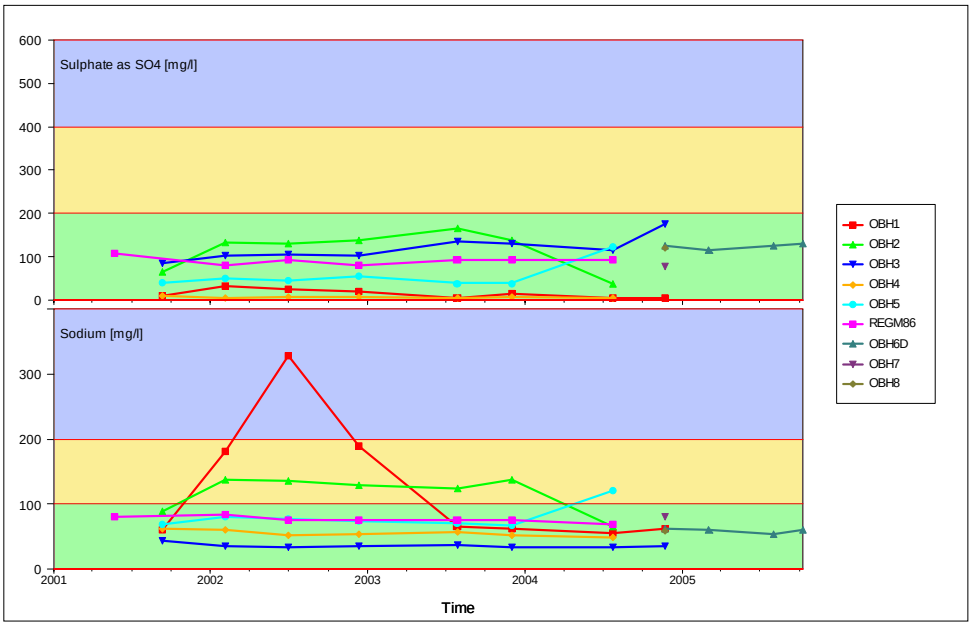


Figure 5.20 Time graphs of sodium and sulphate, the main constituents of the irrigation water.

Overall conclusions from the groundwater monitoring at the different pivots

- The water levels at all the pivots have varied very little over time. The water levels at New Vaal are deeper than most other irrigation schemes. This can be attributed to the high conductivity in the soils above the clay layers, resulting in faster drainage towards the river. The water levels at the other irrigation sites are very shallow due to the increased recharge locally.
- The overall water quality trend in the deeper aquifer indicates that the water quality has not shown significant deterioration over the monitoring period.
- The irrigation water has, as yet, shown a minimal impact on the groundwater. Some exceptions occur, but the boreholes lying outside the pivot areas have all shown no meaningful change in water quality from leaching from the irrigated area. This implies very slow movement of the constituents in the irrigation water, and that these are attenuated by different mechanisms between the surface and the aquifers, often in the clay layers present. The amount leaching through the soil is small enough to be easily diluted by the regional groundwater flow. It thus appears that the soil type and morphology plays a very important role in the vertical movement of the irrigation water constituents.
- It is not known how long this accumulation of salts in the upper layers can continue before leaching into the underlying aquifers will occur, but in the short to medium term,

the evidence from the groundwater monitoring shows that irrigation with mine water does not hold significant threats to regional groundwater quality.

- The trail pivot sites investigated thus far indicate that in the short term the groundwater impacts are limited, and more importantly localised. Research is underway, through the Water Research Commission and Coaltech 2020, to establish the impacts of mine water irrigation on the groundwater resources. For consideration of future large-scale irrigation with mine water, the following aspects should be noted:
- Site selection is very important. Careful consideration of the applicability of the site to irrigation, local geology and geohydrological properties, the proximity of sensitive water users for 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.
- 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 DWAF, to fix different levels or guidelines at which action should be taken to mitigate the impact or even to cease irrigation activities, must be part of such a monitoring plan.
- The regulatory framework regarding the “polluter pays” principle should be negotiated between the mine providing the water, the regulator and the party irrigating with the mine water.
- Detailed guidelines on the site selection, monitoring guidelines and operational considerations from a groundwater perspective will be provided by the outcomes of WRC project K5/1507 that will be completed in 2007.

CHAPTER 6

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

Introduction

In order to predict the impact of large-scale irrigation with mine water on ground and surface water, it is essential that field scale soil water and salt balances be predicted reliably. In this chapter we discuss the ability of the model developed for this purpose (SWB) to predict crop growth, soil water and salt balances.

6.1 Crop growth

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 was necessary to accurately simulate the growth of the crops. For this purpose, specific crop growth parameters already included in the database of SWB (Annandale et al., 1999a), 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 grown at Syferfontein according to the procedure developed by Jovanovic and 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.

At Kleinkopjé Colliery, crops were rotated for 15 seasons in site Major and 16 seasons in site TWF. Each season's data was used to simulate the soil water and salt balance for pivots Major and TWF. Only 12 seasons for Pivot Four were simulated, as this site was established later than the other two. At Syferfontein, 9 pasture harvests and at New Vaal, 7 crop rotations, were simulated.

The 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 Figures 6.1-6.3. 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, and is discussed in this section on crop growth, as the main aim with the modelling was not to accurately simulate crop yields, but rather to have a reasonable estimate of canopy cover in order to get a reasonable description of the soil water balance.

For all crops, the measured values of LAI, TDM and deficit were distributed both above and below the simulated lines, but were generally reasonably accurate Figures 6.1-6.3. When plants are water stressed, the salt concentration of the soil solution increases and as a result the leaf water potential and transpiration rate decreases (McCree and Richardson et al., 1987). This causes a

reduction in growth rate with declining soil water and increasing water stress (Meyer and Green et al., 1980). Thus, the rate of leaf area expansion declined when there was stress, or increased when plants were supplied with sufficient water and rainfall that can dilute the soil solution. The simulations for the other pivots can be found in Appendix G. In general, though, the simulation of crop growth (canopy cover) can be considered to be sufficiently accurate to give reasonable estimates of the soil water balance.

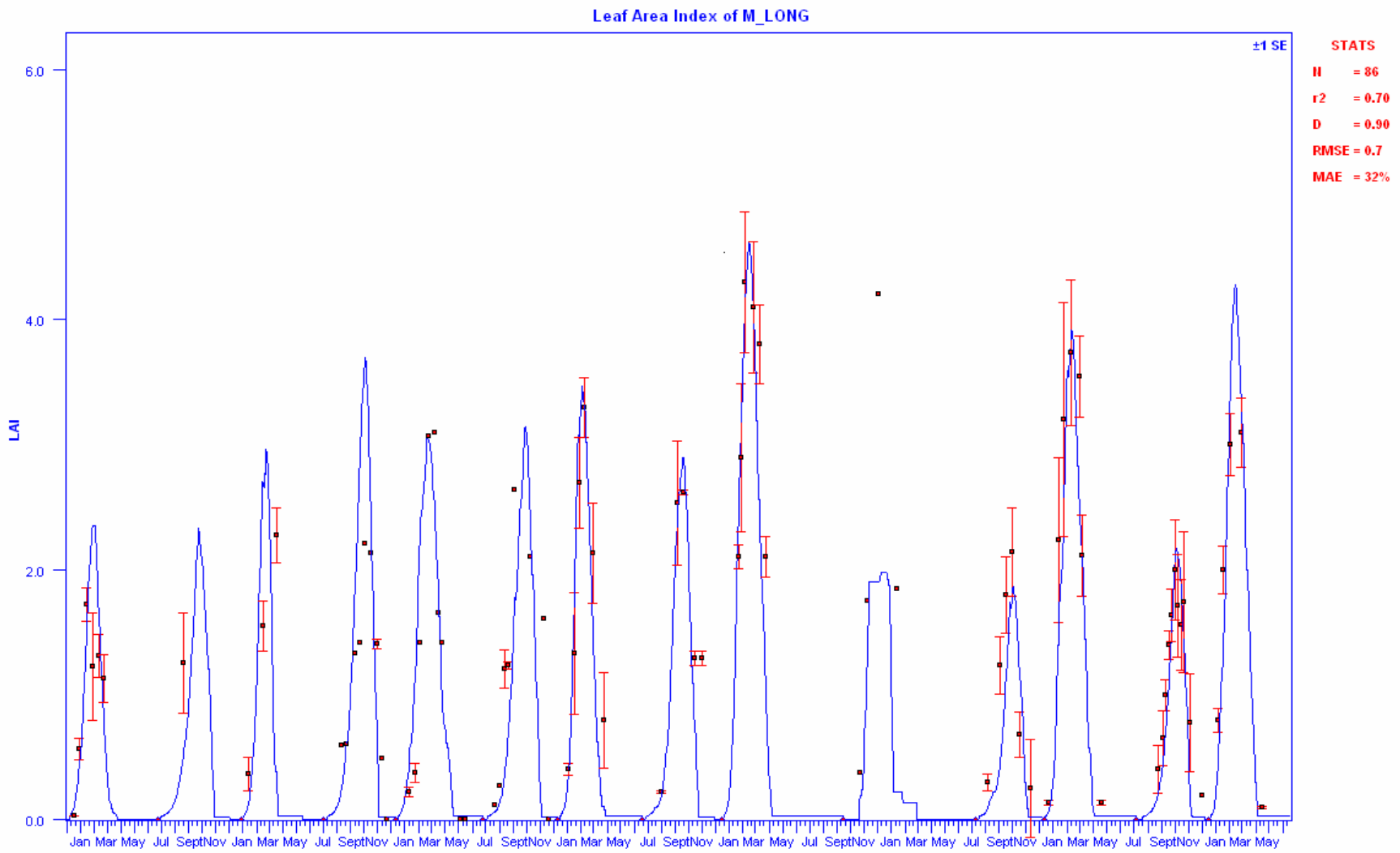


Figure 6.1. Simulated (solid lines) and measured (symbols) for LAI for Pivot Major (1997/98-2004/05)

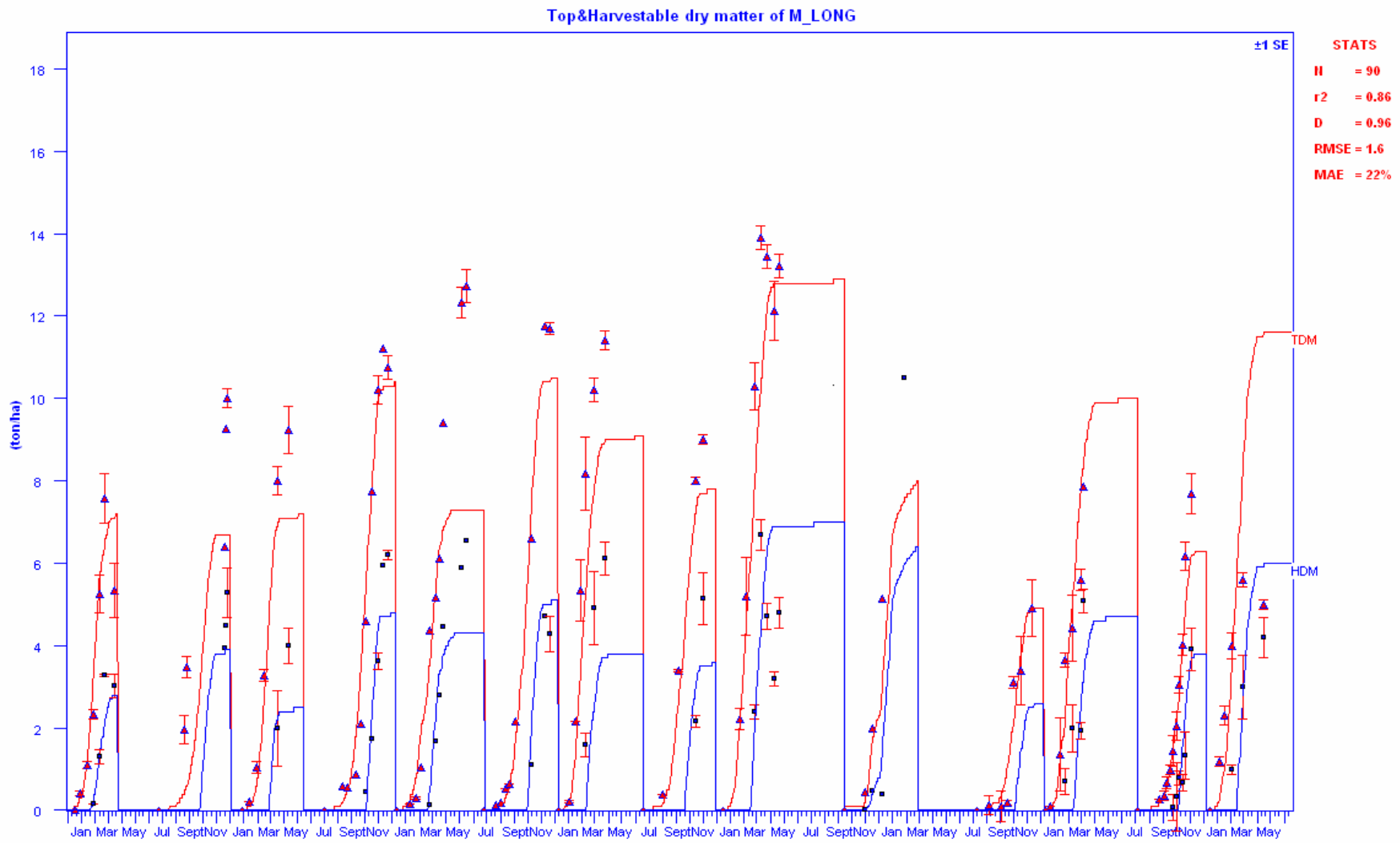


Figure 6.2 Simulated (solid lines) and measured (symbols) TDM for site Major (1997/98-2004/05)

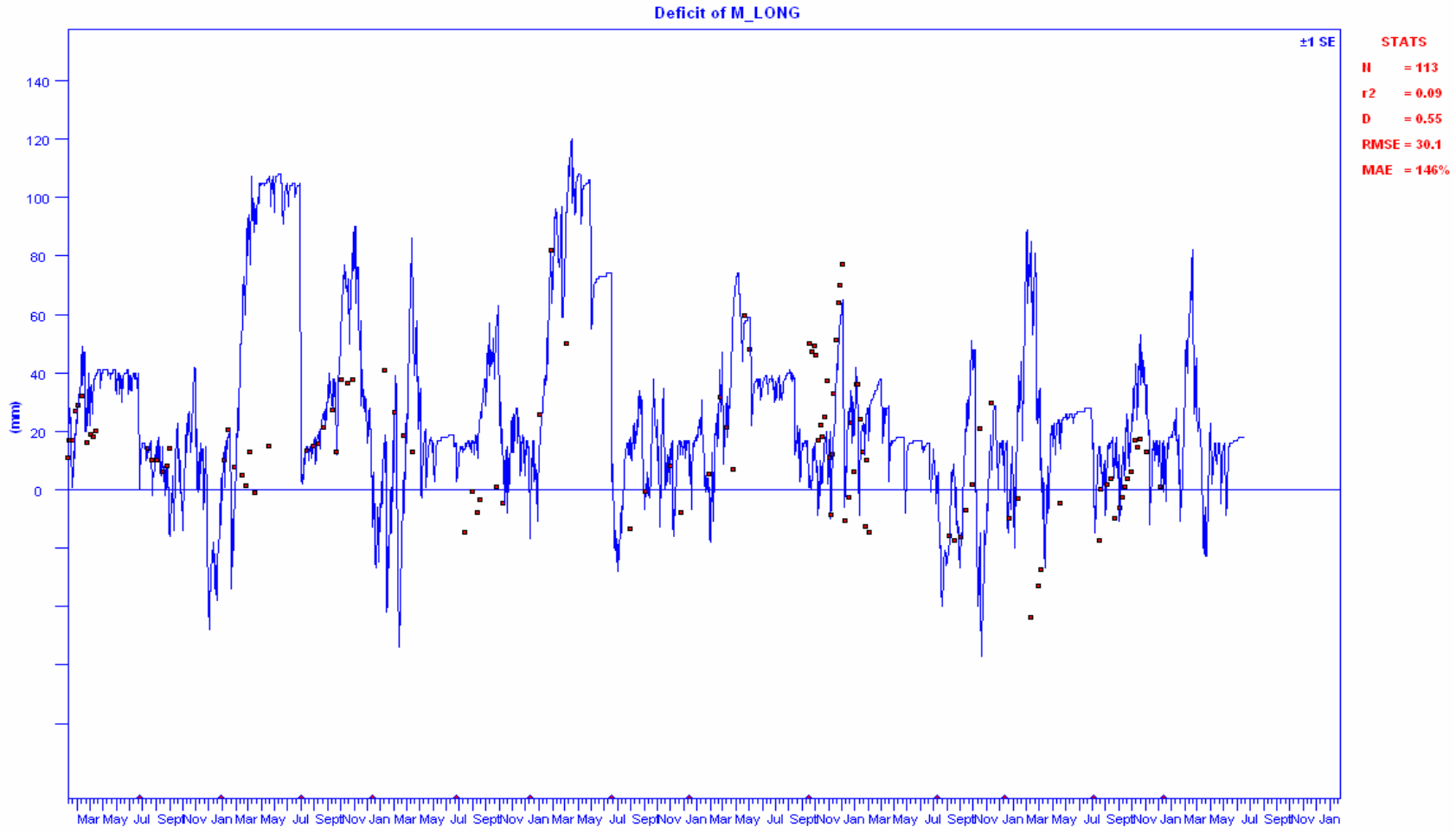


Figure 6.3 Simulated (solid lines) and measured (symbols) soil water deficit to field capacity (Major,1997/98-2004/05)

6.2 Soil solution

The soil solution concentrations of all the irrigated sites varied considerably during the growing period due to irrigation water quality, variability of soil water chemistry (for example: after gypsum precipitates considerable Mg is leached), 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 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 were also fluctuated 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, irrigation and rainwater chemical characteristics as an input to determine the quantity of salts in the soil solution of a given layer in a 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 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.

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 five years of data. The graphic comparisons of the soil solution concentration simulation show fairly good agreement with the measured data Figure 6.4. More model validations are presented in Appendix G. Differences between measured and simulated values could have by several cases. These include: soil heterogeneity and sampling error, preferential paths of water and salt movement through the soil profile, dissolution from weathering soil minerals, and fertilizer input and salts removal by the crop, as none of these effects are considered in the model.

The model predicted the soil solution realistically close to the measured values. This proves the predictive capacity of the model for long-term impact assessment of irrigation with gypsiferous mine water is reliable.

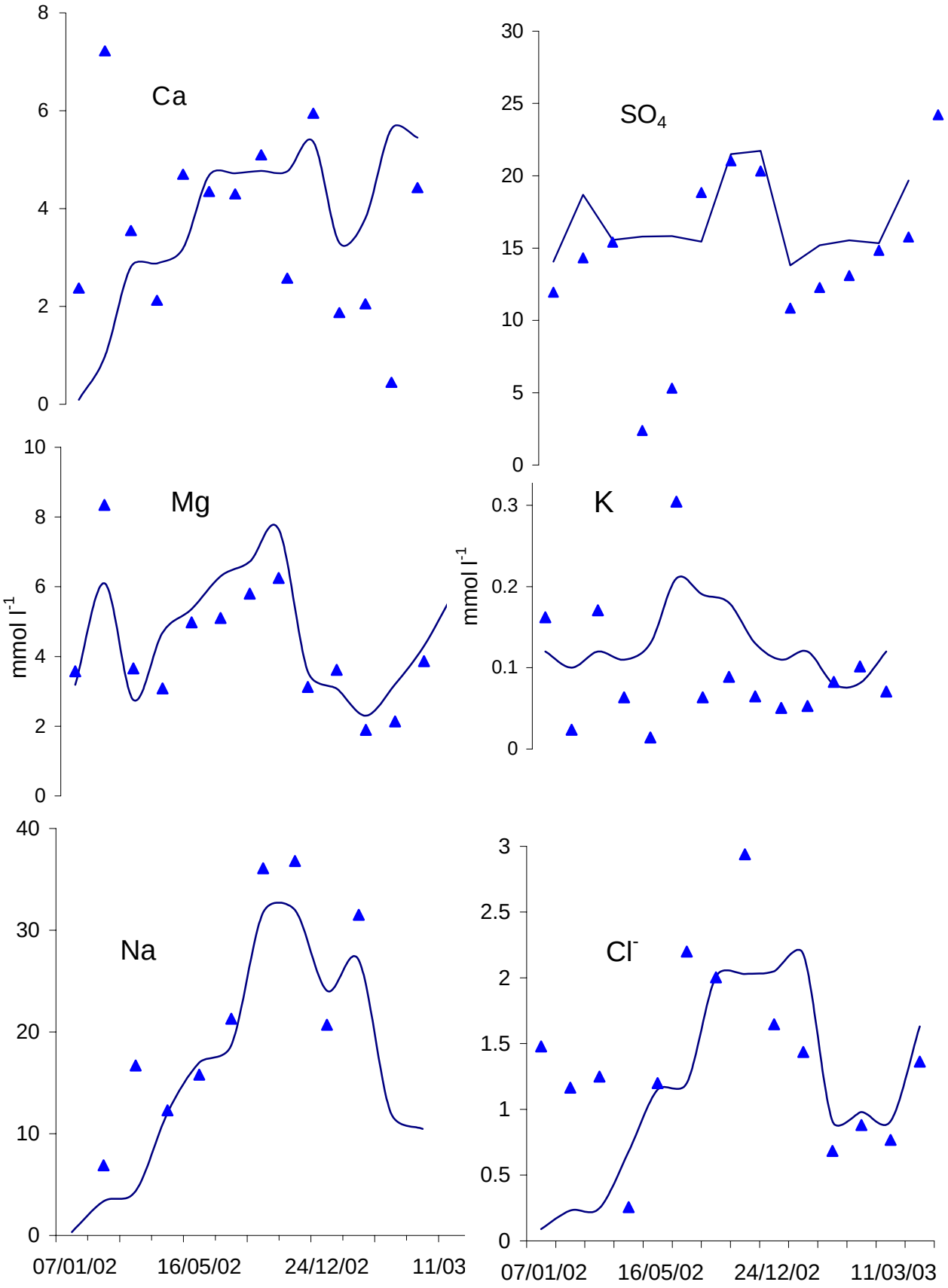


Figure 6.4 Temporal change of soil solution sampled at 0.4 m from WFD (symbols) as compared to model simulations (solid lines) for site Syferfontein

6.3 Comparison between SWB simulations and S and Ca analyses results

In order to compare analytical results to SWB simulations at the same point in time, an approximation of the solute concentration in the soil water is needed at the time of sampling.

Saturated paste extracts are generally accepted as an approximation of the soil solution composition, ion activity and solution speciation. These solution concentrations are often converted to mass or mole of solute per mass of soil, to correct for solutes that precipitated out as evaporate or soluble salts during the drying process. In weathered soils with little soluble and slightly soluble salts this is an acceptable practice, because adsorbed cations have low water extractability and soil minerals are sparingly soluble.

However, it is questionable whether this practice is acceptable for Ca and SO_4 in the soils irrigated with NAMD. The gravimetric water content of the samples collected at the Pivots is far from that of a saturated paste extract (Figure 6.5). Increasing the gravimetric water content of P5 for example, from the field gravimetric water content to that of the saturated paste was equivalent in making up 233 cm^{-3} of water in a volumetric flask to 1000 cm^{-3}. This increase in the water content will definitely result in the dissolution of gypsum and an underestimation of the solid phase gypsum.

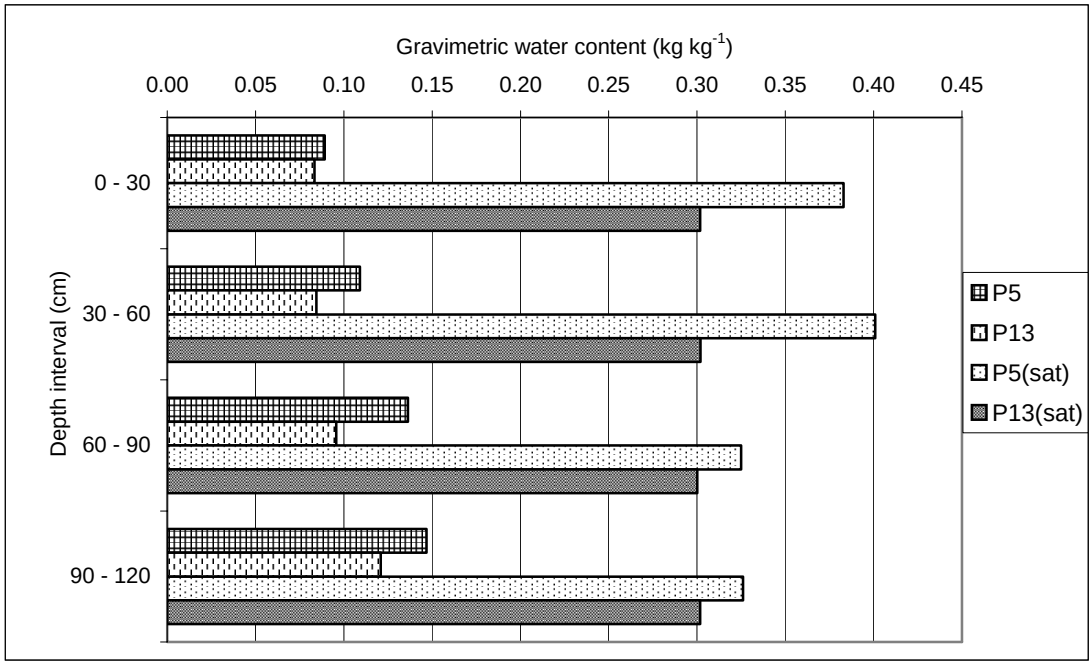


Figure 6.5 Field gravimetric water content of P5 and P13 compared to gravimetric water content of the saturated pastes of the same samples.

Solute concentrations in the saturated pastes were proportional correction/ concentrated based on the field gravimetric water contents of each depth interval. The new concentrations were again entered in PHREEQC and equilibrated with gypsum to correct for the change in total aqueous Ca ($[Ca]_T$) -and SO_4 concentration $[SO_4]_T$ as a result of gypsum precipitation caused by the concentration of the solutions. The same corrections were made to any other solute when it became over saturated with respect to any evaporative solid phase. The new solute concentrations after equilibration with gypsum was then converted to mole of solute per mass of soil to correct for the solid- solution partitioning of S at the time of sampling. The only factor not corrected for was the change in cation selectivity of the soil as a result of increasing

ionic strength. Generally the selectivity of a negative charged particle for di- and polyvalent cations will decrease with an increase in ionic strength. However it is expected that at these high aqueous Ca and Mg concentrations, the change in aqueous cation composition as a result of change in selectivity would be negligible.

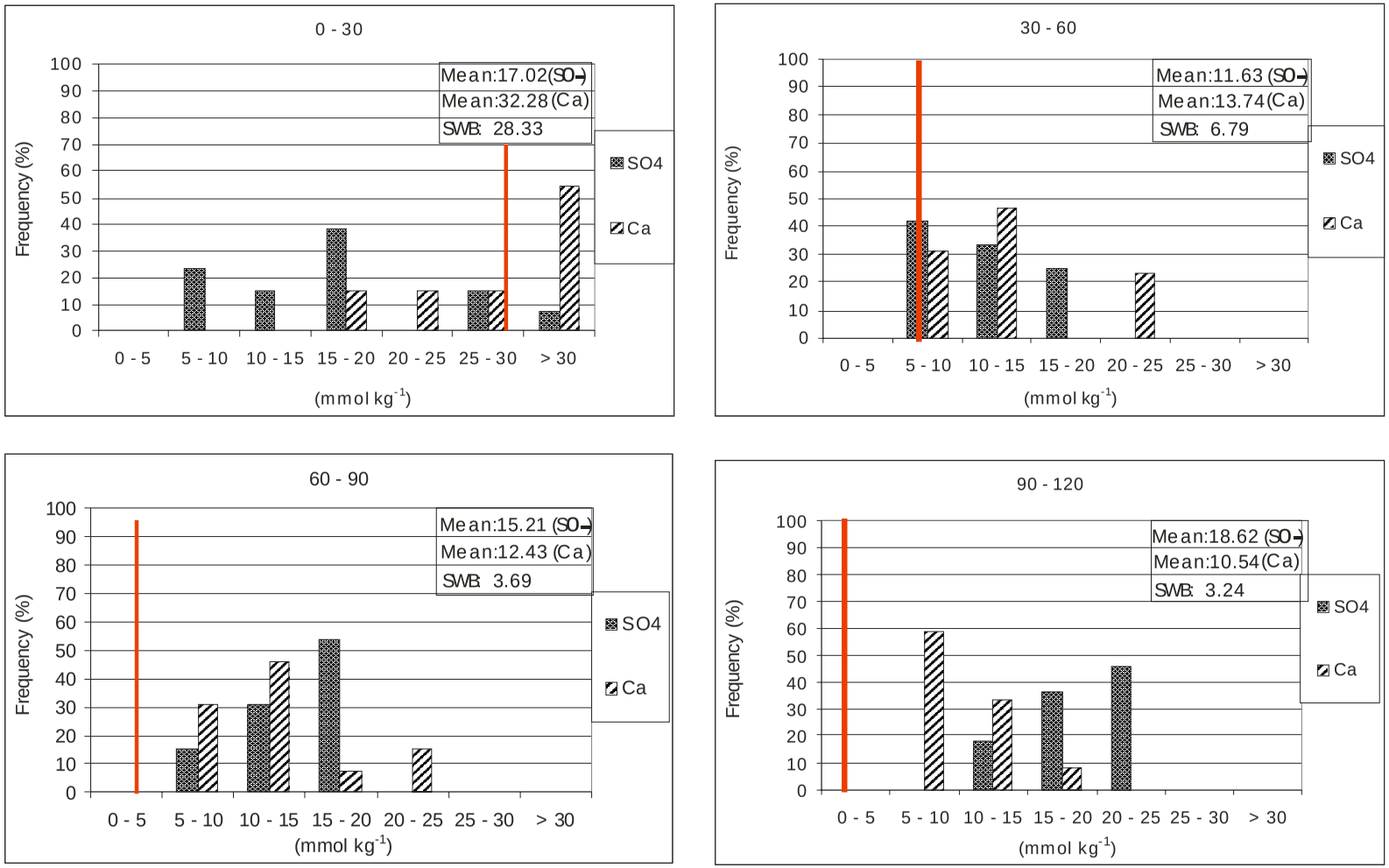


Figure 6.6 Comparison between SWB predictions in mmol kg^{-1} for each 30 cm depth interval (red line on each graph) and the frequency distribution and mean Amm-Aoc extractable Ca and PO_4- extractable S, along the sampling transect at Pivot Four.

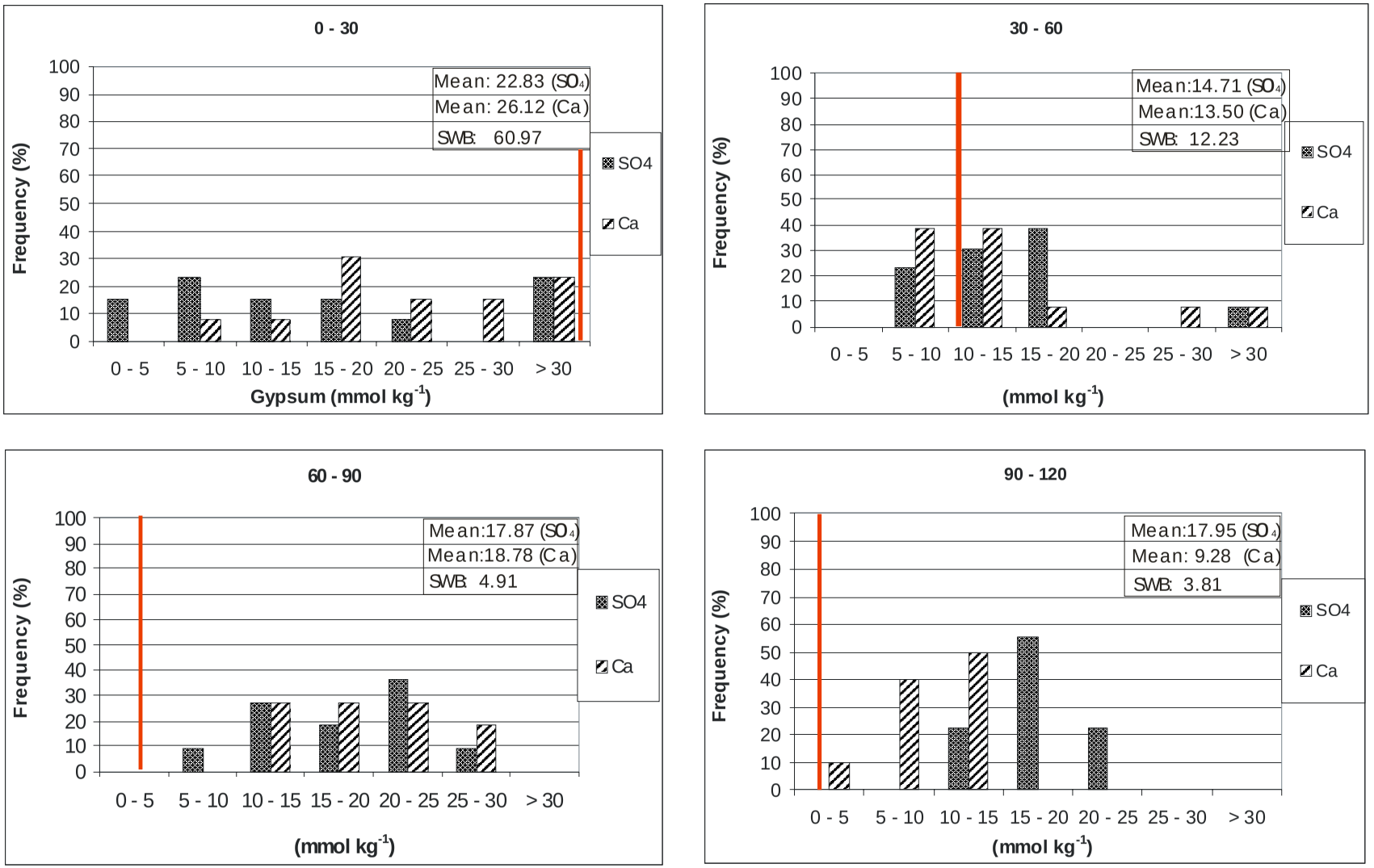


Figure 6.7 Comparison between SWB predictions in mmol kg^{-1} for each 30 cm depth interval (red line on each graph) and the frequency distribution and mean Amm-Aoc extractable Ca and PO_4- extractable S, along the sampling transect at Pivot Major.

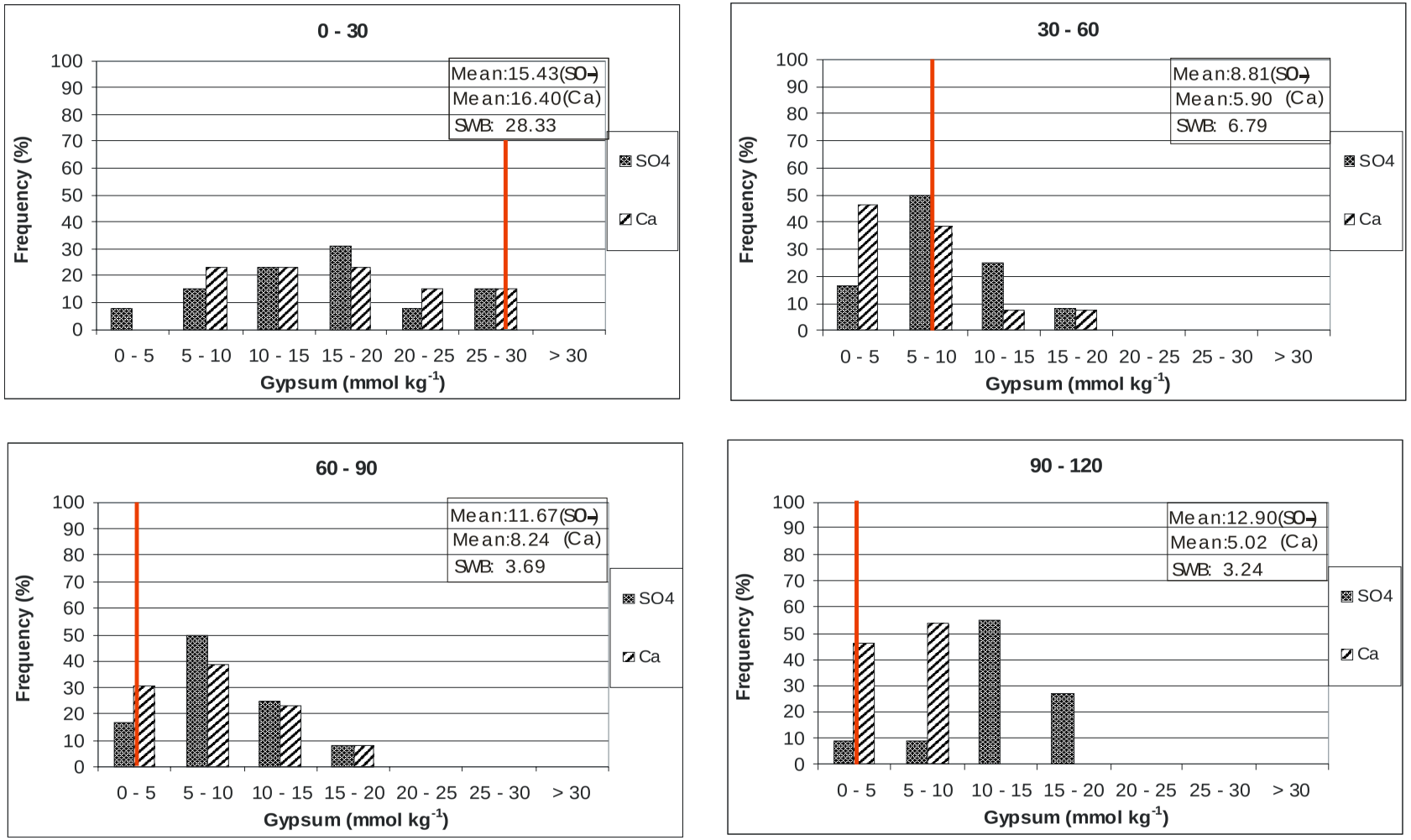


Figure 6.8 Comparison between SWB predictions in mmol kg^{-1} for each 30 cm depth interval (red line on each graph) and the frequency distribution of gypsum calculated from Ca and S analysis, along the sampling transect at Pivot Four.

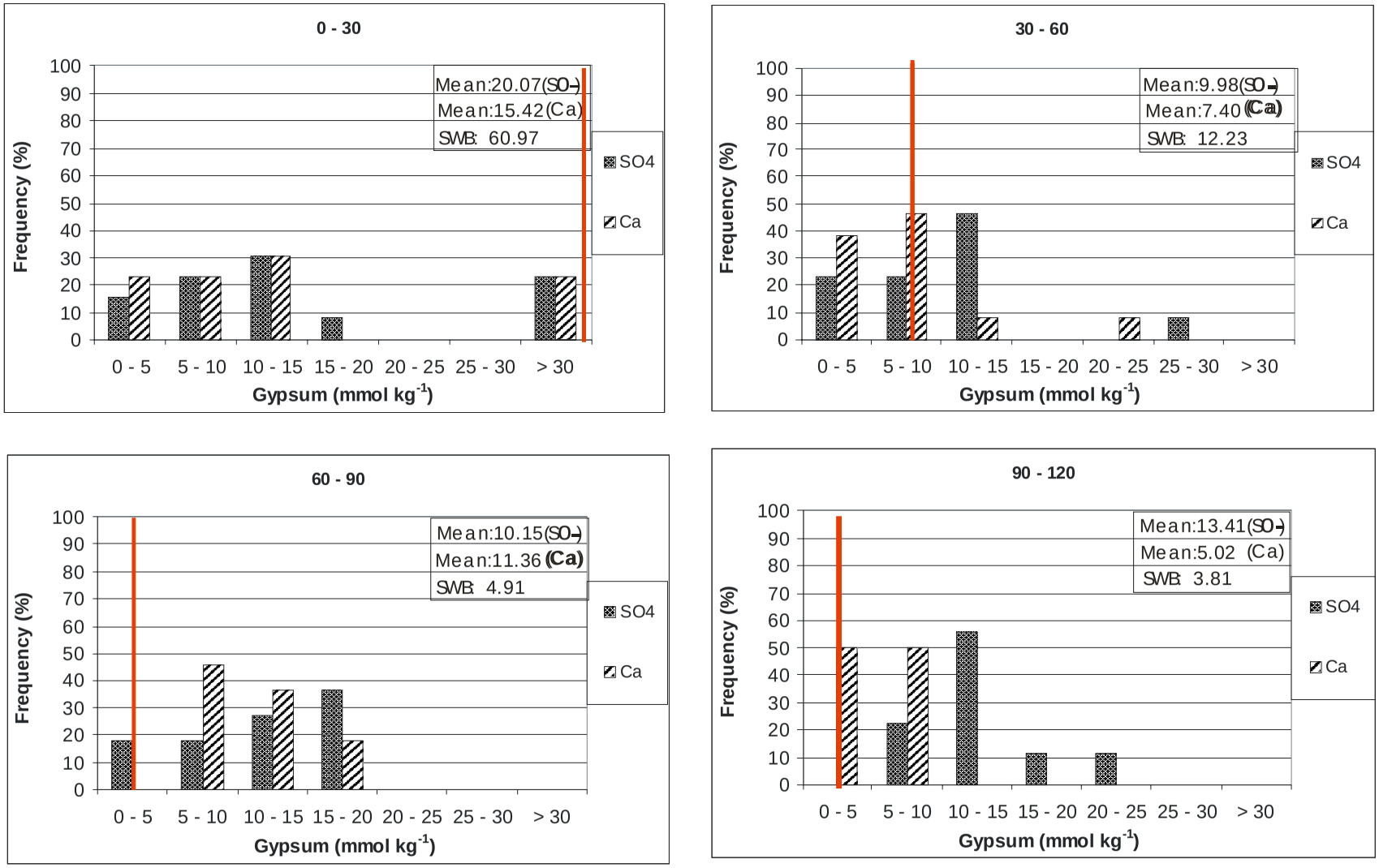


Figure 6.9 Comparison between SWB predictions in mmol kg^{-1} for each 30 cm depth interval (red line on each graph) and the frequency distribution of gypsum calculated from Ca and S analysis, along the sampling transect at Pivot Major.

At both Pivot Major and Pivot Four SWB, underestimated amount of Ca and S immobilised in the soil profile at depth >30 cm Figures 6.6 and 6.7. SWB overestimated the amount of Ca and S accumulated in the top 30 cm of the soil profiles at both Pivots Major- and Four.

The best precipitated gypsum prediction by SWB was for the 30 – 60 cm depth interval at Pivot Four. The predicted value coincided with the highest frequency group (10 – 15 mmol kg^{-1}) Figure 11). The same pattern was observed when SWB simulations was compared to gypsum content calculated from Ca and S analysis, than between SWB simulations and mean Amm-Aoc extractable Ca and PO_4- extractable S. At both Pivot Major and Pivot Four SWB, underestimated amount of gypsum immobilised in the soil profile at depth >30 cm Figures 6.8 and 6.9 and overestimated gypsum accumulated in the top 30 cm of the soil profiles at both Pivots Major- and Four.

In conclusion, there is thermodynamic proof, in the form of calculated Ca and SO_4 activities, that gypsum is present in the soils irrigated with NAMD. The saturation ranges were similar to that reported in literature for natural gypsiferous soils. SWB underestimates the mass transfer of Ca and SO_4 to the sub-soil (depth >30 cm) .The temporal stability of gypsum in the top 30 cm, the interface with the atmosphere, is overestimated by SWB. However S and Ca content in the top 30 cm, as a fraction of the S and Ca in the 120 cm soil profile, is still the greatest.

6.4 Runoff quantity and quality

SWB currently estimates surface runoff or stormflow based on the US-SCS runoff curve number, which represents the antecedent runoff condition (mm) of an irrigated area. This curve number (S) is then compared with measured stormflow values (mm), assuming that stormflow occurs when precipitation is greater or equal to a value representing initial infiltration and surface storage. The curve number (S) that simulates runoff close to measured values can therefore be selected. An example is indicated in Figure 6.8. The graph represents the precipitation-runoff relationship for different S values for Pivot TWF. On the x-axis is the daily rainfall and irrigation in mm. On the y-axis is the surface runoff. The graph shows that as rainfall increases, runoff increases once initial storage is saturated. There are four different curves on the graph to illustrate different S values. In TWF, although not always optimal, it seems that 38 is a reasonable choice of runoff curve number.

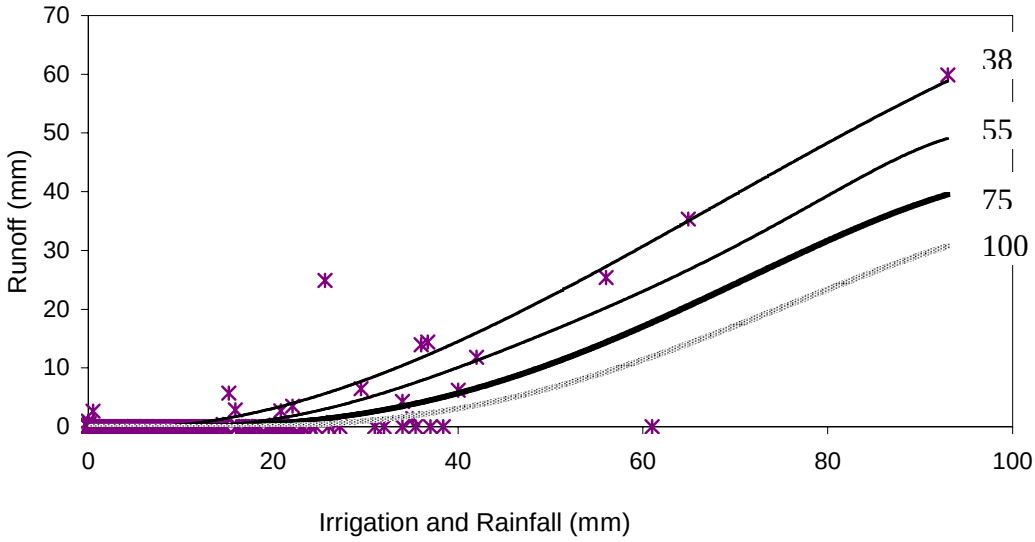


Figure 6.10 Different runoff curve numbers (S) (solid lines) and measured values (symbols) determined for Pivot TWF

The runoff curve number is specific for each site, as soils, topography and rainfall are extremely important in determining runoff. In order to get reliable simulations of components of water and salt balance, runoff measured at Pivot TWF, Major and Syferfontein during the trial period were used to validate the runoff subroutine of SWB. SWB simulated close enough to the measured values, this gives a confidence that the model simulates runoff reasonably well for the specified period of time. An example for TWF is indicated in Figure 6.11.

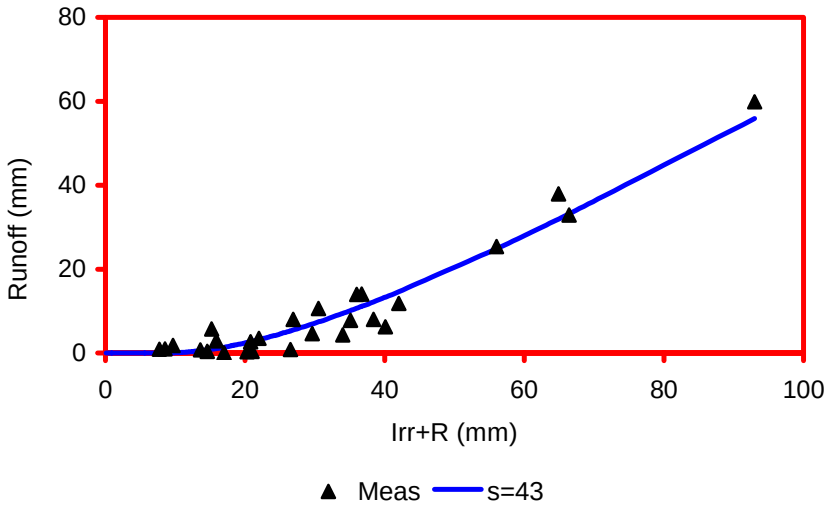


Figure 6.11 Predicted runoff using runoff curve number (S=43) (solid lines) and measured values (symbols) for Pivot TWF

Simulations of runoff seems reasonably well, but more mechanistic way of taking antecedent water content into account will be considered in future.

Salt runoff

In SWB, the salts that runoff from a catchment is assumed to have the same salts as the rainfall. However, runoff salts should vary greatly from the rainfall salinity especially after periods of limited irrigation and rainfall, as salts will be concentrated at the soil surface due to evaporation. When rain falls, accumulated salts near the surface, mix with the stormflow, resulting in a higher salinity than that of the rainfall. The runoff data from TWF and Syferfontein was used to validate the runoff salt subroutine of the model. This is shown in Figure 6.12 for Pivot TWF.

SWB, as can be expected, generally underestimated salt runoff, and will receive attention in future. However, the model should still be able to simulate the field scale salt balance well enough for initial estimates of regional scale salt balances.

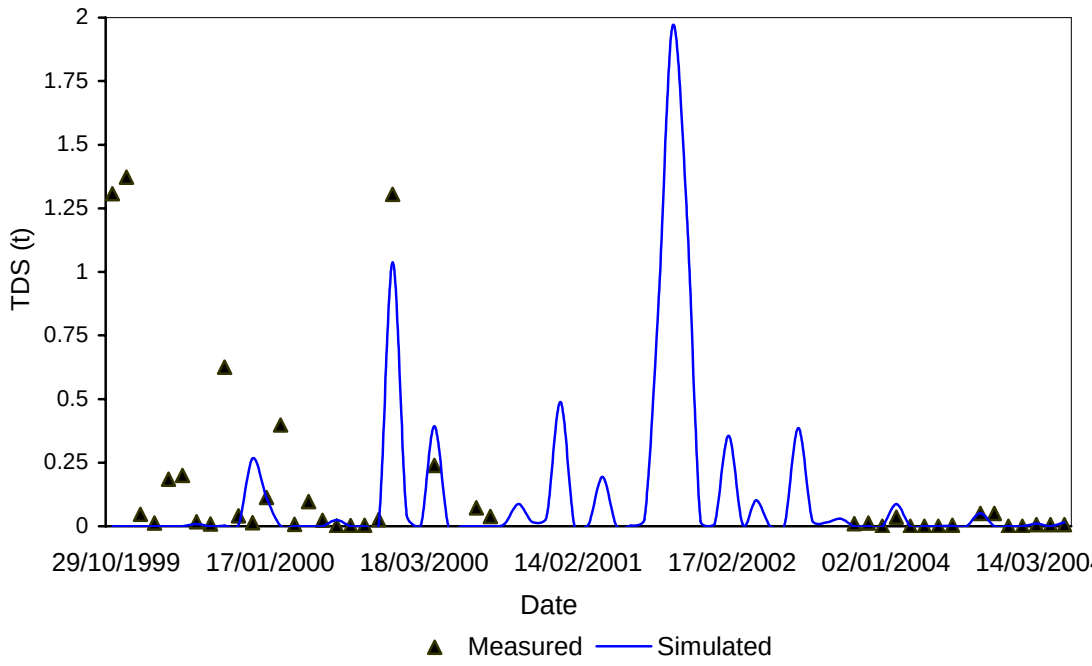


Figure 6.12 Predicted runoff salts (solid lines) compared to measured values (symbols) for Pivot TWF

6.5 Soil water and salt balance

The SWB model predicted the crop growth, water balance as well as the salt content of the soil reasonably well. Tables 6.5 to 6.10 present summaries of the components of the soil water and salt balance for each irrigated field and the periods of measurement with intensive monitoring stations.

6.5.1 Kleinkopjé

The measuring period included seven summer crops and seven winter crops, of which three summer and three winter crops were cultivated at pivot Major and TWF and were included in the previous WRC report (Annandale et al., 2002). Annual crops required a drying off period at the end of each season and this some times resulted in large negative figures for change in soil water storage Table 6.1 This occurs because the simulated crops do not always senescence early enough. 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. 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. Water intercepted by the canopy and evaporated from it was a minor component of the soil water balance and depended on wetting frequency by irrigation and rain. Runoff was simulated after model calibration against data obtained at the weirs. At pivot Four, runoff was assumed zero, as the site is free draining and flat. Salts added depended on irrigation water quality and amounts Table 6.2. Salt runoff at pivot Four was zero because no runoff of water was assumed. 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 sub surface flows. 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 salt leaching and gypsum precipitation during the measuring period.

Table 6.1 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 (1997/1998)	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
Total (summer 1997/1998- winter 2005)	**3562**	**4770**	**2076**	**4381**	**1309**	**203**	**440**	**-122**

Table 6.2 Simulated seasonal values of the salt balance components for pivot Major and crop 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
Total (summer 1997/1998-winter 2005)	**136.62**	**1.41**	**55.12**	**55.44**	**24.64**

Table 6.3 Simulated annual values of the soil water balance components for pivot TWF 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 (1997/1998)	144	295	168	319	0	21	23	-92
Wheat (1998)	79	337	313	48	0	7	65	-17
Sugarbeans (1998/1999)	173	224	252	52	0	7	86	0
Wheat (1999)	101	321	329	21	0	3	65	4
Maize (1999/2000)	528	41	207	226	0	25	110	1
Wheat (2000)	158	482	240	343	0	25	30	2
Maize (2000/01)	305	158	45	342	0	4	53	19
Wheat (2001)	140	350	196	283	0	26	5	-20
Maize (2001/02)	395	155	188	292	0	32	48	-10
Wheat (2002)	136	218	35	248	0	3	68	0
Maize (2002/03)	215	296	198	332	0	18	40	-77
Wheat (2003)	143	367	124	344	0	19	34	-11
Maize (2003/2004)	583	94	276	306	0	21	106	-32
Wheat (2004)	150	180	103	219	0	12	44	-48
Maize (2004/2005)	299	155	78	335	0	8	24	9
Wheat (2005)	76	348	102	283	0	9	35	-5
Total (summer 1998/1999- winter 2005)	**3481**	**3726**	**2686**	**3674**	**0**	**219**	**813**	**-209**

Table 6.4 Simulated seasonal values of the salt balance components for pivot TWF and crop 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)	4.14	0.47	0	2.74	0.93
Wheat (1998)	7.47	1.20	0	4.04	2.23
Sugarbeans (1998/1999)	6.85	1.63	0	3.24	1.98
Wheat (1999)	9.19	1.51	0	4.11	3.57
Maize (1999/2000)	1.19	0.14	0	0.27	0.78
Wheat (2000)	13.52	0.45	0	8.65	4.42
Maize (2000/01)	4.45	0.59	0	2.31	1.55
Wheat (2001)	7.95	1.63	0	4.50	1.82
Maize (2001/02)	2.46	0.42	0	1.36	0.68
Wheat (2002)	6.11	0.65	0	3.62	1.84
Maize (20012/03)	5.39	1.49	0	2.46	1.44
Wheat (2003)	4.13	0.68	0	2.26	1.19
Maize (2003/2004)	0.04	0.02	0	-0.11	0.13
Wheat (2004)	5.01	0.17	0	1.47	3.37
Maize (2004/2005)	4.37	0.24	0	0.79	3.34
Wheat (2005)	6.92	1.62	0	3.16	2.14
Total (summer 1998/1999-winter 2005)	**89.19**	**12.91**	**0**	**44.87**	**31.41**

Table 6.5 Simulated annual values of the soil water balance components for Pivot Four at Kleinkopjé Colliery from the start of irrigation in 1999.

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)
Wheat (1999)	101	65	52	151	30	9	0	-76
Maize (1999/00)	528	0	78	372	38	33	0	7
Wheat (2000)	77	113	42	125	0	11	0	11
Maize (2000/01)	306	237	105	416	0	27	0	-5
Potato (2001/02)	525	294	186	415	82	41	0	95
Wheat (2002)	207	486	188	194	262	23	0	26
Maize (2002/03)	215	278	115	298	95	21	0	-36
Wheat (2003)	143	365	152	186	112	21	0	37
Maize (2003/04)	584	28	102	303	157	16	0	34
Wheat (2004)	101	251	102	136	71	11	0	32
Maize (2004/2005)	263	124	94	158	96	7	0	32
Wheat (2005)	76	367	85	265	83	9	0	1
Total (winter 1999-2005)	**3126**	**2608**	**1301**	**3019**	**1026**	**229**	**0**	**158**

Table 6.6 Simulated seasonal values of the salt balance components for Pivot Four and crop at Kleinkopjé Colliery from the start of irrigation in 1999.

Pivot	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})
Four	Wheat (1999)	1.99	0	0.76	1.34	-0.11
	Maize (1999/00)	0.04	0	0.18	-0.37	0.23
	Wheat (2000)	3.17	0	0	1.77	1.4
	Maize (2000/01)	6.66	0	0	4.51	2.15
	Potato (2001/02)	8.26	0	1.91	3.40	2.95
	Wheat (2002)	12.38	0	9.40	5.87	-2.89
	Maize (2002/03)	5.92	0	0.98	3.49	1.45
	Wheat (2003)	0.01	0	0	0.19	-0.18
	Maize (2003/04)	0.04	0	1.12	-0.97	-0.11
	Wheat (2004)	7.05	0	0.2	0.94	5.91
	Maize (2004/2005)	3.5	0	0.3	0.82	2.38
	Wheat (2005)	6.22	0	0.25	5.13	0.84
	Total (winter 1999- winter 2005)	**55.24**	**0**	**15.1**	**26.12**	**21.55**

6.5.2 New Vaal

The measurement period included three summer crops, one winter crop and three vegetable crops Table 6.9. Only a few irrigations were applied due to high rainfall. Drainage was high and no runoff was assumed for the sandy soil with high infiltration capacity. The negative change in soil water storage indicates the drying off period at the end of the cropping season. Due to the low salts added through irrigation, very little gypsum was predicted to precipitate in the soil profile Table 6.10. The model predicted some leaching of natural salts present in the soil profile during the rainy season.

Table 6.7 Simulated seasonal values of the soil water balance components at New Vaal Colliery.

Crop and season	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)
Maize (2001/02)	419	39	129	236	124	33	0	-64
Wheat (2002)	105	240	177	169	23	18	0	-42
Maize (2002/03)	208	198	176	210	16	26	0	-22
Peas (2003)	0	174	172	84	0	4	0	-86
Sweetcorn (2003/04)	42	230	294	88	23	11	0	-144
Pumpkin (2004)	27	281	92	132	39	25	0	20
Soybean (2004/2005)	285	176	182	203	25	23	0	28
Total (summer 2001/02-summer 2004/05)	**1086**	**1338**	**1222**	**1122**	**250**	**140**	**0**	**-310**

Table 6.8 Simulated seasonal values of the salt balance components at New Vaal Colliery.

Crop and season	Salts added (measured) (Mg ha^{-1})	Salts runoff (simulated) (Mg ha^{-1})	Salts leached (simulated) (Mg ha^{-1})	Gypsum precipitated in the soil (simulated) (Mg ha^{-1})	Change in soluble salt content in the soil (simulated) (Mg ha^{-1})
Maize (2001/02)	0.40	0	1.50	0.07	-1.17
Wheat (2002)	2.63	0	0.25	0	2.31
Maize (2002/03)	2.17	0	0.17	0	2
Peas (2003)	1.91	0	0	0	1.91
Sweetcorn (2003/04)	2.61	0	0.01	0	2.61
Pumpkin (2004)	2.31	0	0.22	0	2.09
Soybean (2004/2005)	1.2	0	0.21	0	0.99
Total (summer 2001/02-summer 2004/05)	**13.23**	**0**	**2.36**	**0.07**	**10.74**

6.5.3 Syferfontein

The measurement period was from 01/10/2001, when the pastures were fully established Table 6.7. Almost full canopy cover of pastures ensured high transpiration and low soil evaporation. Drainage was limited by the heavy texture of the soil. Runoff was simulated after model calibration against data obtained at the weirs. 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 to variability of irrigations and water use of the different species measured. The components of the salt balance varied accordingly Table 6.8. Some gypsum precipitation was assumed at the initial condition of the soil as it was irrigated for a while by the mines. 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.

Table 6.9 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 6.10 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**

Conclusions

The SWB model predicted the crop growth, water balance as well as the salt content of the soil reasonably well. As the main aim with the modelling was not to accurately simulate crop yields, but rather to have a reasonable estimate of canopy cover, the SWB model predicted reasonable estimates of the components of the soil water and salt balance. This proves the predictive capacity of the model for long-term impact assessment of irrigation with gypsiferous mine water.

SWB results of soil solution concentration of each ion simulated in each soil layer were also compared with measured values, captured by suction cups (cc) and wetting front detectors (WFDs), to validate the model. The comparisons were made for five years of data. The graphic comparisons of the soil solution concentration simulation show fairly good agreement with the measured data. Differences between measured and simulated values could have by several cases. These include: soil heterogeneity and sampling error, preferential paths of water and salt movement through the soil profile, dissolution from weathering soil minerals, and fertilizer input and salts removal by the crop, as none of these effects are considered in the model.

In this study, the existence of gypsum in the soils, like calculated Ca and SO_4 activities, was proved. The saturation ranges were similar to that reported in literature for natural gypsiferous soils. It was also found out that, SWB underestimates the mass transfer of Ca and SO_4 to the sub-soil (depth >30 cm). SWB also overestimated the temporal stability of gypsum in the top 30 cm, as the top layer is an interface with the atmosphere. However, S and Ca content in the top 30 cm is a fraction of the S and Ca in the 120 cm soil profile, which is still the greatest. In general, considerable masses of salt were predicted to precipitate in the soil profile in the form of gypsum. A negative change in salt content in the soil was also found due to a decrease in soil salinity through salt leaching and gypsum precipitation during the measuring period.

CHAPTER 7

7. THE IMPACT OF LARGE SCALE IRRIGATION ON GROUNDWATER RESOURCES

Introduction

As the impact of irrigation with gypsiferous water on crops and soils seems minimal and manageable, the focus must be turned to the impact on groundwater quality. Boreholes drilled at the different mines, either inside or in close proximity to the irrigated fields, have shown very little salt moving through the soil profile in the short term (2 to 8 years). However, there are justifiable concerns by regulating authorities that this practice, especially if allowed on a large scale, will merely be 'buying time', and could in fact turn a point source pollution problem into a more difficult to manage non-point source pollution problem. It is essential, therefore, to predict what the likely impact of large-scale irrigation could be on groundwater resources.

The South African National Water Act (No. 36 of 1998) classifies irrigation, including irrigation with excess mine-water, as a controlled activity that can only be practiced under license. A current concern in the water-scarce Olifants River Catchment is that if all excess mine-water is used for irrigation in future, then the basic ecological and domestic needs of downstream water users may not be met. It is likely that a compromise will need to be agreed between all stakeholders that provides for these basic needs, but also allows for irrigation with mine-waters as a cost effective way of providing food security and employment in the future, as the region diversifies its economy away from coal mining.

7.1 Field Water Balance

It is, of course, impossible to measure long term behaviour of a non-existing but proposed large-scale irrigation scheme. Models were therefore used to predict long-term environmental effects by simulating 30 years of irrigation with gypsiferous mine-water. The long-term effect of irrigation with gypsiferous mine-water on the soil was predicted with SWB (Annandale et al., 1999b). This is a daily time step, generic crop, irrigation scheduling model, simulating the soil water and salt balance, as well as water stress- and soil salinity-affected crop growth. Water movement in the soil profile is simulated with a simple cascading model (Campbell and Diaz, 1988). Salt redistribution assumes complete mixing of irrigation and rainfall with the soil solution of the top soil layer, and similarly for the soil solution percolating to the next lower soil layer and so on. Precipitation and dissolution of gypsum and calcite are determined using the approach of Robbins (1991). Potential evapotranspiration is calculated adopting the internationally standardized FAO (Food and Agriculture Organization of the United Nations, Rome, Italy) Penman-Monteith methodology (Allen et al., 1998). Long-term weather records for the simulations with SWB were generated using the CLIMGEN weather data generator of G.S. Campbell (Washington State University), which is a modified version of WGEN (Richardson and Wright, 1984). CLIMGEN has been assessed for South African conditions by Clemence (1997), who showed the estimates to be quite satisfactory.

Long-term simulations were carried out for a lucerne (Medicago sativa cv. Pan 4860) - fescue (Festuca arundinacea cv. A.U. Triumph) perennial pasture, on a loamy sand Bainsvlei soil (Soil Classification Working Group, 1991) or plinthic ferralsol (Allen et al., 1998). Water qualities typical for Kleinkopjé Colliery were used as input (Table 1). Generated weather data for Ogies (lat. 26.13o S; long. 28.72o E; alt. 1571 m, avg. rainfall 738 mm), which is reasonably representative of climatic conditions in the Mpumalanga coalfields, were also used (Annandale et al., 1999b). Irrigations with gypsum-rich water (Table 1) were simulated to refill the soil profile on days when the calculated soil water deficit was >20 mm (Annandale et al., 1999a). Simulated average annual irrigation was 1141 mm, with 279 mm the average annual drainage. Simulations showed that roughly half the added salts would be leached under these circumstances, which reflects a potential groundwater salt load reduction of 46% through gypsum precipitation. The simulated leachate qualities presented in Table 1 were used as inputs to the groundwater model.

Table 7.1 Input salt concentration of irrigation water and leachate concentration simulated by SWB.

Salt (mg ℓ^{-1})	Ca	Mg	Na	K	Cl	SO_4	TDS
Irrigation water (measured)	481	268	47	0	38	1 921	2 755
Average leachate concentration (SWB)	470	1082	191	1	153	4 233	6 131

7.2 Modelling groundwater impact of large-scale irrigation in the Mpumalanga Coalfields

The localised impact of mine-water irrigation has been monitored for periods in excess of eight years. The results to date indicate a limited impact over this time, based on detailed regular groundwater monitoring (Vermeulen and Usher, 2005) as shown in Figure 1. This monitoring is on a localised scale and cannot be used to unequivocally determine larger-scale irrigation impacts. Numerical groundwater models are an extremely useful tool to evaluate different scenarios of groundwater and solute movement (Spitz and Moreno, 1996).

7.2.1 Model description

The model for simulating the transport of groundwater and solutes (salts and other pollutants) is based on the finite element method as described by Pinder and Gray (1977). A dynamic numerical model for the area under investigation was constructed using the modelling package FEFLOW (Diersch, 1988). The first step in constructing such a model is the subdivision of the area to be modeled into elements where the characteristics are similar. Subdivision of an area is typically influenced by the surface geometry, such as topography and streams. The hydraulic characteristics of the underlying aquifer, and the current groundwater quality distribution are also considered in each subdivision. The use of numerical groundwater models in the coalfields has proved to be useful in terms of evaluation of site–specific groundwater migration, regional impacts

and management options (Grobbelaar et al., 2004; Usher et al., 2003). Prediction of water movement across an area in question requires solution of several sets of equations. The governing equations for numerical groundwater models are well described by authors such as Bear and Verruijt (1992). These describe the interpolation of groundwater levels using Bayesian interpolation, and the solution of the groundwater flow equation (a second order partial differential equation) across the whole area. The equations may be solved analytically for simple problems, but for more complex systems like the one to be analysed in this study, piece-wise approximations are obtained through the finite element method. Once the water-level distribution is available over the whole area, seepage velocities and directions are calculated and the response of the aquifer to external influences such as pumpage and recharge from irrigation and rainfall can be determined.

On the basis of the hydraulic gradients and flow velocities, movement of solutes through the aquifer may then be calculated using mass transport equations. It is clear from the above, that coupling of the mass transport equation with the flow equation becomes rather complex under real field conditions, because of the additional variables present and non-linearity in the equations. The dispersive properties of the soil and aquifer, degree of advection in the system, and the chemical reactions that take place, must all be identified before the mass transport equation can be applied successfully.

Certain simplifying assumptions may be made with respect to a specific simulation without jeopardising the value of the model. An example of this is that the vertical dimension in the equations may be eliminated, as most of the flow takes place within the weathered upper 10 to 15 m. Laterally, the aquifer extends over several kilometres, up to the nearest streams and beyond. The vertical dimension is therefore very small in comparison to the lateral dimensions. The time taken for the solute to travel vertically into the aquifer is therefore negligibly small in comparison to that needed for the solute to disperse regionally. Elimination of the vertical dimension, therefore, has little effect on estimated arrival time for the solute at some distant point relative to its source. Elimination of the vertical dimension from the simulation, however, considerably reduces complexity and computational effort. Another acceptable assumption for modelling purposes is that chemical constituents may be grouped into various categories, depending on their reactivity, attenuation and decay properties. For the simulation of the groundwater impact of large-scale irrigation with gypsiferous water, only conservative mass transport can be considered to get an indication of the extent of plume migration. Several retardation mechanisms may play a role to reduce the rate at which certain solutes migrate, but as an initial indication of migration, these can be disregarded.

Variables and constraints that affect the movement of solutes through an aquifer are typically:

- The transmissivity and hydraulic conductivity of the underlying strata.
- The storativity and effective porosity of the underlying strata.
- The hydraulic gradient, dispersion and convection characteristics of the aquifer.
- Boundaries such as dolerite dykes, catchment and surface.
- Other sources of water in the area such as streams, pans, dams and lakes.
- Sinks within the area where groundwater is abstracted or naturally emanates in the form of streams or fountains.

7.2.2 Characteristics of the Mpumalanga Coalfields aquifers

Three distinct superimposed groundwater systems are present in the Mpumalanga coalfields. They are the upper weathered Ecca aquifer, the fractured aquifers within the unweathered Ecca sediments, and the lower aquifer below the Ecca sediments.

Upper Weathered Aquifer

The Ecca sediments are weathered to depths of between 5 and 12 m below the surface throughout the area. The upper aquifer is associated with this weathered zone and water is often found within a few metres below surface. This aquifer is recharged by rainfall. The percentage recharge to this aquifer is estimated to be in the order of 1-3% of the annual rainfall, based on work in other parts of the country by Kirchner et al. (1991) and Bredenkamp (1978).

Observed flow in the catchment confirmed isolated occurrences of recharge values as high as 15% of the annual rainfall (Hodgson and Krantz, 1998). It should, however, be emphasised that in a weathered system, such as the Ecca sediments, highly variable recharge values can be found from one area to the next. This is attributed to the localised impact of mining and the composition of the weathered sediments, which range from coarse-grained sand to fine clay.

The aquifer within the weathered zone is generally low-yielding (range 100-2000 l h^{-1}), because of its insignificant thickness. The good quality of this groundwater can be attributed to the many years of dynamic groundwater flow through the weathered sediments. Leachable salts in this zone have been washed from the system and it is only the slow decomposition of clay particles, which presently releases some salt into the water (Hodgson and Krantz, 1998).

Fractured Ecca Aquifer

The fractured Ecca aquifers are comprised of unweathered Ecca sandstones and shales, where fractures are the principal controls on groundwater movement. The pores within the Ecca sediments are too well-cemented to allow any significant flow of water. All groundwater movement therefore, occurs along secondary structures, such as fractures and joints in the sediments. These structures are better developed in competent rocks, such as sandstone, hence the better water-yielding properties of these rocks. At depths below 30 m, water-bearing fractures with significant yields, were observed to be spaced at 100 m or greater distances (Hodgson and Krantz, 1998). Of all the unweathered sediments in the Ecca, the coal seams often have the highest hydraulic conductivity.

Lower Aquifer

Below the Ecca sediments, the Dwyka tillites have very poor aquifer properties. These aquifers need not be included in the modelling of the impact of mine-water irrigation, as the weathered and fractured aquifer will mainly transport any salt emanating from irrigation activities.

7.2.3 Scenario simulation

To evaluate the utilisation of larger-scale irrigation for post-closure mine-water management, the sub-areas west of Witbank where water will decant from the collieries has been considered. y way of demonstrating the potential impact that irrigating with such a large volume of water will have on the geohydrology of the area, 16 pivots of 40 ha each (Figure 7.1) have been accommodated in the finite element model for the area. The groundwater input quality and flux from each pivot is based on the results from the SWB simulation provided earlier in this paper. For this scenario, the pivots have been placed in an area where the mining effects on soils and aquifers are expected to be minimal and in close proximity to the expected discharge area for the mine-water after closure. This will be convenient for the supply of water to the pivots, but as discussed later, may not be the optimal location from a groundwater hydrology perspective.

The transmissivity and hydraulic conductivity of the underlying strata will influence the movement of solutes. While no pumping tests have been performed at these hypothetical pivot sites, borehole logs indicate low-yielding characteristics for the aquifer. Records show that the average blow yield is in the order of 0.5 l s^{-1}, which translates into a hydraulic conductivity of 0.01 – 0.2 m d^{-1}, with an average value of 0.1 m d^{-1}.

The movement of solutes will also be influenced by the storativity and effective porosity of the underlying strata. The storage coefficient of aquifers in the Witbank/Highveld coalfields has been determined using pumping test methods, and an average value of 10^{-3} can be assumed for the fractured aquifer. The reason for this relatively low storativity value lies in the fact that only a small proportion of the pores and fractures in this aquifer partake in water flow. In the upper, weathered aquifer, the effective porosity is two orders of magnitude higher than the fractured aquifer, and a value of 10^{-1} can be assumed. This higher value is due to the fact that almost all the calcite that normally binds the sedimentary grains together has been leached from this horizon. Water can therefore permeate more easily through the weathered matrix.

As the regional water-table gradient and the dispersion and convection characteristics of the aquifer will also directly influence the movement of solutes, measurement of static water levels in the monitoring boreholes is necessary for the determination of the regional water-table gradient. Since the regional water-table gradient within the area is controlled by the surface topography, the latter may be used as a controlling factor in a Bayesian estimation model to infer groundwater levels in areas where monitoring boreholes are not available.

Groundwater boundaries exist in various forms in nature and have to be accounted for in models. Typical boundaries are dolerite dykes and sills, which may act as impermeable barriers in the transverse direction or as conductive zones along intrusive contacts. Close to the surface, dolerite weathers and groundwater readily permeates through it. Other boundaries are, for instance, catchment boundaries, where a change in the direction of the water-table gradient may occur. Surface boundaries, above which the groundwater level cannot rise without decanting, should also be considered. Boundaries of these types can be accommodated in flow and mass transport models, with the prerequisite that knowledge about these boundaries must be available for the area in question.

Taking all this into account, input data used in these particular simulations are summarised in Table 7.2.

Table 7.2 Input parameters for the groundwater simulations.

Quality of deep drainage	6 000 mg ℓ^{-1} TDS; 4 000 mg ℓ^{-1} SO_4
Attenuation	Zero
Aquifer transmissivity	10 m^2 d^{-1}
Storage coefficient for the weathered strata	0.20
Recharge from rainfall (outside irrigated area)	3%
Annual rainfall	740 mm

The steady state groundwater flow solution was used as basis for the mass transport simulations. This therefore represents the expected average groundwater plume development under natural conditions, without taking into account influences such as abstraction or temporal changes such as floods. For consideration of such aspects further specific scenarios should be simulated.

The steady state groundwater flow and superimposed mass transport solution represents the expected post mine closure geohydrological situation and the mass transport under these conditions provides an indication of unretarded salt migration.

Surface contours, and the position of the pivots relative to the stream to the north and other boundary influences, are shown in Figure 7.1, and the simulated steady state sulphate plume for the specific pivot arrangement is presented in Figure 7.2. Units on the X and Y axes of these maps are in metres.

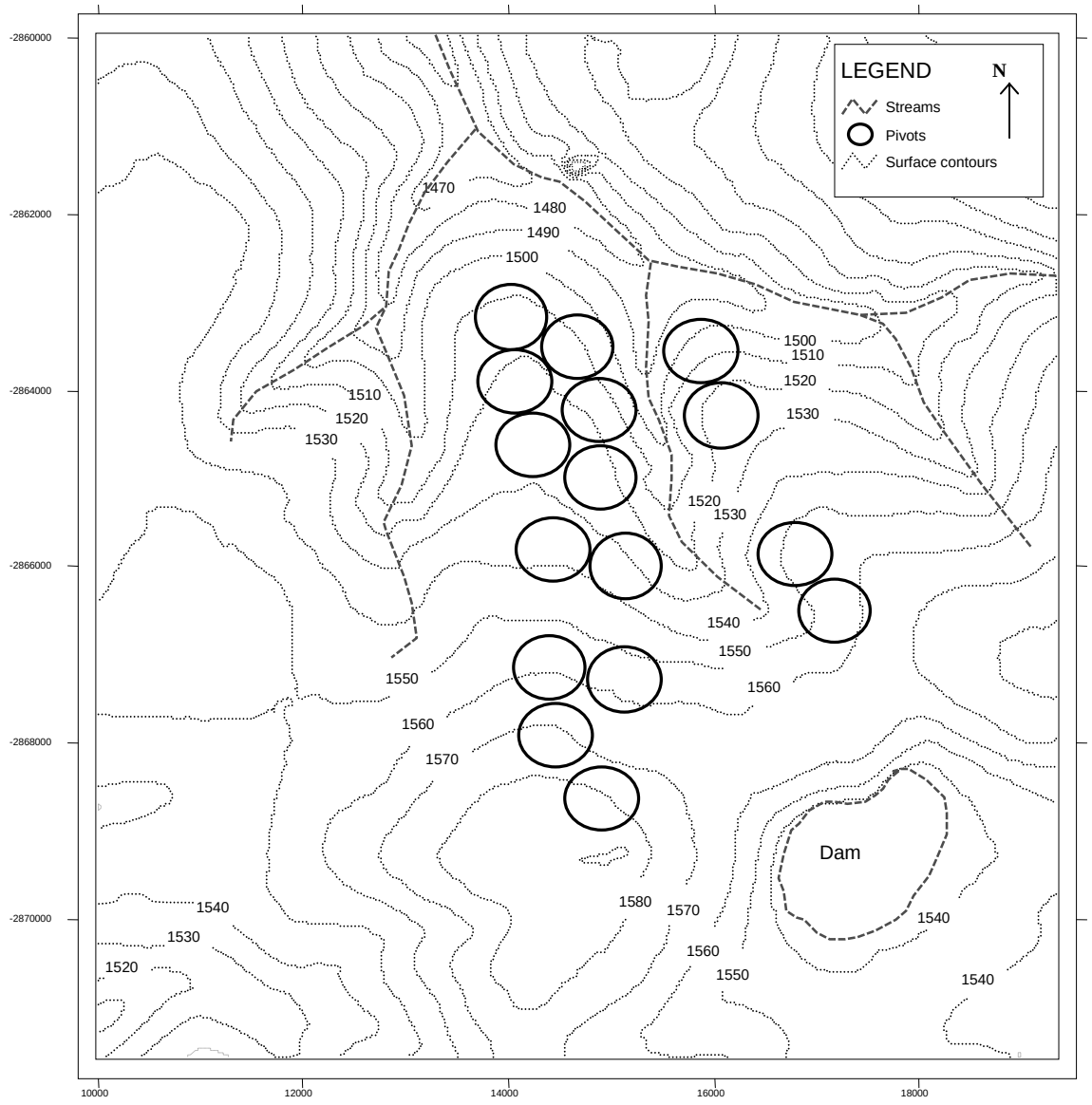


Figure 7.1 Pivot arrangement, surface contours and surface water bodies for the area modelled.

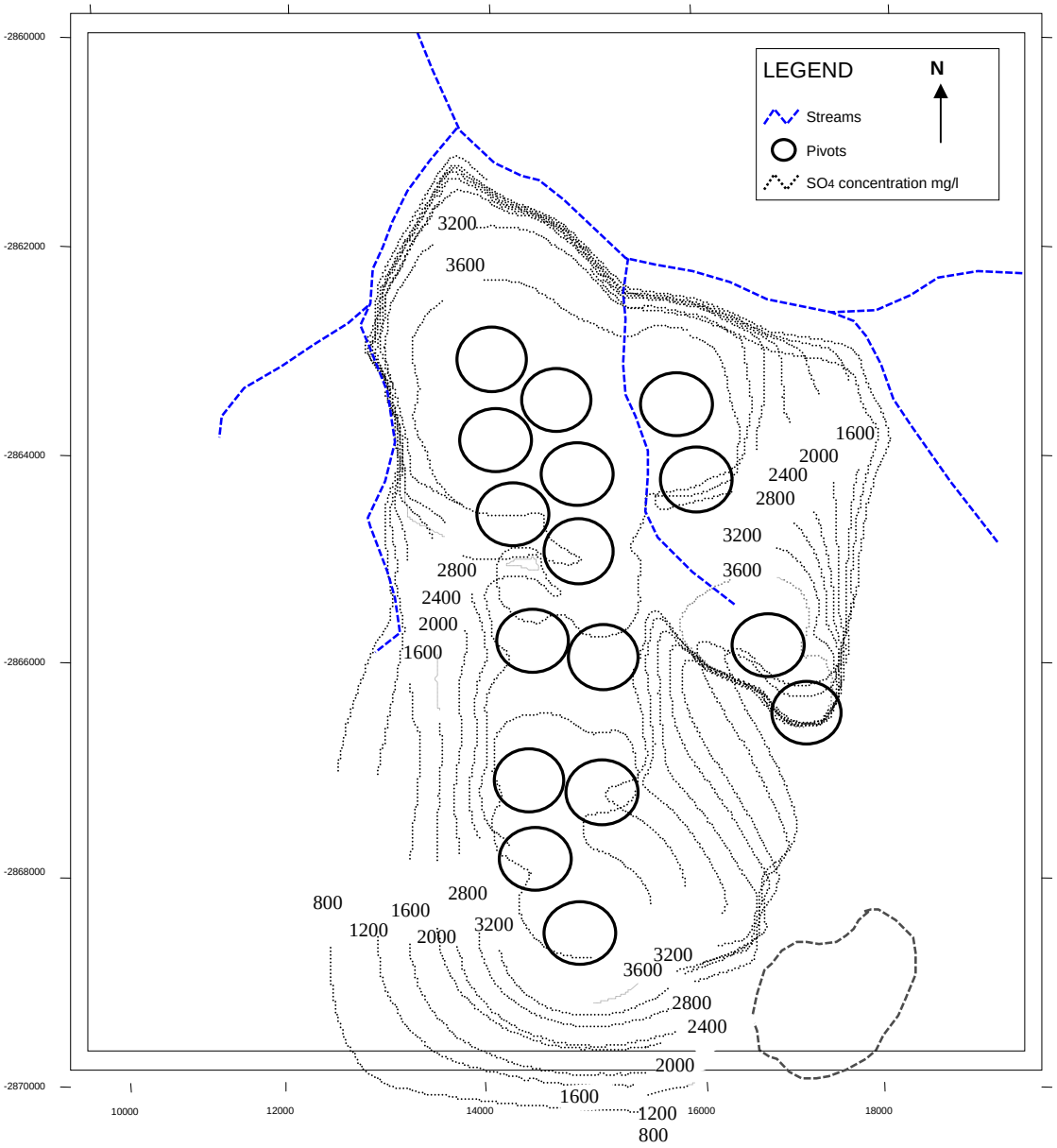


Figure 7.2 Simulated groundwater sulphate concentrations in mg ℓ^{-1}.

As shown in Figure 7.2, groundwater and associated salts, fed by recharge from the pivots, will migrate towards the streams. Salts from the pivots should mainly migrate along the weathered zone. In instances where seepage from irrigation passes into deeper layers, this would flow back into the underlying collieries. The data in Figure 7.2 for sulphate, demonstrate a flow scenario without retardation. Simulations show that groundwater will be intercepted at a rate of just over 2 Mℓ d^{-1} by the streams. In other areas, salt accumulation in the groundwater will be regulated by dilution from rainfall.

It is important to note that 2 Mℓ d^{-1} is the maximum volume of deep drainage water that could flow through this specific aquifer for the indicated pivot configuration. The SWB simulations, however, showed that the deep drainage from the irrigation pivots may be in the order of 4.9 Mℓ d^{-1}. This would result in areas becoming waterlogged and the irrigation scheme would fail in the long term.

While this paints a picture that suggests that mine-water irrigation is not practicable in the longer term, several potential solutions are possible. The first potential solution to this problem would be to rearrange the pivots in a longer N-S transect, if suitable soils were available. This would increase the area to the east and west through which the excess recharge could be transmitted to the streams. Another solution would be to reduce the recharge emanating from the fields by increasing the irrigated area and reducing the irrigation application on an aerial basis.

Perhaps the most promising solution lies in the application of the excess water to rehabilitated opencast spoils. These areas have already been impacted by mining and the salts leached from irrigation can be regarded as being fed into the same system from which they originate. Grobbelaar et al. (2004) report that there are at least 38 000 ha of reclaimed opencast mineland in the Witbank/Highveld coalfields, with this area growing as mining and rehabilitation continue. The benefits of not exporting salts to unimpacted areas and of utilising this vast area of land, provide a great opportunity for mine water irrigation.

Irrigation of reclaimed land, may require piping water to these areas, which are slightly further away than the modelled area described above. Water logging is, however, not likely to be as problematic if the spoils have been rehabilitated in such a way as to allow free drainage from the bottom of the root zone, since the spoil material itself behaves as a highly transmissive unconsolidated porous medium. Mine spoils exhibit average hydraulic conductivities two orders of magnitude greater (geometric mean) than adjacent unmined strata (Hawkins, 1998), provided hardpans do not form or that weathering results in a decrease in permeability in the upper layers of the spoil. Dense layers have been found in spoils in South Africa, but it has been found in older spoils in South African coalfields that these layers appear to become less prevalent over time, and that coarse fragments in the upper soil appear to weather rather rapidly (Viljoen, 1992). Nonetheless, it may be necessary in some places, to enhance drainage by agricultural practices that relieve compaction, or even through the installation of efficient but expensive artificial drainage. Under non-irrigated conditions it has been found that the recharge capacity of the spoils is five to six times (in the order of 15 to 20% of MAP) greater than that occurring in the weathered Ecca not impacted by mining (recharge of around 3%), (Hodgson and Krantz, 1998; Van Tonder et al., 2003).

First indications from the modelling exercise are that such an irrigation configuration could be viable because of the limited aerial extent of the sulphate plume and the interception of the plume that is possible in the streams. As part of an overall mine-water management strategy, irrigation therefore appears to hold significant promise.

Conclusions

Results of this study suggest that irrigating large areas with gypsum-rich waste-water could be feasible and sustainable if careful attention is paid to the specificity of each situation. It is also clear, however, 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 salinisation of the rootzone. This will necessitate the installation of expensive drainage systems, or ultimately, result in the failure of the irrigation scheme. In order to improve on the analyses and results presented in this paper, it is essential that soil water balance and groundwater models are coupled in a way that includes the feedback needed between them to more accurately describe the system to be managed. This will ensure that irrigation with gypsiferous mine-water can be seriously 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. The importance of proper site characterisation for the successful application of mine water irrigation is also evident.

CHAPTER 8

8. CONCLUSIONS AND RECOMMENDATIONS

The conclusions emanating from this research are discussed below, based on the objectives of the project.

Objective 1: Determine impact on crops, soils and groundwater

Crops

Several crops were successfully grown with different mine water qualities and soil combinations. Yields and above ground dry matter of the crops were not negatively affected by the water quality on both virgin and rehabilitated lands. The difference in yields obtained between seasons could be related to pests and diseases, rainfall and temperature, amount of irrigation water applied and fertilization practices. Yields in some cases may have been depressed due to K deficiency in a Ca and Mg saturated soil environment. Fertilizing with potassium containing fertilizers can easily solve this problem, and it is important that the ions added with the irrigation water be taken into account when designing a fertilization program.

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. Unfortunately, the waters do 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.

Soils

Saturated paste electrical conductivity (EC_e) of the seasonally collected samples as well as that of the transect samples showed an increase in salinity compared to EC_e of outside samples. The temporal EC_e data fluctuated depending on seasonal rainfall, as well as on the irrigation and rainfall events prior to soil sampling. 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 the salts below the root zone.

In this study, there is clear thermodynamic proof that gypsum has been precipitated in the soil profiles. The saturation ranges were similar to those reported in literature for naturally occurring gypsiferous soils. Gypsum accumulated in the soils over the past four years to the extent that the solutions became saturated with gypsum.

Groundwater

The impact of irrigation with gypsiferous mine water on groundwater quality was assessed in all the irrigation sites and the water levels at all the pivots have varied very little over time. The overall water quality trend in the deeper aquifer indicates that the water quality has not shown significant deterioration over the monitoring period. Some exceptions did occur, but the boreholes

lying outside the pivot areas have all shown no meaningful change in water quality as a result of leaching from the irrigated areas. This implies very slow movement of the constituents in the irrigation water, and that these are attenuated by different mechanisms between the surface and the aquifers, often in the clay layers present. The amount leaching through the soil is also small enough to be easily diluted by the regional groundwater flow. It thus appears that the soil type and morphology plays a very important role in the vertical movement of the irrigation water constituents, at least in the short to medium term. The trial pivot sites thus investigated that in the short term the groundwater impacts are limited and, more importantly, localised.

Objective 2: Refine SWB model

The SWB model was developed and refined to better predict gypsum precipitation, crop response, soil water and salt balance, and leachate water quality under irrigation with saline mine water. It was also successfully validated by comparing simulations to measurements of crop growth, soil water and salt redistribution obtained in the field trials. For all crops, the measured values of LAI, TDM and soil water deficit to field capacity were distributed both above and below the simulated lines, but were reasonably accurate.

The validation of the chemical equilibrium and solute transport subroutines in SWB was done by comparing SWB results of soil solution concentration of each ion simulated in each soil layer with measured values, captured by suction cups and wetting front detector samples. The comparisons were made for five years of data. In general, the model predicted soil solution concentrations quite close to measured values. This proves some confidence in the predictive capacity of the model for long-term impact assessments of irrigation with mine waters.

As far as gypsum precipitation is concerned, it seems that SWB estimates for the profile as a whole may be quite reasonable. The model may, however, be somewhat overestimating surface accumulation of gypsum, and underestimating what is found in deeper soil layers.

Objective 3: Long-term impact on groundwater

The likely long-term impact of irrigation with gypsiferous water on the groundwater system was assessed. Irrigating large areas with gypsum-rich mine wastewater could be feasible and sustainable if careful attention is paid to the specificity of each situation. It is also clear, however, 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 salinisation of the rootzone. This will necessitate the installation of expensive drainage systems or, ultimately, result in the failure of the irrigation scheme. In order to improve on the analyses and results presented, it is essential that soil water balance and groundwater models are coupled in a way that includes the feedback needed between them to more accurately describe the system to be managed. This will ensure that irrigation with gypsiferous mine-water can be seriously 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. The importance of proper site characterisation for the successful application of mine water irrigation is also evident.

Objective 4: Commercial production of crops

Commercial production of crops under irrigation with gypsiferous and Na_2SO_4 mine water (at least for the short term) is feasible. Higher yields can be achieved with careful irrigation water management and fertilization, in particular compared to dry land cropping. The major problem experienced was waterlogging in fields with limited internal drainage, especially during the summer months, when control over the soil water regime is difficult due to rainfall. The problems encountered, we believe, are not related to the chemistry of the water used for irrigation, it was clearly observed that crop performance was good in well-drained areas of waterlogged fields.

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. Particular attention should be given to K fertilization as it becomes unavailable due to high Ca and Mg in the soil. 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. In this study, wheat yields were as high as 8 t ha^{-1}, potatoes over 50 t ha^{-1} and maize of 10 t ha^{-1} were achieved. Interest from farming companies to continue irrigating with this water shows the commercial potential.

Objective 5: Sustainability of irrigation with gypsiferous mine water

The sustainability of irrigation with mine water on a commercial scale in such a way that surface and groundwater contamination is reduced, while soil suitability and crop production are maintained, was assessed. The data collected were also used to validate the SWB model, which has been used for long-term predictions of the likely impact of irrigation with gypsiferous mine-water on soil and groundwater resources. Crops like sugarbeans, wheat, maize, potatoes and pastures were very successfully produced. Land preparation and fertilization management are critical for successful crop production, especially on rehabilitated soil. In the short to medium term (eight years) irrigation with gypsiferous mine-water proved to be sustainable with a negligible impact on the groundwater. In the field trial carried out at Kleinkopjé Colliery, several crops were successfully irrigated with gypsiferous mine water on a commercial scale. No significant impact on soil, a surface and groundwater resource was observed.

We expect soils to accumulate gypsum but do not see this as a problem. Crops should be able to give good yields if we take into account the ions added in water. The total salt load in the water system is expected to be drastically reduced due to gypsum precipitation, but there will be some impact on ground and water resources.

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. Unfortunately, the waters do 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.

For consideration of future large-scale irrigation with mine water, the following aspects should be noted:

- Site selection is very important. Careful consideration of the applicability of the site to irrigation, local geology and geohydrological properties, the proximity of sensitive water users for 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.
- 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 DWAF, to fix different levels or guidelines at which action should be taken to mitigate the impact or even to cease irrigation activities, must be part of such a monitoring plan.
- The regulatory framework regarding the "polluter pays"-principle should be negotiated between the mine providing the water, the regulator and the party irrigating with the mine water.
- Detailed guidelines on the site selection, monitoring guidelines and operational considerations from a groundwater perspective will be provided by the outcomes of WRC project K5/1507 that will be completed in 2007.

Recommendations for further research

It is recommended that monitoring at Kleinkopjé Collieries continues as an extremely valuable research site where a well monitored history of irrigation (16 successive cropping seasons) with mine water has been established. Attention should be paid to groundwater quality, as it will take significantly longer than 8 years for the salinity plume to migrate through the soil and into the aquifer. Surface runoff volumes and quality should also be monitored closely to generate more data to better model this process.

The long-term impact of the recharge from the irrigation areas on the groundwater quality, as well as surface water resources once the salt plumes reach the river system is not fully understood. A better understanding of these processes is also an essential prerequisite for understanding the impact of large-scale irrigation on water resources. It is therefore, recommended to couple modelling soil water and salt balance at field scale using the SWB model and the surface water using the Water Resource Planning Models to investigate the impact on the surface water quality of the entrainment of the soluble salts or redissolved precipitated gypsum from the irrigation fields and delivery to the river system. An investigation on the impact of irrigation with post closure decants volumes (170 Mℓ d^{-1}) on the ground and surface water resources is also recommended to provide a worst case scenario in terms of impact on the river system, as the SWB predictions will also act as a base for evaluating of different irrigation amount and quality application scenarios, in order to strike the balance between mine water users and environmental impact.

CHAPTER 9

9. REFERENCES

ALLEN RG, PEREIRA LS, RAES D and SMITH M (1998) Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56. FAO, Rome, Italy.

ANNANDALE JG, BENADé N, JOVANOVIC NZ, STEYN JM and DU SAUTOY N (1999a) Facilitating irrigation scheduling by means of the soil water balance model. Water Research Commission Report No. 753/1/99, Pretoria, South Africa.

ANNANDALE JG, JOVANOVIC NZ, BENADé N and TANNER PD (1999b) Modelling the long-term effect of irrigation with gypsiferous water on soil and water resources. *Agriculture, Ecosystems and the Environment* **76** 109-119.

ANNANDALE JG, JOVANOVIC NZ, CLAASSENS AS, BENADé N, LORENTZ SA, JOHNSTON MA, TANNER PD, AKEN ME and HODGSON FDI (2001) The influence of irrigation with gypsiferous mine-water on soil properties and drainage water. Water Research Commission Report No. K5/858, Pretoria, South Africa.

ANNANDALE JG, JOVANOVIC NZ, TANNER PD, BENADé N and DU PLESSIS HM (2002) The sustainability of irrigation with gypsiferous mine-water and implications for the mining industry in South Africa. *Mine-water and the Environment* **21** 81-90.

ANNANDALE JG, JOVANOVIC NZ, HODGSON FDI, USHER B, AKEN ME, VAN DER WESTHUIZEN AM, BRISTOW KL and STEYN JM, 2006. Prediction of the environmental impact and sustainability of large-scale irrigation with gypsiferous mine-water on groundwater resources. *Water SA*, 32 (1), 21-28.

BARBER S A, (1984) Soil nutrient bioavailability: A Mechanistic Approach. A Wiley-Interscience Publication John Wiley and Sons, USA.

BARNARD RO, RETHMAN NFG, ANNANDALE J, MENTZ W and JOVANOVIC NZ (1998) The screening of crop, pasture and wetland species for tolerance of polluted water originating in coal mines. Water Research Commission Report No. 582/1/98, Pretoria, South Africa.

BEAR J and VERRUIJT A (1987) Modelling groundwater flow and pollution. D. Reidel Publishing Company, 414 p**.**

BELETSE YG (2004) Modelling the soil water and salt balance of planted pastures irrigated with sodium sulphate rich mine effluent. MSc dissertation, Dept. of Plant Production & Soil Science, University of Pretoria.

BENNET WF (1993) Nutrient deficiencies and toxicities in crop plants. APS. Press.

BOHN HL and BOHN RK (1986) Solid activity coefficients of soil components. *GEODERMA* 38 3-18.

BREDENKAMP DB (1978) Quantitative estimation of groundwater recharge with special reference to the use of natural radio-active isotopes and hydrological simulation. PhD Thesis, UOFS, Bloemfontein, 367 p.

CAMPBELL GS (1985) Soil Physics with Basic. Elsevier, Amsterdam, 150 pp.

CAMPBELL GS and DIAZ R (1988) Simplified soil-water balance models to predict crop transpiration. In: Bidinger FR, Johansen C (Eds.) *Drought Research Priorities for the Dryland Tropics*, ICRISAT, India, 15-26.

CAMPBELL RB (2001) The chemical response of deeply leached and weathered soils of the Mpumalanga Highveld, South Africa, to irrigation with saline mine water. MSc. Thesis. University of Cape Town. Unpublished.

CARTER BJ and INSKEEP WP (1988) Accumulation of Pedogenic Gypsum in Western Oklahoma Soils. *Soil Sci. Soc. Am. J*. **52** 1107-1113

CLEMENCE BSE (1997) A brief assessment of a weather data generator (CLIMGEN) at South African sites. *Water SA* **23** 271-274.

DIERSCH HG (1988) FEFLOW Reference Manual. Institute for Water Resources Planning and System Research Ltd., Walterdorfer Str 105, D-12526, Berlin.

DOVRAT A (1993) Irrigated forage production. Elsevier Science Publishers, the Netherlands.

DU PLESSIS HM (1983) Using lime treated acid mine water for irrigation. *Wat. Sci. Techl.* **15** 1 45-154.

EPSTEIN E (1972) Mineral nutrition of plants: Principles and perspectives. John Wiley & Sons, New York.

ESSINGTON ME (2004) soil and water chemistry: an integrative approach. crc press, Boca Raton, Florida.

FORD RG, SCHEINOST AC and SPARKS DL (2001) Frontiers in metal sorption/precipitation mechanisms on soil mineral surfaces. Advances in Agronomy 74, 41 – 61

GROBBELAAR R, USHER B, CRUYWAGEN LM, DE NECKER E and HODGSON FDI (2004) Long term impact of intermine flow from collieries in the Mpumalanga area. WRC Report No1056/1/04. Water Research Commission, Pretoria.

HAWKINS JW (1998) Hydrogeologic characteristics of surface mine spoil in coal mine drainage prediction and pollution prevention in Pennsylvania, the Pennsylvania Department of Environmental Protection, Report. 5600-bk-dep2256.

HODGSON FDI and KRANTZ RM (1998) Groundwater quality deterioration in the Olifants river catchment above the Loskop Dam with specialised investigations in the Witbank Dam sub-catchment. WRC report no 291/1/98.

JOVANOVIC NZ and ANNANDALE JG (1999) Crop growth parameters of 19 summer vegetable cultivars for use in mechanistic irrigation scheduling models. *Water SA*. **26(1)**: 67-76.

JOVANOVIC NZ, BARNARD RO, RETHMAN NFG and ANNANDALE JG (1998) Crops can be irrigated with lime-treated acid mine drainage. *Water SA* **24(2**) 113-122.

JOVANOVIC NZ, ANNANDALE JG, VAN DER WESTHUIZEN AM and STEYN JM (2002) Monitoring the soil water and salt balance under irrigation with gypsiferous mine wastewater. Surface Mining 2002 – Modern Development for the New Millennium. ISBN 1–919783–40-7, South African Institute of Mining and Metallurgy.

JOVANOVIC NZ, ANNANDALE JG, VAN DER WESTHUIZEN AM & STEYN JM (2004) Monitoring the effect of irrigation with gypsiferous mine wastewater on crop production potential as affected by soil water and salt balance. *Inst. Mining and Metallurgy*, 104, 2, March, 73-81.

KLAUSNER S (1995) Nutrient management planning. In: K. Steele (Ed.) Animal Waste and the Land-Water Interface. pp383/392. Lewis Publishers, New York

KIRCHNER J, VAN TONDER GJ and LUKAS E (1991) Exploitation Potential of Karoo Aquifers. Water Research Commission Report No.170/1/91, Pretoria, South Africa.

LINDSAY WL (1979) Chemical equilibria in soils. John Wiley and sons, New York.

LORENZ OA and TYLER KB (1993) Plant tissue analysis of vegetable crops. In: Soil and plant tissue testing.

MAAS EV and HOFFMAN GJ (1977) Crop salt tolerance-current assessment. *J. Irrig and Drainage Div., ASCE **103**(IR2)*: 115-134

McCREE KJ and RICHARDSON GS (1987) Salt increases the water use efficiency in water stressed plants. *Crop Sci*. **27**: 543-547.

McNEAL BL and COLEMAN NT (1966) Effect of solution composition on soil hydraulic conductivity. *Soil Sci. Soc. Am. Proc*. **30**: 308-312.

MENGEL K and KIRKBY EA (1987) Principles of plant nutrition. 4th Edition. International Potash Institute, Basel, Switzerland.

MEYER WS and GREEN CG (1980) Water use by wheat and plant indicators of available soil water. *Agron*. **72** 253-257.

MIDGLEY DC, PITMAN WV and MIDDLETON BJ (1994) Surface Water Resources of South Africa. WRC Report No 298/1.4/94 Second Edition.

MONTEITH JL (1977) Climate and efficiency of crop production in Britain. *Philos. Trans. R. Soc. London, Ser.* B **281** 277-294.

NORDSTROM DK, PLUMMER LN, LANGMUIR D, BUSENBERG E, JONES BF and PARKHURST DL (1990) Revised chemical equilibrium data for major water-mineral reactions and their limitations. In: Chemical modelling of aqueous systems II, Melchior D.C. and Bassett, (Eds) ACS Ser. 416, *American Chemical Society*, Washington, DC 398 – 413.

OSTER JD and RHOADES JD (1975) Calculated drainage water composition and salt burdens resulting from irrigation with river waters in the Western United States J. Environ. Qual. 4 (73-79).

PEAK D, ELINGA EJ and SPARKS DL (2001) Understanding Sulphate adsorption mechanisms on iron(III) oxides and hydroxides: Results from ATR-FTIR Spectroscopy. In H.M. Selim & D.L. Sparks (ed). Heavy metal release in soils. Lewis Publishers New York. 167 - 190.

PINDER GF and GRAY WG (1977) Finite element simulation in surface and subsurface hydrology. Academic Press, London. ISBN 0-12-556950-5.

PRETORIUS JJB, DOYER OT, ANNANDALE JG and JOVANOVIC NZ (1999) Managing the environmental impact of irrigation with gypsiferous mine water. *Agrekon*, 38(4), 567-584.

PULLES W, HEATH R and HOWARD M (1996) A manual to assess and manage the impact of gold mining operations on the surface water environment. Water Research Commission Report No. TT 79/96, Pretoria, South Africa.

PULLES W, HOWIE D, OTTO D and EASTON J (1995) A manual on mine water treatment and management in South Africa. Water Research Commission Report No. TT 80/96, Pretoria, South Africa.

REUTER DJ (1986) Temperate and sub-tropical crops. In: Reuter DJ and Robinson JB (eds.) Plant analysis. An interpretation manual. Inkata Press. Melbourne, Sydney.

RICHARDSON CW and WRIGHT DA (1984) WGEN: A model for generating daily weather variables. US Dept. of Agriculture, Agricultural Research Services, 83 pp.

RIETRA RPJJ, HIEMSTRA T and VAN RIEMSDIJK WH (1999) Sulphate adsorption on goethite. *Journal of Colloid and Interface Science* **184**,

ROBBINS CH (1991) Solute transport and reactions in salt-affected soils. In: Hanks RJ, Ritchie JT (Eds) Modelling Plant and Soil Systems. Agronomy Monograph No. 31, ASA-CSSA-SSSA, Madison, Wisconsin, USA, 365-395.

SPITZ K and MORENO J (1996) A practical guide to groundwater and solute transport modelling. John Wiley & Sons, New York.

STEINWAND AL AND RICHARDSON JL (1989) Gypsum occurrence in soils on the margin of semi permanent prairie pothole wetlands. *Soil Sci. Soc. Am. J*. 53 836-842.

STEWART BA, WOOLHISER DA, WISCHMEIER WH, CARO LH and FRERE MH (1976) Control of water pollution from cropland. Vol. 2. An overview. U.S. Department of Agriculture, Agricultural Research Service. Beltsville, Maryland, USA.

TAINTON NM (2000) Pasture management in South Africa. University of Natal, Pietermaritzburg.

TANJI KK (1990) Agricultural salinity assessment and management. American Soc. of Civil Engineers, New York.

TANNER PD, ANNANDALE JG and RETHMAN NFG (1999) Converting problems into opportunities - The use of gypsiferous mine-water for crop irrigation. *Proc. 22nd Conf. Soil Science Soc. of South Africa*, Pretoria, South Africa, 160-162.

TANNER CB and SINCLAIR TR (1983) Efficient water use in crop production: research or re-search? In: Taylor HM, Jordan WR and Sinclair TR (eds.) Limitations to Efficient Water Use in Crop Production. ASA-CSSA-SSSA, 677 S. Segoe Rd., Madison, WI 53711, 1-27.

THOMPSON JG (1980) Acid mine-waters in South Africa and their amelioration. *Water SA* **6** 130-134.

USHER BH, HAVENGA A, HOUGH J, GROBBELAAR R and HODGSON FDI (2003) The challenges of determining intermine flow in the Witbank Coalfield of South Africa. in Proceedings of Water in Mining 2003 : The Role of Water in a Sustainable Minerals Industry, 13-15 October 2003, Brisbane, Australia. The Australian Institute of Mining and Metallurgy, Carlton, Australia.

VAN STADEN CM (1979) How ERPM uses lime to solve unique underground water problem. *Coal, Gold and Base Minerals of Southern Africa* **27(5)** 100-109.

VAN TONDER G, VERMEULEN D, COGHO V and KLEYNHANS J (2003) Prediction of the decant rate and sulphate concentration from rehabilitated open cast coalmines in South Africa. 6th ICARD, Cairns, Queensland, 12-18 July 2003.

VERMEULEN PD and USHER BH (2005) Determination of the impact of mine water irrigation on groundwater resources. Proc. Securing the Future, 2005 – International Conference on Mining and the Environment, Metals and Recovery. June 27-July1 2005 Skelleftea, Sweden. ISBN 91-975190-1-4.

VILJOEN JNJ (1992) Soil development in rehabilitated coal mine spoil: preliminary observations. *Proc. 17th Congress, Soil Sci. Soc. S. Afr*. 28-30 January 1992, Stellenbosch.

CHAPTER 10

10. CAPACITY BUILDING

Several students received training through the execution of this project at the Universities of Pretoria and KwaZulu-Natal.

Yacob Beletse completed his MSc Agric degree on the work he did at Syferfontein Colliery. His dissertation was entitled: Modelling the soil water and salt balance of planted pastures irrigated with sodium sulphate rich mine effluent. The degree was awarded in 2004, and his supervisor was Prof Annandale, with Dr Jovanovic his co-supervisor.

Yacob has now registered for his PhD on the sustainability of large scale irrigation with mine waste water. His supervisors are Prof Annandale and Dr Steyn.

Oupa Mabokela is in the process of writing up his dissertation for the M Inst Agrar degree on the work he did at New Vaal Colliery. His work focusses on modelling the water balances of the vegetable crops grown. His supervisors are Prof Annandale and Dr Steyn.

Pulane Modisane is now employed by the ARC-Roodeplaat, and her Masters Dissertation (MSc Agric) that is in preparation is entitled - Calcium nutrition of potatoes (Solanum tuberosum L.) irrigated with gypsiferous mine water. Her supervisors are Dr Steyn and Prof Annandale.

Chris de Jager is registered for his Soil Chemistry PhD on sulphate reactions in soils, and is using much of the work he has done in this project for his thesis. His supervisor is Prof Claassens.

Olufemi Idowu, is studying under the supervision of Prof Lorentz and Prof Annandale. He is registered at UKZN, and is focusing on large-scale water and salt balance models to predict the impact of large-scale irrigation with mine water on ground- and surface waters.

CHAPTER 11

11. TECHNOLOGY TRANSFER

Publications relevant to this project in peer-reviewed or refereed journals

ANNANDALE, J.G., JOVANOVIC, N.Z., PRETORIUS, J.J.B., LORENTZ, S.A., RETHMAN, N.F.G. & TANNER, P.D., 2001. Gypsiferous mine water use in irrigation on rehabilitated open cast mine land: Crop production, soil water and salt balance. *Ecol. Eng.*, 17, 153-164.

ANNANDALE, J.G., JOVANOVIC, N.Z., TANNER, P.D., BENADé, N. & DU PLESSIS, H.M., 2002. The sustainability of irrigation with gypsiferous mine water and implications for the mining industry in South Africa. *Mine Water and the Environment*, 21, 81-90.

JOVANOVIC, N.Z., ANNANDALE, J.G., CLAASSENS, A.S., LORENTZ,S.A., TANNER, P.D., AKEN, M.E. & HODGSON, F.D.I., 2002. Commercial production of crops irrigated with gypsiferous mine water. *Water SA*, 28(4), 413-421.

VAN DER STOEP, I. & ANNANDALE, J.G., 2002. The use of time domain reflectometry for soil water measurement. *Agricultural Engineering in SA*, 32, 131-136.

GROBLER, L., CLAASSENS, A.S. & ANNANDALE, J.G., 2003. Ceramic suction samplers: A reliable method for extracting soil solutions for analysis. *S. Afr. J. Plant and Soil*, 20(3), 161-164.

JOVANOVIC, N.Z., ANNANDALE, J.G. & BENADé, N., 2003. User-friendly model for chemical equilibrium of $CaSO_4$ solutions. *S. Afr. J. Plant and Soil*, 20(2), 97-99.

JOVANOVIC, N.Z., ANNANDALE, J.G., BENADé, N. & CAMPBELL, G.S., 2003. CLIMGEN-UP : A user-friendly weather data generator. *S. Afr. J. Plant and Soil*, 20(4), 203-205.

JOVANOVIC, N.Z., ANNANDALE, J.G., VAN DER WESTHUIZEN, A.M & STEYN, J.M., 2004. Monitoring the effect of irrigation with gypsiferous mine wastewater on crop production potential as affected by soil water and salt balance. *Inst. Mining and Metallurgy*, 104, 2, March, 73-81.

ANNANDALE, J.G., JOVANOVIC, N.Z., HODGSON, F.D.I., USHER, B., AKEN, M.E., VAN DER WESTHUIZEN, A.M., BRISTOW, K.L & STEYN, J.M., 2006. Prediction of the environmental impact and sustainability of large-scale irrigation with gypsiferous mine-water on groundwater resources. *Water SA*, 32 (1), 21-28.

Presentations at conferences/symposia

ANNANDALE, J.G., 2002. Mining industry research in Plant Production and Soil Science. The School of Mining and Mineral Sciences, *University of Pretoria, Pretoria*, 25 October 2002.

ANNANDALE, J.G., 2003. The environmental impact and sustainability of irrigation with gypsiferous mine water. Coaltech 2020 Colloquium, *Sasol Recreation Club, Secunda*, 6 June 2003.

ANNANDALE, JG, 2005. Sustainability of irrigation with mine water. Coaltech 2020, CSIR Conference Centre, Pretoria. 25 November 2005.

National conference presentations:

ANNANDALE, J.G., JOVANOVIC, N.Z., VAN DER WESTHUIZEN, A.M. & AKEN, M. Sustainability of irrigation with gypsiferous mine waste water (Invited Speaker). *Coal and the Environment, Pre conference to: The World Summit on Sustainable Development, Randburg, Gauteng,* 5-8 August 2002.

VAN DER WESTHUIZEN, A.M., JOVANOVIC, N.Z., ANNANDALE, J.G. & STEYN, J.M. Monitoring the soil water and salt balance under irrigation with gypsiferous mine waste water. *Combined Congress, Soil Science Society of South Africa, South African Society for Crop Production, Southern African Society for Horticultural Sciences, University of Stellenbosch, South Africa*, January 2003.

ANNANDALE, J.G., JOVANOVIC, N.Z., HODGSON, F.D.I., USHER, B., AKEN, M.E. & VAN DER WESTHUIZEN, A.M. Predicting the environmental impact and sustainability of irrigation with gypsiferous mine water. *Proceedings of the Chamber of Mines of South Africa: Mining and Sustainable Development Conference, Johannesburg, South Africa*, November 2003.

BELETSE, Y.G., ANNANDALE, J.G. & STEYN, J.M. Modelling the Soil Water and Salt Balance of planted pastures irrigated with sodium sulphate rich mine effluent. *South African Society of Crop Production Annual Congress, Bloemfontein, South Africa,* 20-22 January 2004.
MABOKELA, P.O., ANNANDALE, J.G. & STEYN, J.M. Growth analysis and SWB parameter determination of peas (*Pisum sativum* L.). *South African Society of Crop Production Annual Congress, Bloemfontein, South Africa,* 20-22 January 2004.

VAN DER WESTHUIZEN, A.M., ANNANDALE, J.G. & STEYN, J.M. Simulating the Soil Water and Salt Balance of crops irrigated with poor quality mine effluent. *South African Society of Crop Production Annual Congress, Bloemfontein, South Africa,* 20-22 January 2004.
ANNANDALE, J.G. The environmental sustainability of large scale irrigation with mine water. *SA National Committee on Irrigation and Drainage Congress, Fish River Sun, Port Alfred, South Africa*, 17-19 November 2004.

DE JAGER, P.C., CLAASSENS, A.S. & ANNANDALE, J.G. The transformation of sulphate in soils irrigated with neutralised acid mine drainage. *Combined Congress 2005 of the Soil Science Society of South Africa, the South African Society of Crop Production, the Southern African Weed Science Society, and the Southern African Society for Horticultural Sciences, Potchefstroom, South Africa*, 10 - 13 January 2005.

DE JAGER, P.C., CLAASSENS, A.S., ANNANDALE, J.G. & SMITH, H.J.C. Transformation and distribution of calcium and magnesium in soils irrigated with neutralized acid mine drainage.

Combined Congress 2005 of the Soil Science Society of South Africa, the South African Society of Crop Production, the Southern African Weed Science Society, and the Southern African Society for Horticultural Sciences, Potchefstroom, South Africa, 10 - 13 January 2005.

MODISANE, P., STEYN, J.M. & ANNANDALE, J.G. Calcium nutrition of potatoes (*Solanum tuberosum* L.) irrigated with gypsiferous water. *Combined Congress 2005 of the Soil Science Society of South Africa, the South African Society of Crop Production, the Southern African Weed Science Society, and the Southern African Society for Horticultural Sciences, Potchefstroom, South Africa*, 10 - 13 January 2005.

SMITH, H.J.C., JOHNSTON, M.A., LORENTZ, S., DE JAGER, P.C., VERMEULEN, D., ANNANDALE, J.G. & DE KLERK, M. Comparing geotechnical measurements with selected chemical properties in saline mine water irrigated soils. *Combined Congress 2005 of the Soil Science Society of South Africa, the South African Society of Crop Production, the Southern African Weed Science Society, and the Southern African Society for Horticultural Sciences, Potchefstroom, South Africa*, 10 - 13 January 2005.

VAN DER WESTHUIZEN, A.M., ANNANDALE, J.G., COLEMAN, T.J., HODGSON, F.D.I., USHER, B. & AKEN, M.A. The environmental impact of large scale irrigation with gypsiferous mine effluent on the Olifants river catchment. *Combined Congress 2005 of the Soil Science Society of South Africa, the South African Society of Crop Production, the Southern African Weed Science Society, and the Southern African Society for Horticultural Sciences, Potchefstroom, South Africa*, 10 - 13 January 2005.

ANNANDALE, J.G. & BELETSE, Y.G. The environmental impact of large scale irrigation with gypsiferous mine effluent on the Olifants River catchment. *Specialist conference on diffuse pollution WISA/IWA (Water Institute of South Africa / International Water Association), Johannesburg, South Africa*, August 2005.

BELETSE, Y.G., ANNANDALE, J.G., VAN DER WESTHUIZEN, A.M., STEYN, J.M. & AKEN, M.E. Modelling the soil water and salt balance of 15 seasons' crop rotations irrigated with different qualities of gypsiferous mine water. *Combined Congress of the Soil Science Society of South Africa and the South African Society of Crop Production, Durban 23-26 January 2006.*

DE JAGER, P.C., CLASSENS, A.C. & ANNANDALE, J.G. Temporal stability of calcium, magnesium and sulphate in soils irrigated with neutralised acid mine drainage. *Combined Congress of the Soil Science Society of South Africa and the South African Society of Crop Production, Durban 23-26 January 2006.*

International conference presentations:

ANNANDALE, J.G., JOVANOVIC, N.Z., TANNER, P.D., BENADé, N. & DU PLESSIS, H.M., 2001. The sustainability of irrigation with gypsiferous mine water and implications for the mining industry in South Africa. *Bouyoucos Conference on "Sustained Management of Irrigated Land for Salinity and Toxic Element Control", International Union of Soil Science.* 25-27 June 2001, Riverside, California, USA.

ANNANDALE, J.G., JOVANOVIC, N.Z., CLAASSENS, A.S., REINHARDT, C.F., VAN DER WESTHUIZEN, A.M., STEYN, J.M., LORENTZ, S.A., TANNER, H.M. & HODGSON, F.D.I. The sustainability of irrigating with mine waste water. *8th International Symposium on Soil and Plant Analysis, Somerset West, Cape Town, South Africa*, January 2003.
Keynote speaker

DE JAGER, P.C., CLAASSENS, A.S. & ANNANDALE, J.G. A method to distinguish between sorbed sulfate and sulfate precipitated as gypsum. *8th International Symposium on Soil and Plant Analysis, Somerset West, Cape Town, South Africa*, January 2003.

ANNANDALE, J.G., JOVANOVIC, N.Z., HODGSON, F.D.I., USHER, B., AKEN, M.E. & VAN DER WESTHUIZEN, A.M. Predicting the environmental impact and sustainability of large scale irrigation with gypsiferous mine water on groundwater resources. *8th International Congress on Mine Water and the Environment, International Mine Water Association, Johannesburg, South Africa,* October 2003.

DE JAGER, P.C., CLAASSENS, A.S. & ANNANDALE, J.G. The transformation of sulphate in soils irrigated with neutralized acid mine drainage. *9th International Symposium on Soil and Plant Ananlysis, Cancun, Mexico*, 30 January – 4 February 2005.

APPENDICES

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Appendix A

Irrigation water qualities

Table A1. Results of chemical analysis for water applied to Major (after blending) as supplied by Kleinkopjé Colliery.

Date	pH	EC	TDS (mg ℓ^{-1})	PAcid	MALK	Ca^{2+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})
10/15/2001	6.4	359	3936	55	88	470	214	46	10	2407	36
10/22/2001	4.8	369	3645	58	4	461	201	37	9	2412	20
10/29/2001	6.8	297	3675	43	72	409	197	30.9	10	2327	50
11/5/2001	6.4	340		32	75	1240					
11/12/2001	5.6	377		27	9	1175					
11/19/2001	6.5	355		28	27	660					
11/26/2001	5.9	356		31	34	513					
11/27/2001	5.9	356		31	34	513					
12/03/2001	5.2	350		32	10	539					
12/10/2001	4.3	322		52	0	539					
12/11/2001	5.6	377		27	9						
12/17/2001	6.3	345		45	66	517					
01/02/2002	5.6	396		17	14	511					
01/07/2002	3.9	334		69	0	448					
01/07/2002	5.6	393		24	12	376					
01/14/2002	6.0	336		38	41	494					
01/28/2002	6.2	361		42	92	492					
02/04/2002	6.9	217		23	136	218					
02/11/2002	4.7	297		93	4	533					
02/18/2002	4.8	369		33	4	521					
02/25/2002	5.6	381		18	16	529					
03/01/2002	5.6	396		17	14	511					
03/03/2002	4.1	369		56	0.01	978					
03/06/2002	6.4	326		11	34	735					
03/11/2002	4.7	318		30	0.01	440					

Date	PH	EC	TDS (mg ℓ^{-1})	PAcid	MALK	Ca^{2+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})
03/18/2002	4.7	302		9	6	1053					
04/02/2002	5.3	389		35	12	533					
04/08/2002	4.4	310		32	0	352					
04/15/2002	4.4	348		43	0	529					
04/22/2002	3.9	360		68	0	573					
04/30/2002	5.6	344		30	10	585					
05/06/2002	5.9	361		30	12	559					
05/13/2002	6.1	313		30	44	535					
05/20/2002	4.1	313		73	0	709					
05/25/2002	6.0	328		47	38	505					
05/27/2002	6.5	349		21	89	468					
05/27/2002	6.5	349		21	89	468					
06/24/2002	6.8	390		14	51	765					
07/01/2002	5.6	393		24	12	376					
07/08/2002	4.7	332		31	2	861					
07/22/2002	5.1	384		33	7	513					
07/30/2002	6.5	295		39	86	408					
08/07/2002	4.7	332		31	2	861					
08/12/2002	7.3	264		22	84	480					
08/19/2002	6.5	368		33	71	517					
08/26/2002	5.5	363		43	0	669					
09/02/2002	6.5	346		35	67	392					
09/09/2002	5.6	311		22	10	549					
09/23/2002	5.4	290		38	7	681					
09/30/2002	5.2	323		49	11	757					
10/07/2002	4.5	317		20	4	733					
09/10/2002	5.7	325		76	0						

Date	pH	EC	TDS (mg ℓ^{-1})	PAcid	MALK	Ca^{2+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})
21/10/2002	4.9	325		190	5						
28/10/2002	4.9	316		50	2						
18/11/2002	6.3	372		34	50						
09/12/2002	4.9	406		69	3						
06/01/2003	4.6	343		79	2						
13/01/2002	4.6	341		65	2						
20/01/2002	4.4	357		58	0						
27/01/2003	6.2	339		10	4						
05/02/2003	5.0	376		67	0						
10/02/2003	6.2	382		35	51						
19/02/2003	4.4	373		8	16						
03/03/2003	4.1	322		88	0						
10/03/2003	4.2	406		91	0	553					
18/03/2003	4.3	104		330	0	380					
01/04/2003	4.2	323		18	0	468					
07/04/2003	4.3	323		97	0	448					
15/04/2003	4.4	332		126	0	396					
15/05/2003	4.2	352		135	0						
19/05/2003	6.5	395		102	49	553					
26/05/2003	4.5	3173		49	0	484					
Average	6.0	386		45.05	45	543	249	38	10	2185	35

Table A2. Results of chemical analysis for water applied to Major (directly from underground) as supplied by Kleinkopjé Colliery.

Date	**pH**	**EC**	**TDS** (mg ℓ^{-1})	**PAcid**	**MALK**	Ca^{2+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})
01/02/2000	6.7	331	2802	12	60	479	187	35	10	1848	19
03/15/2000	6.1	332		6.1	40	486				1930	
04/10/2000	6.8	406	3432		120	511	342	18.5		2372	11
04/18/2000	6.2	334	2716		40	529	197	40.3		1951	14
04/25/2000	6.4	334	2710		48	533	184	38.2		1875	13
05/26/2000	6.3	283								2419	
06/26/2000	6.3	319		26	4					2186	
08/14/2000	6.8	353	3485	150	132	428	237	137	19	2284	78
09/13/2000	5.9	336	3421	22	44	468	173	30	9	2228	10
10/12/2000	6.3	3502	3304	30	620	547	238	48	14	2160	12
11/17/2000	6.6	395	3452	38	42	507	188	358	8	2212	12
01/10/2001	6.1	287	3558	16	35	528	156	34	6	2224	10
02/23/2001	6.3	256	3517	42	39	445	168	42	6	2195	11
03/26/2001	6.4	351	3398	51	32	509	192	46	8	2214	14
05/23/2001	5.2	315	3777	64	6	383	153	38	6	1868	12
06/15/2001	5.9	342	4340	67	16	458	185	45	8	2141	15
09/21/2001	6.3	350	4039	36	52	465	248	36	9	2542	14
10/10/2001	3.7	352	3711	156	2	622	224	43	8	2367	20
08/03/2002	4.9	375	3835	6	2	470	202	47	10	1860	18
31/10/2002	6.4	370	4427	14	69	496	222	52	12	2542	10
12/11/2002	4.2	379	4077	62	0	450	212	40	11	2484	6
16/12/2002	4.0	342	3924	83	0	542	219	55	11	2498	12
22/04/2003	5.2	294	3403	28	4	503	195	37	8	1935	11
28/08/2003	5.2	408	4240	25	34	493	227	65	14	2620	14
15/12/2003	5.7	325	3406	6	22	634	265	45	14	2245	16

12/12/2004	5.4	306	3278	16	12	697	278	55	14	2453	12
24/02/2004	6.2	344	5256	24	34	578	242	52	13	2550	12

Table A3. Results of chemical analysis for water applied to Pivot Tweefontein and Four as supplied by Kleinkopjé Colliery.

Date	**pH**	**EC**	**TDS** (mg ℓ^{-1})	**PAcid**	**MALK**	Ca^{2+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})
01/02/2000	6.7	331	2802	12	60	479	187	35	10	1848	19
01/18/2000	8.2	276		1	52	329				1304	
01/25/2000	7.0	324		11	80	293				1270	
01/26/2000	6.6	310			-1					1931	
02/10/2000	8.2	349	2784	2	689	404	252	63	19	1740	42
02/22/2000	8.5	336	2642		60	388	250	58		1697	41
02/29/2000	8.3	341	2876	3	66	510	269	53	14	2010	38
03/15/2000	7.8	344		3	72	370				1852	
03/23/2000	7.9	337	2820		72	362	212	70		1910	40
04/10/2000	8.0	292	2264		72	344	203	43		1390	32
04/18/2000	7.8	329	2684		90	402	268	60		1746	38
04/25/2000	7.8	329	2626		78	414	241	66		1726	37
05/05/2000	7.9	332		5	80	403				1914	
05/26/2000	7.3	283			-1					2303	
06/01/2000	7.8	337	2438		64	351	229	54	15	1717	42
06/21/2000	7.7	313	2048	36	78					2001	
07/10/2000	7.4	300								1996	
08/16/2000	7.7	311	3129	82	40	403	237	545	18	2080	36
09/13/2000	7.6	331	3092	80	12	408	215	44	16	2149	32
10/17/2000	8.6	351	3441	72	6	451	266	112	14	2070	38

01/03/2001	7.6	124	794	20	98	79	38	79	3	379	44
01/10/2001	6.4	329	3203	0	46	387	225	60	14	1775	35
02/23/2001	8.5	271	3537	18	46	341	198	57	10	1959	38
03/22/2001	6.6	335	3241	23	59	426	243	69	15	2185	38
04/24/2001	6.7	315	3661	27	67	389	233	64	14	2058	40
05/21/2001	6.5	346	3341	14	76	399	221	68	15	2188	44
06/15/2001	8.0	344	4041	24	85	388	226	66	15	2231	44
08/09/2001	7.8	314	4226	13	105	484	293	89	29	2276	46
09/28/2001	7.6	374	3974	19	108	635	292	80	18	2342	50
10/09/2001	8.5	352	3660	20	106	392	228	71	16	2057	50
11/13/2001	8.5	362	3585	0	111	424	248	64	17	2470	46
12/12/2001	8.2	366	3722	9	122	465	259	84	19	2528	42
09/04/2002	8.0	377	3756	18	112	528	324	37	11	2480	44
18/04/2002	8.0	377	3756	18	112	528	324	37	11	2480	44
25/06/2002	8.0	337	4167	18	121	449	251	83	17	2340	44
09/07/2002	8.0	392	4146	10	114	488	270	87	19	2599	44
13/08/2002	7.6	394	4205	14	108	499	289	82	20	2596	44
10/09/2002	8.2	366	4301	10	119	491	276	90	20	2607	48
18/11/2002	8.1	426	4250	6	107	425	294	78	23	2629	50
07/12/2002	8.0	393	4146	10	114	488	270	87	11	2599	44
16/12/2002	8.3	400	4399	26	112	515	295	100	21	3038	50
11/08/2003	8.1	427	5342	6	129	658	371	110	23	2820	54
10/09/2003	8.1	496	5170	18	26	645	406	143	24	3290	58
12/01/2004	8.4	485	5821	14	97	818	476	143	33	4392	68
24/02/2004	8.2	454	6132	6	101	712	448	132	31	3660	64

Table A4. Results of water quality analysis for Syferfontein Evaporation Dam North (as supplied by Syferfontein Colliery).

Date	pH	EC mS m^{-1}	TDS (mg ℓ^{-1})	SS (mg ℓ^{-1})	Cl (mg ℓ^{-1})	SO_4 (mg ℓ^{-1})	Na (mg ℓ^{-1})	F (mg ℓ^{-1})	Fe (mg ℓ^{-1})	Al (mg ℓ^{-1})	Tot Alk (mg ℓ^{-1})	Ca (mg ℓ^{-1})	Mg (mg ℓ^{-1})	K (mg ℓ^{-1})	B (mg ℓ^{-1})	Mn (mg ℓ^{-1})
14/01/2000	9.4	267	1800	17	25	850	520		0.11	0.07	390	22	46.8			0.03
07/02/2000	9.8	221	1490	10	22	868	410		0.01	0.07	327	14	36.4			0.03
12/02/2000	8.9	179	1190	10	14	608	320	1.12	0.11	0.07	267	27	28.6		0.56	0.03
03/08/2000	8.4	299	2682	214	22	1495	587		0.30			73	104			
29/09/2000	9.9	357	2886	98	41	1621	714	1.15	0.01	0.01	572	94	165.8			0.01
13/11/2000	8.8	447	3606	34	22	1555	770	0.32	0.01	0.01	446	72	156.3		0.04	0.01
15/12/2000	8.9	432	3179	178	26	1641	735	0.01	0.04		350	46	140	18	1.31	0.01
06/02/2001	9.3	389	2952	165	31	1850	686	0.50	0.01	0.01	464	19	101.1		0.94	0.01
14/03/2001	9.6	361	2726	69	45	1230	461	1.30	0.01	0.03	423	43	63.2		2.49	0.01
10/07/2001	8.9	381	2870	244	28	1867	660	2.29	0.02	0.01	584	35	95.2			0.01
10/07/2001	9.2	394	2901	148	32	1941	693	1.30	0.04	0.02	446	22	89.5			0.01
28/09/2001	8.8	365	3108	252	58.1	1418	453				647	16	57.3		1.43	
07/11/2001	8.9	372	2815	188	18.6	1648	796	0.87	0.00	0	524	32	88.8			0
06/01/2002	9.4	314	2494	174	25	1163	773	0.76	0.11	0	441	16	67.7		1.22	0
12/02/2002	9.4	331	2603	64	21.2	1453	772	1.61			529	17	72.9		1.16	
20/03/2002	9.1	281	2061	48	20.7	1030	500	1.09			460	20	56.9			
18/03/2003	9.2	319	2172		17.9	1200	806	1.00	0.00		471.4	27	78.8		0.8	
Average	9.2	327	2435	89	27.6	1265	618	1.06	0.10	0.08	443.5	32	78.5	11	1.14	0.03

Table A5. Results of water quality analysis for New Vaal Colliery (Ramp 11).

DATE	pH	EC mS m^{-1}	TDS (mg ℓ^{-1})	M.Alk (mg ℓ^{-1})	Acidity	Cl^- (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})	Ca^{2+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^+ (mg ℓ^{-1})	K^+ (mg ℓ^{-1})	Fe (mg ℓ^{-1})	Mn^{2+} (mg ℓ^{-1})	Al^{3+} (mg ℓ^{-1})
10/01/2000	7.6	71	511	26	8	12	342	79	22	16	4	0.01	0.01	0.13
01/02/2000	7.5	66	529	26	6	2	302	77	19	8	4	0.01	0.01	0.02
06/03/2000	7.8	73	667	28	8	4	352	86	26	14.	5	0.01	0.01	0.04
04/04/2000	7.1	154	1745	170	46	16	968	195	70	117	8	0.02	0.27	0.05
10/05/2000	7.8	194	1871	150	30	14	1092	260	72	100	9	0.01	0.22	0.03
05/06/2000	8.0	202	1752	168	52	20	1019	253	76	99	9	0.01	0.07	0.01
10/07/2000	7.3	116	1200	274	34	10	675	156	63	71	5	0.01	0.51	0.18
08/08/2000	7.6	127	1242	274	50	10	627	14	51	54	5	0.05	0.74	0.02
22/09/2000	7.7	196	1555	102	18	8	982	144	35	127	7	0.01	0.33	0.02
16/10/2000	7.4	125	1151	228	50	26	451	158	40	61	4	0.01	0.34	0.15
20/11/2000	7.2	157	901	254	62	28	493	122	56	47	3	0.02	0.01	0.02
08/12/2000	7.4	185	1818	267	34	14	832	205	61	99	7	0.03	0.48	0.05
04/01/2001	7.3	171	1669	220	47	12	865	214	68	84	6	0.01	0.01	0.04
05/02/2001	7.3	174	880	219	68	14	814.	173	57	86	5	0.11	0.34	0.10
01/03/2001	7.5	166	1442	232	81	12	801	193	66	91	6	0.01	0.47	0.02
23/04/2001	7.5	133	991	302	20	52	348	52	37	140	5	0.03	0.27	0.07
15/05/2001	7.4	139	1087	232	36	36	495	137	44	85	5	0.04	0.42	0.06
18/06/2001	8.0	245	1977	262	91	17	934	226	69	156	9	0.07	0.60	0.06
Average	7.6	117	1277	164	41	21	500	124	42	66	5	0.13	0.25	0.19
Minimum	6.9	22	511	8	6	2	100	17	8	8	1	0.01	0.01	0.01
Maximum	8.2	245	1977	302	91	58	1092	260	76	156	17	1.15	0.80	4.10

Table A6. Results of water quality analysis for New Vaal Colliery (dam595).

DATE	pH	EC mS m^{-1}	TDS (mg ℓ^{-1})	P.ACID	MALK (mg ℓ^{-1})	Ca (mg ℓ^{-1})	Mg (mg ℓ^{-1})	Na (mg ℓ^{-1})	K (mg ℓ^{-1})	SO_4 (mg ℓ^{-1})	Cl (mg ℓ^{-1})	Fe (mg ℓ^{-1})	Mn (mg ℓ^{-1})	Al (mg ℓ^{-1})
04/01/2000	7.3	115	500	36	190	110	38	49	4	433	18	0.01	0.01	0.01
01/02/2000	7.7	132	937	26	228	120	41	51	4	433	22	0.01	0.12	
08/03/2000	7.5	131	1005	38	248	126	45	64	6	468	24	0.09	0.02	0.01
04/04/2000	7.7	93	838	50	232	107	49	69	5	453	28	0.03	0.12	0.03
10/05/2000	8.2	118	994	20	134	88	45	85	4	509	24	0.04	0.01	0.02
05/06/2000	8.2	139	1064	60	166	85	46	135	4	600	42	0.01	0.01	0.01
11/07/2000	7.4	110	1125	152	240	164	49	57	5	600	18	0.08	0.03	0.04
08/08/2000	7.6	136	1278	30	172	143	54	68	6	638	18	0.32	0.01	0.04
22/09/2000	7.6	156	1334	22	22	113	59	78	5	737	20	0.03	0.21	0.01
16/10/2000	7.5	122	952	38	220	122	40	61	4	435	26	0.01	0.01	0.04
13/11/2000	7.7	153	1104	42	196	123	94	88	11	529	52	0.001	0.01	0.01
08/12/2000	7.5	127	1096	24	242	115	41	70	4	467	28	0.002	0.01	0.05
05/01/2001	7.6	104	1034	20	210	121	44	74	4	512	27	0.01	0.01	0.02
05/02/2001	7.9	146	2739	57	198	117	39	66	4	455	27	0.01	0.01	0.09
01/03/2001	7.3	127	906	47	147	110	43	73	4	463	27	0.01	0.07	0.35
23/04/2001	7.7	90	882	29	153	66	39	109	2	429	38	0.01	0.01	0.01
15/05/2001	8.1	151	953	16	236	69	25	124	4	365	52	0.01	0.01	0.02
12/06/2001	8.0	130	997	26	181	86	35	101	4	406	44	0.01	0.03	0.01
18/07/2001	7.8	137	1067	25	260	72	26	135	4	385	61	0.01	0.01	0.08
20/08/2001	8.5	140	1076	30	231	96	46	154	6	482	58	0.01	0.01	0.01
19/09/2001	7.4	151	1013	23	244	74	36	146	7	482	62	0.01	0.01	0.01
12/10/2001	7.2	121	1195	73	244	151	49	87	6	617	32	0.001	0.09	0.01

DATE	pH	EC mS m^{-1}	TDS (mg ℓ^{-1})	P.ACID	MALK (mg ℓ^{-1})	Ca (mg ℓ^{-1})	Mg (mg ℓ^{-1})	Na (mg ℓ^{-1})	K (mg ℓ^{-1})	SO_4 (mg ℓ^{-1})	Cl (mg ℓ^{-1})	Fe (mg ℓ^{-1})	Mn (mg ℓ^{-1})	Al (mg ℓ^{-1})
09/11/2001	7.6	115	1002	42	268	97	35	57	4	539	24	0.01	0.01	0.01
03/12/2001	7.5	162	1429	29	228	170	68	68	5	705	10	0.274	0.02	0.02
09/1/2002	7.5	139	1116	12	90	119	74	66	5	676	14	0.01	0.03	0.01
18/02/2002	7.3	154	1154	15	123	117	67	70	8	528	22	0.122	0.01	0.13
08/03/2002	6.9	173	1178	30	264	119	42	155	5	462	42	0.0	0.0	0.01
11/04/2002	7.5	147	1307	35	287	151	53	112	6	674	18	0.01	0.02	0.01
13/05/2002	7.4	181	1448	19	295	126	44	122	1	586	28	0.01	0.01	0.03
18/06/2002	7.4	146	1434	22	294	196	67	102	6	721	14	0.01	0.002	0.01
23/07/2002	7.0	139	1272	22	226	146	55	98	4	659	18	0.17	0.09	0.07
01/08/2002	6.7	124	1004	18	249	132	44	59	4	477	9	0.05	0.09	0.05
07/08/2002	6.7	125	1051	14	257	133	47	65	3	550	6	0.004	0.08	0.03
14/08/2002	6.7	129	1056	14	238	124.	50	58	3	559	8	0.03	0.107	0.04
21/08/2002	6.7	133	1068	20	255	143	55	58	4	554	6	0.05	0.07	0.09
09/02/2002	7.6	129	1104	12	197	130	62	67	4	622	6	0.01	0.01	0.01
09/09/2002	7.9	123	1167	14	209	160	64	96	5	691	6	0.01	0.01	0.01
09/16/2002	7.8	157	1354	14	231	151	67	77	4	737	6	0.01	0.01	0.01
09/23/2002	7.8	122	932	14	260	68	22	168	3	313	43	0.01	0.01	0.01
01/10/2002	7.2	110	881	0	316	82	30	146	3	423	51	0.01	0.01	0.01
07/10/2002	7.2	129	1021	0	326	88	34	132	5	433	48	0.01	0.01	0.01
14/10/2002	7.2	118	946	0	308	58	20	165	3	348	62	0.01	0.31	0.01
21/10/2002	7.2	111	918	0	316	62	19	160	4	340	59	0.01	0.01	0.01
15/11/2002	7.2	154	1003	24	511	65	24	178	4	308	62	0.01	0.01	0.01

DATE	pH	EC mS m^{-1}	TDS (mg ℓ^{-1})	P.ACID	MALK (mg ℓ^{-1})	Ca (mg ℓ^{-1})	Mg (mg ℓ^{-1})	Na (mg ℓ^{-1})	K (mg ℓ^{-1})	SO_4 (mg ℓ^{-1})	Cl (mg ℓ^{-1})	Fe (mg ℓ^{-1})	Mn (mg ℓ^{-1})	Al (mg ℓ^{-1})
22/11/2002	7.2	149	995	22	278	56	20	160	4	322	62	0.01	0.06	0.01
01/11/2002	8.1	38	254	8	135	26	11	29	3	65	36	0.01	0.1	0.27
08/11/2002	7.2	148	985	18	273	66	19	181	4	317	60	0.01	0.09	0.01
17/12/2002	7.4	126	972	49	265	53	15	160	3	257	52	0.01	0.01	0.01
30/12/2002	7.6	118	855	53	263	54	15	161	3	247	52	0.01	0.01	0.01
02/01/2003	7.5	130	1004	28	315	52	15	199	5	305	70	0.004	0.02	0.002
09/01/2003	7.7	147	1028	30	368	42	11	251	4	359	69	0.002	0.007	0.03
15/01/2003	7.6	137	929	34	358	46	12	232	4	313	69	0.04	0.03	0.12
17/02/2003	7.4	148	1115	16	265	73	20	173	5	350	29	0.01	0.01	0.23
23.01.2003	7.5	297	2032	286	295	68	29	220	71.9	480	112	0.01	0.10	0.01
03.02.2003	7.7	182	1183	37	226	73	25	177	7	500	38	0.01	0.01	0.04
10.02.2003	7.5	155	1969	41	310	37	11	201	0	620	76	0.01	0.01	0.05
24.02.2003	7.7	146	1125	64	246	57	19	162	4	496	44	1.21	0.02	2.07
03.03.2003	7.7	144	1012	68	246	56	18	160	4	484	42	0.42	0.01	0.94
10.03.2003	7.8	148	1040	74	259	58	21	159	3	504	42	0.20	0.01	0.57
17.03.2003	7.7	147	1007	68	273	54	17	162	4	470	46	0.06	0.01	0.36
24.03.2003	6.7	131	1024	76	261	83	20	141	5	432	53	0.01	0.01	0.39
01.04.2003	6.9	133	1015	59	257	67	18	159	4	436	50	0.83	0.01	1.86
07/04/2003	7.1	126	997	86	228	62	17	172	5	394	43	0.25	0.01	0.68
14/04/2003	7.2	132	988	91	299	64	19	165	4	408	44	0.08	0.01	0.48
22/04/2003	7.3	132	994	78	261	75	20	152	4	432	45	0.01	0.01	0.19
19/05/2003	7.7	121	862	6	291	60	18	206	4	364	70	0.01	0.01	0.14
22/05/2003	7.8	21	902	8	296	58	17	208	3	356	68	0.01	0.01	0.12

DATE	pH	EC mS m^{-1}	TDS (mg ℓ^{-1})	P.ACID	MALK (mg ℓ^{-1})	CA (mg ℓ^{-1})	MG (mg ℓ^{-1})	NA (mg ℓ^{-1})	K (mg ℓ^{-1})	SO4 (mg ℓ^{-1})	CL (mg ℓ^{-1})	FE (mg ℓ^{-1})	MN (mg ℓ^{-1})	AL (mg ℓ^{-1})
28/05/2003	7.7	119	883	6	296	57	16	207	4	306	76	10.76	0.21	0.63
09/05/2003	7.9	120	842	10	501	64	20	201	4	376	68	0.01	0.01	0.11
02/06/2003	7.6	139	986	14	293	47	14	202	3	302	76	0.01	0.01	0.05
09/06/2003	7.5	140	932	18	301	48	14	199	3	300	76	0.01	0.01	0.05
17/06/2003	7.4	139	916	20	301	49	14	195	3	302	132	0.01	0.01	0.049
23/06/2003	7.5	155	2096	14	240	76	27	180	5	486	52	0.01	0.01	0.037
	7.5	134	1094	36	252	92	35	129	5	463	420	0.21	0.04	0.15
07/01/2003	7.5	130	997	14	305	53	12	184	4	344	74	0.01	0.01	0.04
07/08/2003	7.6	127	986	20	311	47	114	184	3	326	68	0.01	0.01	0.02
14/07/2003	7.5	125	990	18	327	43	9	181	3	268	70	0.01	0.01	0.03
21/07/2003	7.5	127	979	18	325	42	9	190	3	290	68	0.01	0.01	0.01
01/08/2003	7.6	121	962	37	327	42	8	197	3	296	53	3.14	0.01	0.30
08/08/2003	7.7	123	957	12	331	42	8	204	4	292	86	0.01	0.01	0.02
15/08/2003	8.0	125	971	12	333	40	9	208	4	302	80	0.01	0.01	0.02
22/08/2003	8.0	125	956	108	321	33	9	213	4	280	78	0.01	0.01	0.03
01/09/2003	7.2	160	1204	25	281	175	55.590	103	5	566	16	1.34	0.01	0.06
08/09/2003	7.2	143	1088	20	319	89	27	153	4	396	46	4.72	0.01	0.09
15/09/2003	7.2	138	1138	39	298	116	35	103	3	346	34	0.01	0.01	0.08
22/09/2003	7.5	137	1067	20	327	91	26	127	3	353	40	0.01	0.01	0.01
01/10/2003	7.1	151	1088	39	321	122	41	173	5	462	42	0.01	0.58	0.26
01/10/2003	7.1	154	1241	39	329	116	39	182	5	424	50	0.01	0.80	0.24
17/10/2003	7.5	156	1041	38.	358	44.	7	231	4	262	54	0.01	0.27	0.01
24/10/2003	7.2	186	1257	57	321	142	39	202	6	396	34	0.01	0.58	0.01

Table A7. Results of chemical analysis of water samples from Syferfontein (2003/2004, Soil Science Laboratory, University of Pretoria).

Pivot	Date	pH	EC mS m^{-1}	Ca^{2+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})
Syferfontein Irrigation water quality	30/06/03	8.5	321	38	76	10.8	1	314.8	23.2
	30/06/03	8.6	310	36	73	10.6	1	283.2	20.6
	30/06/03	8.6	319	38	75	10.2	0.96	360	21.1
	15/09/03	8.6	400	59	93	17.3	400	2496.1	53.4
Syferfontein Rainfall quality	11/03/03	5.8	11	0.01	0	1.53	23	4.4	0.5
	10/04/03	4.2	15	6	0.05	0.04	0.52	1.5	3
	12/01/04	7.5	8.37	5	2	0.4	17	4.6	1

Table A8. Results of chemical analysis of water samples from Major (2004/2005, Soil Science Laboratory, University of Pretoria).

Pivot	Date	pH	EC mS m^{-1}	Ca^{2+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})
Major Irrigation water quality	14/08/04	7.0	325	666	348	15.1	37	2463.8	13.6
	25/08/04	6.4	328	697	359	17.9	39	2469.9	30.7
	18/09/04	7.2	384	680	409	16	41	3264.5	5
	24/09/04	7.1	384	770	399	16.9	38	2852.2	13.1
	02/10/04	6.7	381	764	397	16.1	41	2923.2	17.1
	06/11/04	7.2	349	737	358	16.7	38	1395.6	13.1
	21/06/2005	7.3	332	512	260	16	40	1798.3	10.1
	13/09/2005	7.1	355	478	242	14.7	40	1345	0
Major Rainfall quality	23/07/04	8.0	343	666	447	15.2	161	1982.7	15.6

Table A9. Results of chemical analysis of water samples from Pivot four (2004/2005, Soil Science Laboratory, University of Pretoria).

Pivot	Date	pH	EC mS m^{-1}	Ca^{2+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})
P4 Irrigation water quality	06/08/04 (1)	7.6	488	828	731	41.6	242	3421.7	102.7
	06/08/04 (2)	7.8	494	854	774	42.3	250	3352.7	71
	14/08/04	6.9	476	856	563	36.4	123	4652.2	68.5
	25/08/04	6.9	482	892	609	36.2	124	5376.3	68
	04/09/04	7.8	452	897	612	36.2	121	4752.5	71.5
	02/10/04	7.6	537	942	661	37.1	129	3296.5	71
	21/10/04	7.6	541	919	697	38.5	130	3589.5	73.5
	18/09/04	7.2	529	921	631	37	51	3937.9	72
	4/2/2005	7.1	530	730	541	43.3	155	3812.6	0
	13/09/2005	8.4	5.18	732	482	37.9	112	4118	78.3
P4 Rainfall quality	06/08/04	8	67	28	21	33.3	16	89.5	8.6

Table A10. Results of chemical analysis of water samples from New Vaal (2004/2005, Soil Science Laboratory, University of Pretoria).

Pivot	Date	pH	EC mS m^{-1}	Ca^{2+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})
NewVaal Irrigation water quality	17/03/04	8.6	127	107	35	7.2	144	461.2	52.9
	03/03/04	7.4	124	79	31	6.24	159	389.6	50.4
	05/01/04	8.6	151	128	39	5.2	145	389.6	41.8
	11/02/04	8.5	128	99	34	5.3	139	386.8	44.8
	18/02/04	7.0	126	73	30	5.83	149	422.4	508.1
	25/02/04	7.7	129	78	42	6.32	147	382.9	729.1
	16/01/04	7.0	147	126	39	7.49	142	273.7	48.8
	29/01/04	7.4	164	140	46	7.58	180	431.4	43.8
	17/12/03	8.7	177	72	50	9.9	337	470.1	64.5
	17/12/03	8.5	142	99	36	6.4	198	384.3	48.8
	09/01/04	8.7	157	43	47	7.1	157	571.3	26.2
	26/09/03	7.9	140	63	35	5.5	175	305.4	54.9
	05/02/05	6.7	120	70	29	6	165	375.1	37.3
NewVaal Rainfall quality	03/03/04	7.7	21	10	3	0.97	25	49.1	8.1
	26/01/04	7.7	22	16	5	0.19	28	32.5	2
	26/01/04	4.6	15	13	1	0.24	2	12.1	3
	09/01/04	9.0	4	0.73	1	0.9	3	10.3	2
	09/01/04	8.2	16	10	3	0.9	11	9.2	3
	31/03/04	7.2	17	10	7	3.3	8	26.1	5
	26/03/04	9.1	18	5	2	0.3	5	0.3	4.5
	03/03/04	7.6	15	7	3	1.7	4	35	4.5
	10/03/04	7.8	4	2	0.77	0.22	0.16	5.2	1
	11/02/04	8.8	9	6	4	0.9	19	3.9	7
	18/02/04	5.5	8	10	2	0.37	5	18.5	49.8

	25/02/04	5.1	8	9	3	0.51	5	22.2	2
	25/02/04	5.3	2	6	0.3	0.21	0.16	2.6	49.8
	04/12/04	7.5	31	34	19	3.9	21	0.8	28.2
	10/12/03	7.0	113	61	37	5.54	166	424.7	25.2
	10/12/03	7.1	170	164	49	6.65	196	644.7	35.8
	21/11/03	7.5	72	46	18	3.7	107	326.2	18.6
	28/11/03	6.7	6	8	1	0.3	4	4.7	1
	28/11/03	7.0	13	17	184	1	3	1.6	3

Appendix B

Plant analyses

Table B1. Plant analysis data of maize (cv. PAN 6710) sampled at Kleinkopjé, Summer 2000/2001.

Pivot	Growth stage	Plant part sampled	N (%)		P (%)		K (%)		Ca (%)		Mg (%)		Na (%)		SO_4 (%)		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})	
			Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas
M	42 DAP	WP	3.0-3.5	2.75	0.25-0.45	0.39	2.0-2.5	**3.21**	0.25-0.5	0.21	0.13-0.3	0.19	-	0.01	0.5-1.5	0.68	3-15	8.3	30-200	107.7	15-300	34.0	15-60	54.3
T	39 DAP	WP	3.0-3.5	2.98	0.25-0.45	**0.48**	2.0-2.5	**3.52**	0.25-0.5	0.16	0.13-0.3	0.17	-	0.01	0.5-1.5	0.64	3-15	8.0	30-200	86.3	15-300	25.3	15-60	**67.7**
F	40 DAP	WP	3.0-3.5	2.89	0.25-0.45	0.45	2.02.5	**3.31**	0.25-0.5	0.21	0.13-0.3	0.21	-	0.01	0.5-1.5	0.63	3-15	8.3	30-200	67.7	15-300	35.7	15-60	57.3
M	69 DAP	WP	3.0-3.5	2.54	0.25-0.45	0.30	2.0-2.5	2.13	0.25-0.5	0.43	0.13-0.3	0.28	-	0.02	0.5-1.5	**2.06**	3-15	**20.0**	30-200	**371.0**	15-300	56.0	15-60	56.0
T	66 DAP	WP	3.0-3.5	2.74	0.25-0.45	0.33	2.0-2.5	1.91	0.25-0.5	0.35	0.13-0.3	**0.35**	-	0.03	0.5-1.5	**1.51**	3-15	**20.0**	30-200	**366.0**	15-300	36.0	15-60	**62.0**
F	67 DAP	WP	3.0-3.5	3.26	0.25-0.45	0.35	2.0-2.5	1.89	0.25-0.5	0.44	0.13-0.3	**0.32**	-	0.05	0.5-1.5	1.45	3-15	**18.0**	30-200	155.0	15-300	48.0	15-60	57.0
M	76 DAP	YL	2.75-3.5	**3.81**	0.25-0.45	0.40	1.75-2.25	**4.45**	0.25-0.5	**0.51**	0.13-0.3	0.23	-	0.00	0.5-1.5	0.72	3-15	12.0	30-200	**354**	15-300	90.0	15-60	**75.0**
T	73 DAP	YL	2.75-3.5	**4.47**	0.25-0.45	**0.57**	1.75-2.25	**4.97**	0.25-0.5	0.50	0.13-0.3	0.22	-	0.00	0.5-1.5	0.64	3-15	14.0	30-200	**266**	15-300	51.0	15-60	**87.0**
F	74 DAP	YL	2.75-3.5	**3.70**	0.25-0.45	0.42	1.75-2.25	**5.10**	0.25-0.5	0.48	0.13-0.3	0.30	-	0.00	0.5-1.5	0.48	3-15	9.0	30-200	**345**	15-300	41.0	15-60	**72.0**

DAP - Days after planting	M – Major
WP - Whole plant	T - Tweefontein
YL – Young leaves	F – Pivot Fourth
Norm - Normal	
Meas - Measured	

Table B2. Plant analysis data of wheat (cv. SST 825) sampled at Kleinkopjé, Winter 2001.

Pivot	Growth stage	Plant part sampled	N (%)		P (%)		K (%)		Ca (%)		Mg (%)		Na (%)		SO_4 (%)		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})	
			Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas
T	Tiller	WT	4.0 - 5.0	**5.58**	0.4 - 0.7	0.49	3.2 – 4.0	**4.69**	0.2 - 0.5	0.29	0.15 - 0.5	0.31	-	0.04	0.66 -1.65	1.43	5-25	9.0	25-100	-	11-13	**50.0**	15-70	57.0
T	Tiller	WT	4.0 - 5.0	**5.35**	0.4 – 0.7	0.33	3.2 - 4.0	**4.95**	0.2 - 0.5	0.33	0.15 - 0.5	0.34	-	0.04	0.66 -1.65	**1.93**	5-25	9.0	25-100	**137.0**	11-13	**54.0**	15-70	36.0
T	Tiller	WT	4.0 - 5.0	**5.87**	0.4 – 0.7	0.42	3.2 – 4.0	**4.56**	0.2 - 0.5	0.35	0.15 - 0.5	0.35	-	0.04	0.66 -1.65	**1.68**	5-25	9.0	25-100	**375.0**	11-13	**36.0**	15-70	36.0
M	Tiller	WT	4.0 - 5.0	**5.22**	0.2 - 0.4	**0.42**	2.0 – 3.5	**4.47**	0.2 - 0.5	0.31	0.15 - 0.5	0.29	-	0.03	0.57-1.65	**1.78**	5-25	10.0	25-100	**239.0**	11-13	**70.0**	15-70	41.0
M	Tiller	WT	4.0 - 5.0	**5.29**	0.2 - 0.4	**0.48**	2.0 - 3.5	**4.96**	0.2 - 0.5	0.35	0.15 - 0.5	0.32	-	0.03	0.57 -1.65	**2.00**	5-25	8.0	25-100	**260.0**	11-13	**81.0**	15-70	64.0
M	Tiller	WT	4.0 - 5.0	**5.58**	0.2 - 0.4	**0.48**	2.0 – 3.5	**4.64**	0.2 - 0.5	0.35	0.15 - 0.5	0.33	-	0.03	0.57-1.65	1.64	5-25	7.0	25-100	**220.0**	11-13	**61.0**	15-70	60.0
T	Heading	WT	3.0 - 4.0	2.05	0.2 - 0.4	0.18	1.8 - 3.0	2.77	0.2 - 0.5	0.38	0.15 - 0.5	0.24	-	0.03	0.51-1.65	**1.91**	5-25	6.0	25-100	**123.0**	11-13	**75.0**	15-70	29.0
T	Heading	WT	3.0 - 4.0	2.37	0.2 - 0.4	0.24	1.8 - 3.0	2.81	0.2 - 0.5	0.27	0.15 - 0.5	0.29	-	0.04	0.51-1.65	1.63	5-25	6.0	25-100	69.0	11-13	**84.0**	15-70	48.0
T	Heading	WT	3.0 - 4.0	2.22	0.2 – 0.4	0.20	1.8 – 3.0	2.82	0.2 - 0.5	0.23	0.15 – 0.5	0.32	-	0.04	0.51 -1.65	**1.80**	5-25	6.0	25-100	87.0	11-13	**90.0**	15-70	42.0
M	Heading	WT	3.0 - 4.0	2.42	0.2 – 0.4	0.21	1.8 – 3.0	**3.52**	0.2- 0.5	0.22	0.15 – 0.5	.024	-	0.03	0.51 -1.65	1.55	5-25	7.0	25-100	**147.0**	11-13	**67.0**	15-70	32.0
M	Heading	WT	3.0 - 4.0	2.41	0.2 – 0.4	0.21	1.8 – 3.0	**4.01**	0.2 - 0.5	0.28	0.15 – 0.5	.029	-	0.04	0.51 -1.65	1.64	5-25	6.0	25-100	**162.0**	11-13	**143.0**	15-70	52.0
M	Heading	WT	3.0 - 4.0	2.14	0.2 - 0.4	0.23	1.8 - 3.0	**3.70**	0.2 - 0.5	0.31	0.15 - 0.5	0.28	-	0.04	0.51-1.65	1.33	5-25	6.0	25-100	**121.0**	11-13	**124.0**	15-70	40.0

DAP - Days after planting	M – Major
WT - Whole tops	T - Tweefontein
Norm – Normal	
Meas - Measured	

Table B3. Plant analysis data of maize (cv. PHI 32P75) sampled at Kleinkopjé, Summer 2001/2002.

Pivot	Growth stage	Plant part sampled	N (%)		P (%)		K (%)		Ca (%)		Mg (%)		Na (%)		SO_4 (%)		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})	
			Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas
M	78 DAP	YL	2.75-3.5	2.9	0.25-0.45	0.25	1.75-2.25	2.16	0.25-0.5	0.37	0.13-0.3	**0.32**	-	0.00	0.5-1.5	**1.75**	3-15	**24.0**	30-200	**270.0**	15-300	63.0	15-60	36.0
M	78 DAP	YL	2.75-3.5	2.81	0.25-0.45	0.25	1.75-2.25	1.8	0.25-0.5	0.36	0.13-0.3	**0.32**	-	0.00	0.5-1.5	1.48	3-15	**24.0**	30-200	**236.0**	15-300	69.0	15-60	39.0
M	78 DAP	YL	2.75-3.5	2.61	0.25-0.45	0.24	1.75-2.25	1.82	0.25-0.5	0.34	0.13-0.3	0.30	-	0.00	0.5-1.5	**1.64**	3-15	**27.0**	30-200	**365.0**	15-300	75.0	15-60	44.0
M	78 DAP	YL	2.75-3.5	2.91	0.25-0.45	0.28	1.75-2.25	1.95	0.25-0.5	0.36	0.13-0.3	0.27	-	0.00	0.5-1.5	1.35	3-15	12.0	30-200	**375.0**	15-300	71.0	15-60	44.0
M	78 DAP	YL	2.75-3.5	2.81	0.25-0.45	0.26	1.75-2.25	1.83	0.25-0.5	0.40	0.13-0.3	**0.35**	-	0.00	0.5-1.5	**1.73**	3-15	11.0	30-200	**296.0**	15-300	75.0	15-60	**71.0**
T	79 DAP	YL	2.75-3.5	2.46	0.25-0.45	0.26	1.75-2.25	2.04	0.25-0.5	0.31	0.13-0.3	**0.34**	-	0.02	0.5-1.5	**1.68**	3-15	11.0	30-200	**242.0**	15-300	38.0	15-60	33.0
T	79 DAP	YL	2.75-3.5	2.41	0.25-0.45	0.27	1.75-2.25	1.86	0.25-0.5	0.33	0.13-0.3	**0.41**	-	0.02	0.5-1.5	**1.63**	3-15	12.0	30-200	186.0	15-300	68.0	15-60	51.0
T	79 DAP	YL	2.75-3.5	2.61	0.25-0.45	0.27	1.75-2.25	1.91	0.25-0.5	0.31	0.13-0.3	**0.37**	-	0.02	0.5-1.5	1.36	3-15	**17.0**	30-200	198.0	15-300	39.0	15-60	38.0
T	79DAP	YL	2.75-3.5	2.90	0.25-0.45	0.31	1.75-2.25	1.76	0.25-0.5	0.40	0.13-0.3	0.27	-	0.02	0.5-1.5	1.28	3-15	**21.0**	30-200	**212.0**	15-300	50.0	15-60	36.0
T	79 DAP	YL	2.75-3.5	2.26	0.25-0.45	0.22	1.75-2.25	2.05	0.25-0.5	0.31	0.13-0.3	0.29	-	0.02	0.5-1.5	0.78	3-15	**20.0**	30-200	**228.0**	15-300	35.0	15-60	26.0

DAP - Days after planting	M – Major
YL – Young leaves	T - Tweefontein
Norm - Normal	F – Pivot Fourth
Meas - Measured	

Table B4. Plant analysis data of maize (cv. PHI 32P75) sampled at Kleinkopjé, Summer 2002/2003.

Pivot	Growth stage	Plant part sampled	N (%)		P (%)		K (%)		Ca (%)		Mg (%)		Na (%)		SO_4 (%)		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})	
			Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas
T1	79 DAP	YL	2.75-3.5	**5.41**	0.25-0.45	**0.49**	1.75-2.25	**4.57**	0.25-0.5	0.31	0.13-0.3	**0.40**	-	0.08	0.5-1.5	**3.22**	15-Mar	11.0	30-200	**671.0**	15-300	78.0	15-60	60.0
T2	79 DAP	YL	2.75-3.5	**6.29**	0.25-0.45	**0.67**	1.75-2.25	**4.14**	0.25-0.5	0.36	0.13-0.3	**0.34**	-	0.06	0.5-1.5	**2.96**	15-Mar	9.0	30-200	**303.0**	15-300	60.0	15-60	54.0
T3	79 DAP	YL	2.75-3.5	**6.04**	0.25-0.45	**0.56**	1.75-2.25	**4.45**	0.25-0.5	0.26	0.13-0.3	0.30	-	0.05	0.5-1.5	**2.50**	15-Mar	6.0	30-200	**240.0**	15-300	60.0	15-60	48.0
F1	79 DAP	YL	2.75-3.5	**6.68**	0.25-0.45	**0.60**	1.75-2.25	**4.05**	0.25-0.5	0.32	0.13-0.3	0.29	-	0.04	0.5-1.5	**3.06**	15-Mar	8.0	30-200	**383.0**	15-300	102.0	15-60	59.0
F2	79 DAP	YL	2.75-3.5	**6.06**	0.25-0.45	**0.62**	1.75-2.25	**4.21**	0.25-0.5	0.40	0.13-0.3	0.30	-	0.04	0.5-1.5	**2.57**	15-Mar	6.0	30-200	**321.0**	15-300	71.0	15-60	49.0
F3	79 DAP	YL	2.75-3.5	**6.17**	0.25-0.45	**0.65**	1.75-2.25	**4.21**	0.25-0.5	0.50	0.13-0.3	**0.35**	-	0.03	0.5-1.5	**2.83**	15-Mar	8.0	30-200	**404.0**	15-300	81.0	15-60	62.0

DAP - Days after planting	M – Major
YL – Young leaves	T - Tweefontein
Norm - Normal	F – Pivot Fourth
Meas - Measured	

Table B5. Plant analysis data of wheat (cv. SST 825) sampled at Kleinkopjé, winter 2003.

Date	Site	N (%)		P (%)		K (%)		Ca (%)		Mg (%)		Na (%)		SO_4 (%)		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})	
		Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas
70 DAP	M1	4.0 - 5.0	4.90	0.4 - 0.7	0.50	3.2 – 4.0	1.53	0.2 - 0.5	**0.71**	0.15 - 0.5	0.26	-	0.01	0.66 -1.65	0.00	5-25	6.0	25-100	**224.0**	11-13	**131.0**	15-70	20.0
70 DAP	M2	4.0 - 5.0	**5.80**	0.4 – 0.7	0.50	3.2 - 4.0	1.77	0.2 - 0.5	**0.79**	0.15 - 0.5	0.26	-	0.01	0.66 -1.65	0.00	5-25	12.0	25-100	**258.0**	11-13	**117.0**	15-70	20.0
81 DAP	M1	4.0 - 5.0	**5.10**	0.4 - 0.7	0.40	3.2 – 4.0	**4.95**	0.2 - 0.5	0.46	0.15 - 0.5	0.43	-	0.05	0.66 -1.65	**2.46**	5-25	14.0	25-100	**465.0**	11-13	**173.0**	15-70	54.0
81 DAP	M2	4.0 - 5.0	**5.10**	0.4 – 0.7	0.30	3.2 – 4.0	**4.53**	0.2 - 0.5	0.47	0.15 - 0.5	0.49	-	0.05	0.57-1.65	**2.46**	5-25	14.0	25-100	**368.0**	11-13	**186.0**	15-70	57.0
81 DAP	M3	4.0 - 5.0	**5.10**	0.4 – 0.7	0.30	3.2 - 4.0	**4.79**	0.2 - 0.5	0.47	0.15 - 0.5	0.49	-	0.06	0.57 -1.65	**2.46**	5-25	15.0	25-100	**602.0**	11-13	**171.0**	15-70	53.0
81 DAP	F1	4.0 - 5.0	**5.70**	0.4 - 0.7	0.50	3.2 – 4.0	**4.47**	0.2 - 0.5	0.40	0.15 - 0.5	0.32	-	0.04	0.57-1.65	**2.18**	5-25	14.0	25-100	**392.0**	11-13	**123.0**	15-70	50.0
81 DAP	F2	4.0 - 5.0	**5.50**	0.4 – 0.7	0.50	3.2 – 4.0	**4.54**	0.2 - 0.5	0.36	0.15 - 0.5	0.37	-	0.05	0.51-1.65	**2.28**	5-25	14.0	25-100	**581.0**	11-13	**108.0**	15-70	60.0
81 DAP	F3	4.0 - 5.0	4.80	0.4 – 0.7	0.50	3.2 - 4.0	3.82	0.2 - 0.5	0.38	0.15 - 0.5	0.32	-	0.04	0.51-1.65	**2.29**	5-25	18.0	25-100	**1209.0**	11-13	**77.0**	15-70	57.0
81 DAP	T1	4.0 - 5.0	**5.50**	0.4 - 0.7	0.40	3.2 – 4.0	**4.73**	0.2 - 0.5	0.32	0.15 – 0.5	0.29	-	0.02	0.51 -1.65	**1.97**	5-25	18.0	25-100	**551.0**	11-13	**74.0**	15-70	47.0
81 DAP	T2	4.0 - 5.0	**5.40**	0.4 – 0.7	0.40	3.2 - 4.0	**4.61**	0.2- 0.5	0.32	0.15 – 0.5	0.32	-	0.02	0.51 -1.65	**2.09**	5-25	15.0	25-100	**516.0**	11-13	**84.0**	15-70	48.0
81 DAP	T3	4.0 - 5.0	**5.30**	0.4 – 0.7	0.40	3.2 – 4.0	**5.00**	0.2 - 0.5	0.35	0.15 – 0.5	0.28	-	0.02	0.51 -1.65	**2.11**	5-25	17.0	25-100	**420.0**	11-13	**72.0**	15-70	44.0

Norm - Normal	M – Major
Meas - Measured	T - Tweefontein
	F – Pivot Fourth

Table B6. Plant analysis data of wheat (cv. SST 825) sampled at Kleinkopjé, winter 2003.

Date	Site	N (%)		P (%)		K (%)		Ca (%)		Mg (%)		Na (%)		SO_4 (%)		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})	
		Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas
81 DAP	C1 T1 (a)	4.0 - 5.0	1.70	0.4 - 0.7	0.45	3.2 – 4.0	2.73	0.2 - 0.5	0.04	0.15 - 0.5	0.14	-	0.02	0.66 -1.65	0.63	5-25	11.0	25-100	86.0	11-13	11.0	15-70	29.0
81 DAP	C1 T1 (b)	4.0 - 5.0	1.90	0.4 – 0.7	0.30	3.2 - 4.0	2.37	0.2 - 0.5	0.04	0.15 - 0.5	0.16	-	0.02	0.66 -1.65	0.66	5-25	9.0	25-100	47.0	11-13	8.0	15-70	56.0
81 DAP	C1 T2 (a)	4.0 - 5.0	2.00	0.4 - 0.7	0.40	3.2 – 4.0	2.83	0.2 - 0.5	0.05	0.15 - 0.5	0.15	-	0.03	0.66 -1.65	0.82	5-25	14.0	25-100	75.0	11-13	9.0	15-70	33.0
81 DAP	C1 T2 (b)	4.0 - 5.0	2.00	0.4 – 0.7	0.40	3.2 – 4.0	2.37	0.2 - 0.5	0.05	0.15 - 0.5	0.14	-	0.02	0.57-1.65	0.70	5-25	12.0	25-100	**126.0**	11-13	12.0	15-70	65.0
81 DAP	C2 T1 (a)	4.0 - 5.0	1.50	0.4 – 0.7	0.30	3.2 - 4.0	2.57	0.2 - 0.5	0.16	0.15 - 0.5	0.14	-	0.02	0.57 -1.65	0.77	5-25	11.0	25-100	45.0	11-13	6.0	15-70	33.0
81 DAP	C2 T1 (b)	4.0 - 5.0	1.70	0.4 - 0.7	0.34	3.2 – 4.0	2.11	0.2 - 0.5	0.03	0.15 - 0.5	0.16	-	0.01	0.57-1.65	0.74	5-25	9.0	25-100	45.0	11-13	8.0	15-70	29.0
81 DAP	C2 T2 (a)	4.0 - 5.0	2.00	0.4 – 0.7	0.40	3.2 – 4.0	2.57	0.2 - 0.5	0.05	0.15 - 0.5	0.13	-	0.02	0.51-1.65	0.84	5-25	15.0	25-100	60.0	11-13	8.0	15-70	42.0
81 DAP	C2 T2 (b)	4.0 - 5.0	2.10	0.4 - 0.7	0.40	3.2 - 4.0	2.30	0.2 - 0.5	0.03	0.15 - 0.5	0.14	-	0.02	0.51-1.65	0.72	5-25	15.0	25-100	**102.0**	11-13	8.0	15-70	60.0
81 DAP	C3 T1 (a)	4.0 - 5.0	1.40	0.4 – 0.7	0.20	3.2 – 4.0	2.20	0.2 - 0.5	0.06	0.15 - 0.5	0.11	-	0.02	0.51 -1.65	0.42	5-25	9.0	25-100	59.0	11-13	6.0	15-70	30.0
81 DAP	C3 T1 (b)	4.0 - 5.0	1.50	0.4 - 0.7	0.30	3.2 - 4.0	2.04	0.2- 0.5	0.05	0.15 - 0.5	0.13	-	0.01	0.51 -1.65	0.53	5-25	9.0	25-100	53.0	11-13	**14.0**	15-70	41.0
81 DAP	C3 T2 (b)	4.0 - 5.0	1.80	0.4 – 0.7	0.40	3.2 – 4.0	2.35	0.2 - 0.5	0.08	0.15 - 0.5	0.13	-	0.01	0.51 -1.65	0.76	5-25	14.0.	25-100	56.0	11-13	8.0	15-70	50.0
81 DAP	C3 T2 (b)	4.0 - 5.0	1.90	0.4 – 0.7	0.30	3.2 – 4.0	2.04	0.2 - 0.5	0.03	0.15 - 0.5	0.13	-	0.01	0.51-1.65	0.70	5-25	15.0	25-100	42.0	11-13	8.0	15-70	51.0
81 DAP	C4 T1 (a)	4.0 - 5.0	1.60	0.4 - 0.7	0.30	3.2 - 4.0	2.42	0.2 - 0.5	0.05	0.15 - 0.5	0.13	-	0.01	0.51 -1.65	0.60	5-25	11.0	25-100	80.0	11-13	9.0	15-70	21.0
81 DAP	C4 T1 (b)	4.0 - 5.0	1.70	0.4 – 0.7	0.30	3.2 – 4.0	2.03	0.2- 0.5	0.08	0.15 - 0.5	0.14	-	0.01	0.51 -1.65	0.73	5-25	11.0	25-100	53.0	11-13	9.0	15-70	35.0
81 DAP	C4 T2 (a)	4.0 - 5.0	2.00	0.4 – 0.7	0.40	3.2 – 4.0	2.50	0.2 - 0.5	0.06	0.15 - 0.5	0.14	-	0.02	0.51 -1.65	0.73	5-25	17.0	25-100	57.0	11-13	8.0	15-70	29.0
81 DAP	C4 T2 (b)	4.0 - 5.0	2.08	0.4 - 0.7	0.41	3.2 - 4.0	2.23	0.2 - 0.5	0.13	0.15 – 0.5	0.13	-	0.01	0.51 -1.65	0.86	5-25	15.0	25-100	60.0	11-13	9.0	15-70	**89.0**

Norm - Normal

Meas -Measured

Table B7. Plant analysis data of wheat (cv. SST 825) sampled at Kleinkopjé, winter 2003.

Date	Site	N (%)		P (%)		K (%)		Ca (%)		Mg (%)		Na (%)		SO_4 (%)		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})	
		Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas
87 DAP	M1	4.0 - 5.0	4.80	0.4 - 0.7	0.40	3.2 – 4.0	**5.09**	0.2 - 0.5	0.50	0.15 - 0.5	0.42	-	0.02	0.66 -1.65	0.91	5-25	3.0	25-100	**201.0**	11-13	**180.0**	15-70	66.0
87 DAP	M2	4.0 - 5.0	4.10	0.4 – 0.7	0.30	3.2 - 4.0	**5.00**	0.2 - 0.5	0.49	0.15 - 0.5	0.40	-	0.02	0.66 -1.65	1.19	5-25	6.0	25-100	**179.0**	11-13	**158.0**	15-70	**116.0**
87 DAP	M3	4.0 - 5.0	4.30	0.4 - 0.7	0.30	3.2 – 4.0	**4.34**	0.2 - 0.5	0.50	0.15 - 0.5	0.35	-	0.01	0.66 -1.65	0.94	5-25	14.0	25-100	**237.0**	11-13	**152.0**	15-70	74.0
87 DAP	F1	4.0 - 5.0	4.70	0.4 – 0.7	0.40	3.2 – 4.0	**4.55**	0.2 - 0.5	**0.64**	0.15 - 0.5	0.43	-	0.08	0.57-1.65	**1.84**	5-25	2.0	25-100	**362.0**	11-13	**129.0**	15-70	80.0
87 DAP	F2	4.0 - 5.0	**5.10**	0.4 – 0.7	0.50	3.2 - 4.0	**4.25**	0.2 - 0.5	**0.64**	0.15 - 0.5	0.46	-	0.07	0.57 -1.65	**1.75**	5-25	2.0	25-100	**363.0**	11-13	**119.0**	15-70	66.0
87 DAP	F3	4.0 - 5.0	**5.10**	0.4 - 0.7	0.50	3.2 – 4.0	**4.53**	0.2 - 0.5	**0.59**	0.15 - 0.5	0.47	-	0.08	0.57-1.65	0.90	5-25	2.0	25-100	**317.0**	11-13	**120.0**	15-70	71.0
87 DAP	T1	4.0 - 5.0	**5.20**	0.4 – 0.7	0.60	3.2 – 4.0	**4.76**	0.2 - 0.5	**0.62**	0.15 - 0.5	0.41	-	0.05	0.51-1.65	1.39	5-25	2.0	25-100	**486.0**	11-13	**95.0**	15-70	74.0
87 DAP	T2	4.0 - 5.0	5.00	0.4 - 0.7	0.50	3.2 - 4.0	**4.53**	0.2 - 0.5	**0.65**	0.15 - 0.5	0.42	-	0.04	0.51-1.65	1.44	5-25	3.0	25-100	**479.0**	11-13	**90.0**	15-70	72.0
87 DAP	T3	4.0 - 5.0	**5.30**	0.4 – 0.7	0.60	3.2 - 4.0	**5.17**	0.2 - 0.5	**0.69**	0.15 - 0.5	0.44	-	0.06	0.51 -1.65	**1.63**	5-25	2.0	25-100	**326.0**	11-13	**92.0**	15-70	69.0

Norm - Normal

Meas -Measured

Table B8. Plant analysis data of wheat (cv. SST 825) sampled at Kleinkopjé, winter 2003.

Date	Site	N (%)		P (%)		K (%)		Ca (%)		Mg (%)		Na (%)		SO_4 (%)		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})	
		Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas
115 DAP	F1	4.0 - 5.0	2.60	0.4 - 0.7	0.30	3.2 – 4.0	3.28	0.2 - 0.5	0.43	0.15 - 0.5	0.46	-	0.11	0.66 -1.65	**2.21**	5-25	14.0	25-100	**110.0**	11-13	**99.0**	15-70	48.0
115 DAP	F2	4.0 - 5.0	2.60	0.4 – 0.7	0.30	3.2 - 4.0	2.94	0.2 - 0.5	0.45	0.15 - 0.5	0.48	-	0.10	0.66 -1.65	**2.32**	5-25	8.0	25-100	**110.0**	11-13	**125.0**	15-70	45.0
115 DAP	F3	4.0 - 5.0	3.00	0.4 - 0.7	0.30	3.2 – 4.0	3.66	0.2 - 0.5	0.50	0.15 - 0.5	0.48	-	0.11	0.66 -1.65	**2.33**	5-25	9.0	25-100	**119.0**	11-13	**110.0**	15-70	20.0
115 DAP	M1	4.0 - 5.0	2.20	0.4 – 0.7	0.20	3.2 – 4.0	2.31	0.2 - 0.5	0.34	0.15 - 0.5	0.33	-	0.02	0.57-1.65	1.59	5-25	12.0	25-100	**128.0**	11-13	**164.0**	15-70	32.0
115 DAP	M2	4.0 - 5.0	2.20	0.4 – 0.7	0.20	3.2 - 4.0	1.99	0.2 - 0.5	0.37	0.15 - 0.5	0.35	-	0.02	0.57 -1.65	**1.78**	5-25	12.0	25-100	**195.0**	11-13	**200.0**	15-70	33.0
115 DAP	M3	4.0 - 5.0	2.50	0.4 - 0.7	0.20	3.2 – 4.0	2.11	0.2 - 0.5	0.42	0.15 - 0.5	0.47	-	0.03	0.57-1.65	**2.03**	5-25	8.0	25-100	**210.0**	11-13	**194.0**	15-70	59.0
115 DAP	T1	4.0 - 5.0	3.20	0.4 – 0.7	0.30	3.2 – 4.0	3.04	0.2 - 0.5	0.46	0.15 - 0.5	0.40	-	0.09	0.51-1.65	**2.03**	5-25	9.0	25-100	**108.0**	11-13	**59.0**	15-70	59.0
115 DAP	T2	4.0 - 5.0	2.90	0.4 - 0.7	0.30	3.2 - 4.0	2.20	0.2 - 0.5	0.41	0.15 - 0.5	0.41	-	0.08	0.51-1.65	**2.16**	5-25	9.0	25-100	**135.0**	11-13	**50.0**	15-70	38.0
115 DAP	T3	4.0 - 5.0	3.80	0.4 – 0.7	0.40	3.2 - 4.0	2.13	0.2 - 0.5	0.39	0.15 - 0.5	0.37	-	0.05	0.51 -1.65	**1.98**	5-25	8.0	25-100	**143.0**	11-13	**86.0**	15-70	48.0

Norm - Normal	M – Major
Meas - Measured	T - Tweefontein
	F – Pivot Fourth

Table B9. Plant analysis data of wheat (cv. SST 825) sampled at Kleinkopjé, winter 2003.

Date	Site	N (%)		P (%)		K (%)		Ca (%)		Mg (%)		Na (%)		SO_4 (%)		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})	
		Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas
131 DAP	F1	4.0 - 5.0	1.90	0.4 - 0.7	0.30	3.2 – 4.0	1.60	0.2 - 0.5	0.41	0.15 - 0.5	0.48	-	0.11	0.66 -1.65	**2.34**	5-25	8.0	25-100	**176.0**	11-13	**177.0**	15-70	59.0
131 DAP	F2	4.0 - 5.0	1.90	0.4 – 0.7	0.30	3.2 - 4.0	1.98	0.2 - 0.5	0.35	0.15 - 0.5	0.41	-	0.09	0.66 -1.65	**2.03**	5-25	9.0	25-100	**113.0**	11-13	**114.0**	15-70	47.0
131 DAP	F3	4.0 - 5.0	2.00	0.4 - 0.7	0.30	3.2 – 4.0	1.87	0.2 - 0.5	0.42	0.15 - 0.5	0.47	-	0.11	0.66 -1.65	**2.16**	5-25	5.0	25-100	**123.0**	11-13	**119.0**	15-70	3.0
131 DAP	T1	4.0 - 5.0	1.80	0.4 – 0.7	0.30	3.2 – 4.0	0.99	0.2 - 0.5	0.33	0.15 - 0.5	0.34	-	0.08	0.66 -1.65	**1.92**	5-25	3.0	25-100	89.0	11-13	**72.0**	15-70	23.0
131 DAP	T2	4.0 - 5.0	2.10	0.4 – 0.7	0.30	3.2 - 4.0	1.60	0.2 - 0.5	0.38	0.15 - 0.5	0.43	-	0.09	0.66 -1.65	**2.24**	5-25	6.0	25-100	99.0	11-13	**71.0**	15-70	35.0
131 DAP	T3	4.0 - 5.0	1.90	0.4 - 0.7	0.30	3.2 – 4.0	1.36	0.2 - 0.5	0.29	0.15 - 0.5	0.36	-	0.09	0.66 -1.65	**2.10**	5-25	9.0	25-100	**113.0**	11-13	**63.0**	15-70	30.0
131 DAP	M1	4.0 - 5.0	1.40	0.4 – 0.7	0.20	3.2 – 4.0	0.49	0.2 - 0.5	0.19	0.15 - 0.5	0.23	-	0.01	0.66 -1.65	1.25	5-25	5.0	25-100	**219.0**	11-13	**149.0**	15-70	27.0
131 DAP	M2	4.0 - 5.0	1.40	0.4 - 0.7	0.20	3.2 - 4.0	0.61	0.2 - 0.5	0.21	0.15 - 0.5	0.28	-	0.02	0.66 -1.65	1.20	5-25	3.0	25-100	**174.0**	11-13	**173.0**	15-70	24.0
131 DAP	M3	4.0 - 5.0	1.60	0.4 – 0.7	0.20	3.2 - 4.0	0.72	0.2 - 0.5	0.20	0.15 - 0.5	0.25	-	0.02	0.66 -1.65	1.54	5-25	3.0	25-100	**161.0**	11-13	**155.0**	15-70	23.0
131 DAP	M3	4.0 - 5.0	**5.60**	0.4 - 0.7	0.40	3.2 - 4.0	**4.38**	0.2 - 0.5	**1.08**	0.15 - 0.5	**0.64**	-	0.02	0.66 -1.65	**1.88**	5-25	**27.0**	25-100	**854.0**	11-13	**290.0**	15-70	47.0

Norm - Normal	M – Major
Meas - Measured	T - Tweefontein
	F – Pivot Fourth

Table B10. Plant analysis data of wheat (cv. SST 825) sampled at Kleinkopjé, winter 2003.

Date	Site	N (%)		P (%)		K (%)		Ca (%)		Mg (%)		Na (%)		SO_4 (%)		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})	
		Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas
DAP 151	M1	4.0 - 5.0	3.60	0.4 - 0.7	0.30	3.2 – 4.0	**4.46**	0.2 - 0.5	**0.52**	0.15 - 0.5	0.34	-	0.00	0.66 -1.65	1.03	5-25	12.0	25-100	**411.0**	11-13	**122.0**	15-70	69.0
DAP 151	M2	4.0 - 5.0	4.00	0.4 – 0.7	0.40	3.2 - 4.0	**4.75**	0.2 - 0.5	**0.69**	0.15 - 0.5	0.46	-	0.01	0.66 -1.65	0.95	5-25	15.0	25-100	**59.0**	11-13	**189.0**	15-70	65.0
DAP 151	M3	4.0 - 5.0	3.70	0.4 - 0.7	0.30	3.2 – 4.0	**4.88**	0.2 - 0.5	**0.56**	0.15 - 0.5	0.32	-	0.00	0.66 -1.65	0.99	5-25	17.0	25-100	**483.0**	11-13	**152.0**	15-70	63.0
DAP 151	F1	4.0 - 5.0	4.10	0.4 – 0.7	0.40	3.2 – 4.0	**4.73**	0.2 - 0.5	**0.68**	0.15 - 0.5	0.43	-	0.11	0.66 -1.65	1.52	5-25	8.0	25-100	**164.0**	11-13	**102.0**	15-70	56.0
DAP 151	F2	4.0 - 5.0	4.00	0.4 – 0.7	0.40	3.2 - 4.0	**4.83**	0.2 - 0.5	**0.75**	0.15 - 0.5	0.51	-	0.11	0.66 -1.65	**2.05**	5-25	8.0	25-100	**182.0**	11-13	**101.0**	15-70	57.0
DAP 151	F3	4.0 - 5.0	4.20	0.4 - 0.7	0.40	3.2 – 4.0	**4.32**	0.2 - 0.5	**0.74**	0.15 - 0.5	**0.52**	-	0.12	0.66 -1.65	0.99	5-25	3.0	25-100	**197.0**	11-13	**113.0**	15-70	62.0
DAP 151	T1	4.0 - 5.0	3.70	0.4 – 0.7	0.30	3.2 – 4.0	**4.68**	0.2 - 0.5	**0.63**	0.15 - 0.5	0.31	-	0.01	0.66 -1.65	1.12	5-25	6.0	25-100	**263.0**	11-13	**56.0**	15-70	42.0
DAP 151	T2	4.0 - 5.0	3.90	0.4 - 0.7	0.40	3.2 - 4.0	**4.81**	0.2 - 0.5	**0.59**	0.15 - 0.5	0.27	-	0.00	0.66 -1.65	0.82	5-25	5.0	25-100	**188.0**	11-13	**56.0**	15-70	45.0
DAP 151	T3	4.0 - 5.0	4.00	0.4 – 0.7	0.40	3.2 - 4.0	**4.84**	0.2 - 0.5	**0.62**	0.15 - 0.5	0.31	-	0.01	0.66 -1.65	0.99	5-25	11.0	25-100	**233.0**	11-13	**63.0**	15-70	47.0

Norm - Normal	M - Major
Meas - Measured	F- Fourth
	T-Tweefontein

Table B11. Plant analysis data of maize (cv. PHI 32P75) sampled at Kleinkopjé, summer 2003/2004.

Date	Site	N (%)		P (%)		K (%)		Ca (%)		Mg (%)		Na (%)		SO_4 (%)		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})	
		Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas
30 DAP	M1	3.0-3.5	2.50	0.25-0.45	0.40	2.0-2.5	**3.46**	0.25-0.5	0.26	0.13-0.3	0.23	-	0.04	0.5-1.5	0.64	3-15	**17.0**	30-200	**251.0**	15-300	62.0	15-60	**87.0**
30 DAP	M2	3.0-3.5	2.80	0.25-0.45	0.40	2.0-2.5	**3.72**	0.25-0.5	0.23	0.13-0.3	0.21	-	0.03	0.5-1.5	0.65	3-15	14.0	30-200	**234.0**	15-300	44.0	15-60	**255.0**
30 DAP	M3	3.0-3.5	2.90	0.25-0.45	0.30	2.0-2.5	**3.34**	0.25-0.5	0.28	0.13-0.3	0.23	-	0.03	0.5-1.5	0.74	3-15	15.0	30-200	**239.0**	15-300	39.0	15-60	**179.0**
59 DAP	M1	3.0-3.5	2.70	0.25-0.45	0.30	2.0-2.5	2.11	0.25-0.5	0.40	0.13-0.3	**0.35**	-	0.06	0.5-1.5	0.90	3-15	**17.0**	30-200	**237.0**	15-300	30.0	15-60	
59 DAP	M2	3.0-3.5	2.60	0.25-0.45	0.30	2.0-2.5	2.19	0.25-0.5	0.38	0.13-0.3	**0.35**	-	0.05	0.5-1.5	0.78	3-15	**17.0**	30-200	**234.0**	15-300	45.0	15-60	
59 DAP	M3	3.0-3.5	2.60	0.25-0.45	0.30	2.0-2.5	2.40	0.25-0.5	0.37	0.13-0.3	**0.34**	-	0.05	0.5-1.5	0.97	3-15	**18.0**	30-200	**242.0**	15-300	39.0	15-60	
94 DAP	M1	2.75-3.5	2.80	0.25-0.45	0.30	1.75-2.25	1.99	0.25-0.5	0.29	0.13-0.3	0.16	-	0.01	0.5-1.5	**1.91**	3-15	15.0	30-200	168.0	15-300	59.0	15-60	42.0
94 DAP	M2	2.75-3.5	2.80	0.25-0.45	0.30	1.75-2.25	1.81	0.25-0.5	0.33	0.13-0.3	**0.34**	-	0.01	0.5-1.5	**1.66**	3-15	14.0	30-200	**201.0**	15-300	54.0	15-60	60.0
94 DAP	M3	2.75-3.5	2.90	0.25-0.45	0.30	1.75-2.25	2.14	0.25-0.5	0.29	0.13-0.3	0.14	-	0.01	0.5-1.5	**1.51**	3-15	15.0	30-200	174.0	15-300	60.0	15-60	47.0
94 DAP	T1	2.75-3.5	2.90	0.25-0.45	0.30	1.75-2.25	1.96	0.25-0.5	0.29	0.13-0.3	0.14	-	0.01	0.5-1.5	**1.68**	3-15	**17.0**	30-200	134.0	15-300	113.0	15-60	59.0
94 DAP	T2	2.75-3.5	2.80	0.25-0.45	0.30	1.75-2.25	1.98	0.25-0.5	0.35	0.13-0.3	0.15	-	0.01	0.5-1.5	1.43	3-15	**20.0**	30-200	173.0	15-300	107.0	15-60	53.0
94 DAP	T3	2.75-3.5	3.00	0.25-0.45	0.40	1.75-2.25	2.19	0.25-0.5	0.28	0.13-0.3	0.13	-	0.01	0.5-1.5	**1.75**	3-15	15.0	30-200	159.0	15-300	92.0	15-60	56.0
94 DAP	F1	2.75-3.5	2.90	0.25-0.45	0.40	1.75-2.25	2.23	0.25-0.5	0.25	0.13-0.3	0.15	-	0.01	0.5-1.5	**1.64**	3-15	15.0	30-200	159.0	15-300	81.0	15-60	53.0
94 DAP	F2	2.75-3.5	2.80	0.25-0.45	0.30	1.75-2.25	2.22	0.25-0.5	0.24	0.13-0.3	0.14	-	0.01	0.5-1.5	**1.57**	3-15	12.0	30-200	171.0	15-300	65.0	15-60	48.0
94 DAP	F3	2.75-3.5	2.70	0.25-0.45	0.30	1.75-2.25	1.99	0.25-0.5	0.23	0.13-0.3	0.16	-	0.01	0.5-1.5	**1.56**	3-15	14.0	30-200	144.0	15-300	80.0	15-60	47.0

Norm - Normal	M – Major
Meas - Measured	F – Pivot Fourth
	T- Tweefontein

Table B12. Plant analysis data of maize (cv. PHI 32P75) sampled at Kleinkopjé, summer 2004/2005.

Date	Site	N (%)		P (%)		K (%)		Ca (%)		Mg (%)		Na (%)		SO_4 (%)		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})	
		Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas
123 DAP	M1	2.75-3.5	2.40	0.25-0.45	0.40	1.75-2.25	1.51	0.25-0.5	0.48	0.13-0.3	**0.31**	-	0.00	0.5-1.5	**1.71**	3-15	12.0	30-200	**297.0**	15-300	134.0	15-60	**90.0**
123 DAP	M2	2.75-3.5	2.10	0.25-0.45	0.40	1.75-2.25	1.39	0.25-0.5	0.45	0.13-0.3	**0.38**	-	0.00	0.5-1.5	**1.66**	3-15	14.0	30-200	**254.0**	15-300	174.0	15-60	**96.0**
123 DAP	M3	2.75-3.5	2.40	0.25-0.45	0.30	1.75-2.25	1.57	0.25-0.5	0.40	0.13-0.3	**0.38**	-	0.01	0.5-1.5	**1.80**	3-15	15.0	30-200	**267.0**	15-300	152.0	15-60	**101.0**
123 DAP	T1	2.75-3.5	1.90	0.25-0.45	0.30	1.75-2.25	1.41	0.25-0.5	0.46	0.13-0.3	**0.50**	-	0.00	0.5-1.5	**1.83**	3-15	15.0	30-200	**375.0**	15-300	131.0	15-60	**72.0**
123 DAP	T2	2.75-3.5	1.60	0.25-0.45	0.30	1.75-2.25	1.44	0.25-0.5	0.47	0.13-0.3	**0.39**	-	0.00	0.5-1.5	**1.66**	3-15	14.0	30-200	**285.0**	15-300	158.0	15-60	**62.0**
123 DAP	T3	2.75-3.5	1.80	0.25-0.45	0.30	1.75-2.25	1.51	0.25-0.5	0.45	0.13-0.3	**0.37**	-	0.00	0.5-1.5	**1.64**	3-15	11.0	30-200	**377.0**	15-300	92.0	15-60	**62.0**
123 DAP	F1	2.75-3.5	1.90	0.25-0.45	0.30	1.75-2.25	1.31	0.25-0.5	0.40	0.13-0.3	**0.43**	-	0.00	0.5-1.5	**1.60**	3-15	12.0	30-200	**252.0**	15-300	164.0	15-60	**71.0**
123 DAP	F2	2.75-3.5	1.70	0.25-0.45	0.30	1.75-2.25	1.29	0.25-0.5	0.42	0.13-0.3	**0.36**	-	0.00	0.5-1.5	1.44	3-15	12.0	30-200	**332.0**	15-300	129.0	15-60	**78.0**
123 DAP	F3	2.75-3.5	1.80	0.25-0.45	0.28	1.75-2.25	1.31	0.25-0.5	0.39	0.13-0.3	**0.43**	-	0.00	0.5-1.5	1.42	3-15	15.0	30-200	**257.0**	15-300	197.0	15-60	**89.0**

Norm - Normal	M – Major
Meas - Measured	F – Pivot Fourth
	T- Tweefontein

Table B13. Plant analysis data of wheat (cv. SST 825) sampled at Kleinkopjé, winter 2005.

Date	Site	N (%)		P (%)		K (%)		Ca (%)		Mg (%)		Na (%)		SO_4 (%)		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})	
		Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas
13/09/2005	T1	4.0 - 5.0	2.76	0.4 - 0.7	0.40	3.2 – 4.0	0.34	0.2 - 0.5	4.57	0.15 - 0.5	0.40	-	0.12	0.66 -1.65	0.00	5-25	15.0	25-100	**192.0**	11-13	41.0	15-70	44.0
13/09/2005	T2	4.0 - 5.0	3.18	0.4 – 0.7	0.35	3.2 - 4.0	0.25	0.2 - 0.5	4.14	0.15 - 0.5	0.37	-	0.09	0.66 -1.65	0.00	5-25	12.0	25-100	**173.0**	11-13	57.0	15-70	51.0
13/09/2005	T3	4.0 - 5.0	2.98	0.4 - 0.7	0.38	3.2 – 4.0	0.30	0.2 - 0.5	3.00	0.15 - 0.5	0.35	-	0.06	0.66 -1.65	0.00	5-25	12.0	25-100	**125.0**	11-13	30.0	15-70	26.0
03/10/2005	T1	4.0 - 5.0	1.80	0.4 – 0.7	0.28	3.2 – 4.0	0.21	0.2 - 0.5	2.52	0.15 - 0.5	0.37	-	0.06	0.66 -1.65	0.00	5-25	8.0	25-100	59.0	11-13	42.0	15-70	62.0
03/10/2005	T2	4.0 - 5.0	1.18	0.4 – 0.7	0.23	3.2 - 4.0	0.25	0.2 - 0.5	2.68	0.15 - 0.5	0.43	-	0.07	0.66 -1.65	0.00	5-25	12.0	25-100	68.0	11-13	39.0	15-70	38.0
03/10/2005	T3	4.0 - 5.0	1.46	0.4 - 0.7	0.24	3.2 – 4.0	0.22	0.2 - 0.5	2.92	0.15 - 0.5	0.44	-	0.09	0.66 -1.65	0.00	5-25	11.0	25-100	86.0	11-13	29.0	15-70	38.0
13/09/2005	M1	4.0 - 5.0	1.60	0.4 – 0.7	0.28	3.2 – 4.0	0.29	0.2 - 0.5	3.51	0.15 - 0.5	0.26	-	0.06	0.66 -1.65	0.00	5-25	12.0	25-100	**110.0**	11-13	42.0	15-70	95.0
13/09/2005	M2	4.0 - 5.0	1.95	0.4 - 0.7	0.30	3.2 - 4.0	0.28	0.2 - 0.5	3.91	0.15 - 0.5	0.23	-	0.03	0.66 -1.65	0.00	5-25	14.0	25-100	**117.0**	11-13	137.0	15-70	54.0
13/09/2005	M3	4.0 - 5.0	1.73	0.4 - 0.7	0.28	3.2 - 4.0	0.33	0.2 - 0.5	3.84	0.15 - 0.5	0.27	-	0.04	0.66 -1.65	0.00	5-25	12.0	25-100	**143.0**	11-13	75.0	15-70	38.0
03/10/2005	M1	4.0 - 5.0	0.87	0.4 – 0.7	0.24	3.2 – 4.0	0.25	0.2 - 0.5	2.44	0.15 - 0.5	0.23	-	0.03	0.66 -1.65	0.00	5-25	12.0	25-100	**159.0**	11-13	57.0	15-70	36.0
03/10/2005	M2	4.0 - 5.0	0.55	0.4 - 0.7	0.24	3.2 – 4.0	0.23	0.2 - 0.5	2.29	0.15 - 0.5	0.29	-	0.03	0.66 -1.65	0.00	5-25	14.0	25-100	**150.0**	11-13	74.0	15-70	48.0
03/10/2005	M3	4.0 - 5.0	0.56	0.4 – 0.7	0.25	3.2 - 4.0	0.21	0.2 - 0.5	1.90	0.15 - 0.5	0.23	-	0.03	0.66 -1.65	0.00	5-25	12.0	25-100	95.0	11-13	74.0	15-70	29.0
13/09/2005	F1	4.0 - 5.0	2.75	0.4 – 0.7	0.29	3.2 – 4.0	0.29	0.2 - 0.5	4.08	0.15 - 0.5	0.46	-	0.07	0.66 -1.65	0.00	5-25	15.0	25-100	**128.0**	11-13	60.0	15-70	41.0
13/09/2005	F2	4.0 - 5.0	2.51	0.4 - 0.7	0.32	3.2 – 4.0	0.34	0.2 - 0.5	4.32	0.15 - 0.5	0.47	-	0.10	0.66 -1.65	0.00	5-25	14.0	25-100	**137.0**	11-13	56.0	15-70	39.0
13/09/2005	F3	4.0 - 5.0	1.52	0.4 – 0.7	0.30	3.2 - 4.0	0.33	0.2 - 0.5	3.85	0.15 - 0.5	0.48	-	0.10	0.66 -1.65	0.00	5-25	12.0	25-100	**137.0**	11-13	45.0	15-70	45.0
03/10/2005	F1	4.0 - 5.0	0.55	0.4 - 0.7	0.24	3.2 – 4.0	0.25	0.2 - 0.5	2.19	0.15 - 0.5	0.33	-	0.06	0.66 -1.65	0.00	5-25	11.0	25-100	72.0	11-13	50.0	15-70	27.0
03/10/2005	F2	4.0 - 5.0	1.07	0.4 – 0.7	0.21	3.2 – 4.0	0.22	0.2 - 0.5	2.01	0.15 - 0.5	0.31	-	0.06	0.66 -1.65	0.00	5-25	11.0	25-100	54.0	11-13	39.0	15-70	24.0
03/10/2005	F3	4.0 - 5.0	1.20	0.4 - 0.7	0.25	3.2 - 4.0	0.27	0.2 - 0.5	2.29	0.15 - 0.5	0.36	-	0.06	0.66 -1.65	0.00	5-25	11.0	25-100	69.0	11-13	47.0	15-70	38.0

Norm - Normal	M – Major
Meas - Measured	T - Tweefontein
	F – Pivot Fourth

Table B14. Plant analysis data of Wheat (cv. SST 825) sampled at Pivot Fourth, winter 2004.

Date	Site	N (%)		P (%)		K (%)		Ca (%)		Mg (%)		Na (%)		SO_4 (%)		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})	
		Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas
44 DAP	S1	4.0 - 5.0	3.1	0.4 - 0.7	0.3	3.2 – 4.0	3.58	0.2 - 0.5	0.43	0.15 - 0.5	0.34	-	0.07	0.66 -1.65	**2.55**	5-25	9.0	25-100	**240.0**	11-13	**54.0**	15-70	30.0
44 DAP	S2	4.0 - 5.0	3.4	0.4 - 0.7	0.4	3.2 – 4.0	**4.29**	0.2 - 0.5	0.45	0.15 - 0.5	0.40	-	0.08	0.66 -1.65	**2.88**	5-25	12.0	25-100	**171.0**	11-13	**59.0**	15-70	26.0
44 DAP	S3	4.0 - 5.0	3.4	0.4 - 0.7	0.4	3.2 – 4.0	**4.09**	0.2 - 0.5	0.46	0.15 - 0.5	0.39	-	0.07	0.66 -1.65	**2.70**	5-25	9.0	25-100	**245.0**	11-13	**92.0**	15-70	35.0
51 DAP	S1	4.0 - 5.0	3.6	0.4 - 0.7	0.4	3.2 – 4.0	**4.20**	0.2 - 0.5	0.36	0.15 - 0.5	0.28	-	0.03	0.66 -1.65	1.56	5-25	14.0	25-100	**110.0**	11-13	**59.0**	15-70	26.0
51 DAP	S2	4.0 - 5.0	3.2	0.4 - 0.7	0.3	3.2 – 4.0	**4.20**	0.2 - 0.5	0.44	0.15 - 0.5	0.34	-	0.04	0.66 -1.65	**1.77**	5-25	14.0	25-100	**159.0**	11-13	**62.0**	15-70	29.0
58 DAP	S1	4.0 - 5.0	2.8	0.4 - 0.7	0.3	3.2 – 4.0	2.58	0.2 - 0.5	0.29	0.15 - 0.5	0.38	-	0.06	0.66 -1.65	**1.93**	5-25	11.0	25-100	**131.0**	11-13	**138.0**	15-70	63.0
58 DAP	S2	4.0 - 5.0	2.8	0.4 - 0.7	0.2	3.2 – 4.0	2.68	0.2 - 0.5	0.37	0.15 - 0.5	0.35	-	0.06	0.66 -1.65	**2.10**	5-25	11.0	25-100	**111.0**	11-13	**122.0**	15-70	54.0
58 DAP	S3	4.0 - 5.0	3.5	0.4 - 0.7	0.4	3.2 – 4.0	2.56	0.2 - 0.5	0.38	0.15 - 0.5	0.45	-	0.07	0.66 -1.65	**2.40**	5-25	9.0	25-100	**137.0**	11-13	**156.0**	15-70	54.0
74 DAP	S1	4.0 - 5.0	1.5	0.4 - 0.7	0.2	3.2 – 4.0	2.79	0.2 - 0.5	0.23	0.15 - 0.5	0.28	-	0.04	0.66 -1.65	1.42	5-25	9.0	25-100	71.0	11-13	**98.0**	15-70	33.0
74 DAP	S2	4.0 - 5.0	1.4	0.4 - 0.7	0.2	3.2 – 4.0	2.56	0.2 - 0.5	0.24	0.15 - 0.5	0.26	-	0.04	0.66 -1.65	1.46	5-25	11.0	25-100	74.0	11-13	**77.0**	15-70	32.0
74 DAP	S3	4.0 - 5.0	1.4	0.4 - 0.7	0.3	3.2 – 4.0	2.47	0.2 - 0.5	0.26	0.15 - 0.5	0.32	-	0.05	0.66 -1.65	1.62	5-25	12.0	25-100	72.0	11-13	**96.0**	15-70	38.0
93 DAP	S1	4.0 - 5.0	1.3	0.4 - 0.7	0.3	3.2 – 4.0	1.49	0.2 - 0.5	0.18	0.15 - 0.5	0.27	-	0.06	0.66 -1.65	1.56	5-25	14.0	25-100	38.0	11-13	**84.0**	15-70	14.0
93 DAP	S2	4.0 - 5.0	1.2	0.4 - 0.7	0.2	3.2 – 4.0	1.38	0.2 - 0.5	0.19	0.15 - 0.5	0.27	-	0.06	0.66 -1.65	1.48	5-25	14.0	25-100	75.0	11-13	**56.0**	15-70	20.0
93 DAP	S3	4.0 - 5.0	1.7	0.4 - 0.7	0.3	3.2 – 4.0	2.22	0.2 - 0.5	0.28	0.15 - 0.5	0.44	-	0.08	0.66 -1.65	**2.34**	5-25	17.0	25-100	92.0	11-13	**102.0**	15-70	12.0

Norm - Normal
Meas - Measured

Table B15. Plant analysis data of Maize (cv. PHI 32P75) sampled at Pivot Forth, summer 2004/2005.

Date	Site	N (%)		P (%)		K (%)		Ca (%)		Mg (%)		Na (%)		SO_4 (%)		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})	
		Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas
45 DAP	S1	2.75-3.5	1.9	0.25-0.45	0.2	1.75-2.25	**2.83**	0.25-0.5	0.46	0.13-0.3	**0.36**	-	0.00	0.5-1.5	**1.73**	3-15	11.0	30-200	**218.0**	15-300	56.0	15-60	32.0
45 DAP	S2	2.75-3.5	1.5	0.25-0.45	0.1	1.75-2.25	**3.04**	0.25-0.5	0.42	0.13-0.3	**0.39**	-	0.00	0.5-1.5	**2.01**	3-15	11.0	30-200	**210.0**	15-300	63.0	15-60	24.0
45 DAP	S3	2.75-3.5	1.6	0.25-0.45	0.1	1.75-2.25	**2.55**	0.25-0.5	0.38	0.13-0.3	0.28	-	0.01	0.5-1.5	**1.63**	3-15	9.0	30-200	**231.0**	15-300	50.0	15-60	27.0
67 DAP	S1	2.75-3.5	2.2	0.25-0.45	0.2	1.75-2.25	1.78	0.25-0.5	0.25	0.13-0.3	0.31	-	0.01	0.5-1.5	1.36	3-15	11.0	30-200	**209.0**	15-300	26.0	15-60	35.0
67 DAP	S2	2.75-3.5	3.0	0.25-0.45	0.2	1.75-2.25	1.46	0.25-0.5	0.20	0.13-0.3	0.26	-	0.00	0.5-1.5	0.76	3-15	12.0	30-200	129.0	15-300	33.0	15-60	36.0
67 DAP	S3	2.75-3.5	2.9	0.25-0.45	0.2	1.75-2.25	2.02	0.25-0.5	0.21	0.13-0.3	0.24	-	0.00	0.5-1.5	1.18	3-15	11.0	30-200	168.0	15-300	32.0	15-60	32.0
92 DAP	S1	2.75-3.5	2.6	0.25-0.45	0.2	1.75-2.25	1.13	0.25-0.5	**0.51**	0.13-0.3	**0.58**	-	0.04	0.5-1.5	**2.01**	3-15	**23.0**	30-200	**285.0**	15-300	**419.0**	15-60	**87.0**
92 DAP	S2	2.75-3.5	2.6	0.25-0.45	0.2	1.75-2.25	1.05	0.25-0.5	**0.71**	0.13-0.3	**0.57**	-	0.04	0.5-1.5	**2.17**	3-15	**29.0**	30-200	**258.0**	15-300	132.0	15-60	**84.0**
92 DAP	S3	2.75-3.5	2.9	0.25-0.45	0.3	1.75-2.25	1.06	0.25-0.5	**0.68**	0.13-0.3	**0.64**	-	0.04	0.5-1.5	**2.19**	3-15	**23.0**	30-200	**225.0**	15-300	179.0	15-60	**86.0**

Norm - Normal
Meas - Measured

Table B16. Plant analysis data of wheat (cv. SST 825) sampled at Major, winter 2004.

Date	Site	N (%)		P (%)		K (%)		Ca (%)		Mg (%)		Na (%)		SO_4 (%)		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})	
		Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas
51 DAP	S1	4.0 - 5.0	3.5	0.4 - 0.7	0.4	3.2 – 4.0	4.50	0.2 - 0.5	0.45	0.15 - 0.5	0.28	-	0.02	0.66 -1.65	**2.40**	5-25	17.0	25-100	**213.0**	11-13	**102.0**	15-70	42.0
51 DAP	S2	4.0 - 5.0	2.8	0.4 - 0.7	0.3	3.2 – 4.0	2.26	0.2 - 0.5	0.44	0.15 - 0.5	0.34	-	0.02	0.66 -1.65	**2.55**	5-25	17.0	25-100	**230.0**	11-13	**119.0**	15-70	36.0
51 DAP	S3	4.0 - 5.0	2.5	0.4 - 0.7	0.3	3.2 – 4.0	3.88	0.2 - 0.5	0.45	0.15 - 0.5	0.28	-	0.03	0.66 -1.65	**2.01**	5-25	14.0	25-100	**237.0**	11-13	**146.0**	15-70	39.0
74 DAP	S1	4.0 - 5.0	2.5	0.4 - 0.7	0.1	3.2 – 4.0	2.37	0.2 - 0.5	0.24	0.15 - 0.5	0.29	-	0.02	0.66 -1.65	1.55	5-25	9.0	25-100	**104.0**	11-13	**90.0**	15-70	44.0
74 DAP	S2	4.0 - 5.0	3.5	0.4 - 0.7	0.1	3.2 – 4.0	3.34	0.2 - 0.5	0.39	0.15 - 0.5	0.40	-	0.02	0.66 -1.65	**1.74**	5-25	11.0	25-100	**131.0**	11-13	**107.0**	15-70	42.0
74 DAP	S3	4.0 - 5.0	2.6	0.4 - 0.7	0.3	3.2 – 4.0	3.25	0.2 - 0.5	0.24	0.15 - 0.5	0.32	-	0.02	0.66 -1.65	**1.71**	5-25	12.0	25-100	**116.0**	11-13	**161.0**	15-70	44.0
93 DAP	S1	4.0 - 5.0	1.1	0.4 - 0.7	0.2	3.2 – 4.0	1.62	0.2 - 0.5	0.16	0.15 - 0.5	0.20	-	0.01	0.66 -1.65	1.19	5-25	18.0	25-100	93.0	11-13	**93.0**	15-70	21.0
93 DAP	S2	4.0 - 5.0	1.4	0.4 - 0.7	0.2	3.2 – 4.0	1.83	0.2 - 0.5	0.18	0.15 - 0.5	0.24	-	0.01	0.66 -1.65	1.29	5-25	23.0	25-100	**107.0**	11-13	**131.0**	15-70	35.0
93 DAP	S3	4.0 - 5.0	1.2	0.4 - 0.7	0.2	3.2 – 4.0	1.53	0.2 - 0.5	0.17	0.15 - 0.5	0.23	-	0.01	0.66 -1.65	0.99	5-25	21.0	25-100	**1160**	11-13	**134.0**	15-70	23.0

Norm - Normal
Meas - Measured

Table B17. Plant analysis data of Maize (cv. PHI 32P75) sampled at Major, summer 2004/2005.

Date	Site	N (%)		P (%)		K (%)		Ca (%)		Mg (%)		Na (%)		SO_4 (%)		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})	
		Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas
67 DAP	S1	2.75-3.5	2.6	0.25-0.45	0.2	1.75-2.25	2.14	0.25-0.5	0.39	0.13-0.3	**0.34**	-	0.01	0.5-1.5	**2.53**	3-15	14.0	30-200	144.0	15-300	33.0	15-60	39.0
67 DAP	S2	2.75-3.5	3.1	0.25-0.45	0.3	1.75-2.25	2.40	0.25-0.5	0.32	0.13-0.3	0.23	-	0.01	0.5-1.5	1.46	3-15	**17.0**	30-200	135.0	15-300	35.0	15-60	48.0
67 DAP	S3	2.75-3.5	3.3	0.25-0.45	0.3	1.75-2.25	**2.28**	0.25-0.5	0.40	0.13-0.3	0.22	-	0.00	0.5-1.5	**2.00**	3-15	15.0	30-200	128.0	15-300	54.0	15-60	32.0
92 DAP	S1	2.75-3.5	2.6	0.25-0.45	0.3	1.75-2.25	1.68	0.25-0.5	0.38	0.13-0.3	**0.37**	-	0.04	0.5-1.5	**1.94**	3-15	**17.0**	30-200	**360.0**	15-300	65.0	15-60	**84.0**
92 DAP	S2	2.75-3.5	2.7	0.25-0.45	0.3	1.75-2.25	1.62	0.25-0.5	0.35	0.13-0.3	**0.31**	-	0.03	0.5-1.5	**1.74**	3-15	**17.0**	30-200	**273.0**	15-300	60.0	15-60	57.0
92 DAP	S3	2.75-3.5	2.9	0.25-0.45	0.3	1.75-2.25	1.72	0.25-0.5	0.31	0.13-0.3	**0.34**	-	0.04	0.5-1.5	**2.03**	3-15	15.0	30-200	**270.0**	15-300	80.0	15-60	63.0

Norm - Normal
Meas - Measured

Table B18. Plant analysis data of Wheat (cv. SST 825) sampled at Tweefontein, Winter 2004.

Date	Site	N (%)		P (%)		K (%)		Ca (%)		Mg (%)		Na (%)		SO_4 (%)		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})	
		Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas
44 DAP	S1	4.0 - 5.0	3.3	0.4 - 0.7	0.4	3.2 – 4.0	**4.17**	0.2 - 0.5	0.36	0.15 - 0.5	0.24	-	0.03	0.66 -1.65	**2.00**	5-25	11.0	25-100	**263.0**	11-13	**48.0**	15-70	41.0
44 DAP	S2	4.0 - 5.0	2.9	0.4 - 0.7	0.3	3.2 – 4.0	3.76	0.2 - 0.5	0.24	0.15 - 0.5	0.27	-	0.02	0.66 -1.65	**1.82**	5-25	12.0	25-100	**219.0**	11-13	**38.0**	15-70	35.0
44 DAP	S3	4.0 - 5.0	3.0	0.4 - 0.7	0.4	3.2 – 4.0	3.82	0.2 - 0.5	0.37	0.15 - 0.5	0.25	-	0.03	0.66 -1.65	**2.24**	5-25	12.0	25-100	**362.0**	11-13	**72.0**	15-70	41.0
51 DAP	S1	4.0 - 5.0	2.1	0.4 - 0.7	0.4	3.2 – 4.0	3.25	0.2 - 0.5	0.33	0.15 - 0.5	0.43	-	0.06	0.66 -1.65	**2.47**	5-25	17.0	25-100	**152.0**	11-13	**41.0**	15-70	38.0
51 DAP	S2	4.0 - 5.0	2.8	0.4 - 0.7	0.4	3.2 – 4.0	3.30	0.2 - 0.5	0.41	0.15 - 0.5	0.38	-	0.06	0.66 -1.65	**2.24**	5-25	15.0	25-100	**150.0**	11-13	**191.0**	15-70	39.0
51 DAP	S3	4.0 - 5.0	3.2	0.4 - 0.7	0.5	3.2 – 4.0	**4.20**	0.2 - 0.5	0.41	0.15 - 0.5	0.40	-	0.07	0.66 -1.65	**2.18**	5-25	14.0	25-100	**149.0**	11-13	**47.0**	15-70	42.0
58 DAP	S1	4.0 - 5.0	3.0	0.4 - 0.7	0.3	3.2 – 4.0	3.37	0.2 - 0.5	0.38	0.15 - 0.5	0.40	-	0.07	0.66 -1.65	**2.75**	5-25	9.0	25-100	**240.0**	11-13	**54.0**	15-70	57.0
58 DAP	S2	4.0 - 5.0	2.9	0.4 - 0.7	0.3	3.2 – 4.0	2.64	0.2 - 0.5	0.34	0.15 - 0.5	0.39	-	0.07	0.66 -1.65	**2.38**	5-25	9.0	25-100	**177.0**	11-13	**45.0**	15-70	50.0
58 DAP	S3	4.0 - 5.0	3.5	0.4 - 0.7	0.2	3.2 – 4.0	2.71	0.2 - 0.5	0.36	0.15 - 0.5	0.43	-	0.08	0.66 -1.65	**2.76**	5-25	12.0	25-100	**206.0**	11-13	**45.0**	15-70	51.0
74 DAP	S1	4.0 - 5.0	2.3	0.4 - 0.7	0.3	3.2 – 4.0	2.41	0.2 - 0.5	0.18	0.15 - 0.5	0.40	-	0.05	0.66 -1.65	1.52	5-25	11.0	25-100	87.0	11-13	**74.0**	15-70	47.0
74 DAP	S2	4.0 - 5.0	2.8	0.4 - 0.7	0.4	3.2 – 4.0	2.59	0.2 - 0.5	0.21	0.15 - 0.5	0.37	-	0.05	0.66 -1.65	**1.74**	5-25	14.0	25-100	71.0	11-13	**42.0**	15-70	59.0
74 DAP	S3	4.0 - 5.0	2.3	0.4 - 0.7	0.2	3.2 – 4.0	2.26	0.2 - 0.5	0.22	0.15 - 0.5	0.40	-	0.06	0.66 -1.65	**1.87**	5-25	11.0	25-100	99.0	11-13	**51.0**	15-70	50.0
93 DAP	S1	4.0 - 5.0	1.4	0.4 - 0.7	0.3	3.2 – 4.0	1.68	0.2 - 0.5	0.17	0.15 - 0.5	0.28	-	0.08	0.66 -1.65	**2.03**	5-25	15.0	25-100	**104.0**	11-13	**69.0**	15-70	30.0
93 DAP	S2	4.0 - 5.0	1.2	0.4 - 0.7	0.3	3.2 – 4.0	1.39	0.2 - 0.5	0.23	0.15 - 0.5	0.26	-	0.08	0.66 -1.65	1.49	5-25	17.0	25-100	66.0	11-13	**71.0**	15-70	26.0
93 DAP	S3	4.0 - 5.0	1.5	0.4 - 0.7	0.3	3.2 – 4.0	1.63	0.2 - 0.5	0.19	0.15 - 0.5	0.32	-	0.08	0.66 -1.65	**2.05**	5-25	20.0	25-100	87.0	11-13	**44.0**	15-70	32.0

Norm - Normal
Meas - Measured

Table B19. Plant analysis data of Maize (cv. PHI 32P75) sampled at Tweefontein, summer 2004/2005.

Date	Site	N (%)		P (%)		K (%)		Ca (%)		Mg (%)		Na (%)		SO_4 (%)		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})	
		Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas
45 DAP	S1	2.75-3.5	2.0	0.25-0.45	0.1	1.75-2.25	**3.61**	0.25-0.5	**0.54**	0.13-0.3	**0.45**	-	0.02	0.5-1.5	**2.95**	3-15	12.0	30-200	**305.0**	15-300	48.0	15-60	51.0
45 DAP	S2	2.75-3.5	2.1	0.25-0.45	0.1	1.75-2.25	**3.18**	0.25-0.5	0.35	0.13-0.3	0.30	-	0.01	0.5-1.5	**2.37**	3-15	12.0	30-200	**258.0**	15-300	48.0	15-60	50.0
45 DAP	S3	2.75-3.5	2.0	0.25-0.45	0.1	1.75-2.25	**2.88**	0.25-0.5	0.41	0.13-0.3	**0.36**	-	0.00	0.5-1.5	**2.66**	3-15	14.0	30-200	**317.0**	15-300	63.0	15-60	54.0
67 DAP	S1	2.75-3.5	2.4	0.25-0.45	0.2	1.75-2.25	2.08	0.25-0.5	0.21	0.13-0.3	**0.36**	-	0.01	0.5-1.5	1.26	3-15	14.0	30-200	**225.0**	15-300	39.0	15-60	44.0
67 DAP	S2	2.75-3.5	1.9	0.25-0.45	0.2	1.75-2.25	**2.26**	0.25-0.5	0.27	0.13-0.3	**0.42**	-	0.01	0.5-1.5	**2.55**	3-15	14.0	30-200	**236.0**	15-300	32.0	15-60	42.0
67 DAP	S3	2.75-3.5	2.2	0.25-0.45	0.1	1.75-2.25	2.04	0.25-0.5	0.21	0.13-0.3	**0.40**	-	0.00	0.5-1.5	**1.58**	3-15	14.0	30-200	**215.0**	15-300	39.0	15-60	47.0
92 DAP	S1	2.75-3.5	2.7	0.25-0.45	0.3	1.75-2.25	1.32	0.25-0.5	0.46	0.13-0.3	**0.58**	-	0.06	0.5-1.5	**2.16**	3-15	15.0	30-200	**219.0**	15-300	120.0	15-60	**83.0**
92 DAP	S2	2.75-3.5	2.8	0.25-0.45	0.3	1.75-2.25	1.51	0.25-0.5	0.42	0.13-0.3	**0.63**	-	0.06	0.5-1.5	**2.35**	3-15	15.0	30-200	**230.0**	15-300	104.0	15-60	**87.0**
92 DAP	S3	2.75-3.5	2.5	0.25-0.45	0.4	1.75-2.25	1.29	0.25-0.5	0.43	0.13-0.3	**0.59**	-	0.07	0.5-1.5	**2.10**	3-15	14.0	30-200	**263.0**	15-300	104.0	15-60	**83.0**

Norm - Normal
Meas - Measured

Table B20. Plant analysis data of grasses sampled at Syferfontein, Summer 2001/2002.

Date	Site	N (%)		P (%)		K (%)		Ca (%)		Mg (%)		Na (%)		SO_4 (%)		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})	
		Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas
28/11/2001	S1	2.8-3.8	5.19	0.26-0.40	0.35	2.5-3.5	4.15		0.77		0.79		0.00		2.01		9.0		618.0		251.0		33.0
28/11/2001	S2	3.0-5.0	5.28	0.25-0.70	0.37	2.0-3.5	3.55	0.8-3.0	1.27	0.25-1.0	1.04	-	0.00	0.25-0.50	2.08	4-30	11.0	30-250	819.0	25-100	137.0	20-70	30.0
28/11/2001	S3	2.8-3.8	4.99	0.26-0.40	0.33	2.5-3.5	3.62		1.51		1.17		0.00		2.39		11.0		434.0		168.0		33.0
28/11/2001	S4		5.19		0.31		4.26		0.90		0.95		0.00		1.70		11.0		633.0		456.0		51.0
28/11/2001	S5		5.08		0.36		5.43		0.98		0.94		0.01		1.19		11.0		596.0		212.0		38.0

Norm – Normal
Meas –Measured

Table B21. Plant analysis data of grasses sampled at Syferfontein, summer 2003/2004.

Date	Site	N (%)		P (%)		K (%)		Ca (%)		Mg (%)		Na (%)		SO_4 (%)		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})	
		Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas
29/01/2004	S1	2.8-3.8	1.80	0.26-0.40	0.30	2.5-3.5	1.66		0.22		0.41	-	1.09		1.76		11.0		101.0		77.0		36.0
29/01/2004	S2	3.0-5.0	1.90	0.25-0.70	0.30	2.0-3.5	1.63	0.8-3.0	0.21	0.25-1.0	0.42	-	1.24	0.25-0.50	1.46	4-30	11.0	30-250	74.0	25-100	75.0	20-70	27.0
29/01/2004	S3	2.8-3.8	2.00	0.26-0.40	0.40	2.5-3.5	2.16		0.24		0.38	-	0.57		1.75		12.0		69.0		81.0		27.0
29/01/2004	S1	2.8-3.8	1.90	0.26-0.40	0.20	2.5-3.5	2.14		0.25		0.37	-	0.49		1.73		11.0		131.0		95.0		17.0
29/01/2004	S2	3.0-5.0	1.80	0.25-0.70	0.30	2.0-3.5	2.22	0.8-3.0	0.26	0.25-1.0	0.35	-	0.42	0.25-0.50	1.67	4-30	11.0	30-250	68.0	25-100	92.0	20-70	23.0
29/01/2004	S3	2.8-3.8	1.80	0.26-0.40	0.30	2.5-3.5	2.14		0.26		0.42	-	0.48		1.76		11.0		56.0		104.0		20.0
29/01/2004	S1	2.8-3.8	1.60	0.26-0.40	0.60	2.5-3.5	2.68		0.23		0.35	-	0.22		1.32		14.0		68.0		53.0		45.0
29/01/2004	S2	3.0-5.0	2.00	0.25-0.70	0.60	2.0-3.5	3.06	0.8-3.0	0.26	0.25-1.0	0.39	-	0.16	0.25-0.50	1.61	4-30	15.0	30-250	90.0	25-100	54.0	20-70	54.0
29/01/2004	S3	2.8-3.8	1.80	0.26-0.40	0.60	2.5-3.5	2.86		0.27		0.40	-	0.22		1.58		12.0		86.0		48.0		48.0

Table B22. Plant analysis data of grasses sampled at Syferfontein, summer 2004.

Date	Site	N (%)		P (%)		K (%)		Ca (%)		Mg (%)		Na (%)		SO_4 (%)		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})	
		Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas
04/03/2004	ST1 S1	2.8-3.8	1.80	0.26-0.40	0.40	2.5-3.5	2.67		0.24		0.41		0.63		1.67		8.0		108.0		68.0		50.0
04/03/2004	ST1 S2	2.8-3.8	1.70	0.26-0.40	0.30	2.5-3.5	2.62		0.23		0.40		0.61		1.60		6.0		108.0		62.0		45.0
04/03/2004	ST1 S3	2.8-3.8	1.60	0.26-0.40	0.30	2.5-3.5	2.17		0.25		0.42		0.73		1.82		6.0		96.0		80.0		42.0
04/03/2004	ST2 S1	3.0-5.0	3.70	0.25-0.70	0.20	2.0-3.5	2.01	0.8-3.0	0.68	0.25-1.0	0.27	-	-149.86	0.25-0.50	1.23	4-30	11.0	30-250	116.0	25-100	38.0	20-70	56.0
04/03/2004	ST2 S2	3.0-5.0	4.00	0.25-0.70	0.20	2.0-3.5	2.26	0.8-3.0	0.65	0.25-1.0	0.30	-	0.70	0.25-0.50	0.92	4-30	11.0	30-250	147.0	25-100	36.0	20-70	44.0
04/03/2004	ST2 S3	3.0-5.0	4.00	0.25-0.70	0.20	2.0-3.5	2.17	0.8-3.0	0.87	0.25-1.0	0.33	-	0.80	0.25-0.50	1.37	4-30	12.0	30-250	126.0	25-100	48.0	20-70	63.0
04/03/2004	ST3 S1	2.8-3.8	1.20	0.26-0.40	0.20	2.5-3.5	1.83		0.33		0.45		0.39		1.66		6.0		101.0		122.0		24.0
04/03/2004	ST3 S2	2.8-3.8	1.50	0.26-0.40	0.20	2.5-3.5	2.29		0.25		0.38		0.57		1.40		6.0		93.0		101.0		38.0
04/03/2004	ST3 S3	2.8-3.8	1.40	0.26-0.40	0.20	2.5-3.5	1.96		0.29		0.48		0.52		1.70		5.0		78.0		107.0		27.0
04/03/2004	ST5 S1		1.30		0.40		2.53		0.24		0.15		0.22		0.91		9.0		461.0		68.0		51.0
04/03/2004	ST5 S2		1.30		0.40		2.73		0.23		0.14		0.11		0.61		11.0		446.0		53.0		57.0
04/03/2004	ST5 S3		1.20		0.40		2.67		0.26		0.40		0.16		0.80		9.0		984.0		80.0		69.0

Norm - Normal
Meas - Measured

Table B23. Plant analysis data of maize (cv. PHB 3203) sampled at New Vaal, Summer 2001/2002.

Growth stage	Plant part sampled	N (%)		P (%)		K (%)		Ca (%)		Mg (%)		Na (%)		SO_4 (%)		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})	
		Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas
41 DAP	YL	2.75-3.5	2.57	0.25-0.45	0.34	1.75-2.25	**2.65**	0.25-0.5	0.35	0.13-0.3	0.18	-	0.00	0.5-1.5	0.75	3-15	**30.0**	30-200	99.0	15-300	23.0	15-60	32.0
81 DAP	YL	2.75-3.5	2.75	0.25-0.45	0.32	1.75-2.25	1.24	0.25-0.5	**0.54**	0.13-0.3	0.28	-	0.01	0.5-1.5	0.65	3-15	**2.0**	30-200	192.0	15-300	45.0	15-60	**78.0**
81 DAP	YL	2.75-3.5	2.41	0.25-0.45	0.25	1.75-2.25	1.14	0.25-0.5	**0.53**	0.13-0.3	0.28	-	0.01	0.5-1.5	0.63	3-15	**2.0**	30-200	129.0	15-300	38.0	15-60	54.0
81 DAP	YL	2.75-3.5	2.71	0.25-0.45	0.17	1.75-2.25	1.15	0.25-0.5	**0.55**	0.13-0.3	**0.33**	-	0.00	0.5-1.5	0.64	3-15	3**.0**	30-200	108.0	15-300	21.0	15-60	38.0
81 DAP	YL	2.75-3.5	2.57	0.25-0.45	0.22	1.75-2.25	1.10	0.25-0.5	**0.53**	0.13-0.3	**0.34**	-	0.01	0.5-1.5	0.53	3-15	**-4.50**	30-200	141.0	15-300	32.0	15-60	48.0
96 DAP	YL	2.75-3.5	2.63	0.25-0.45	0.16	1.75-2.25	1.53	0.25-0.5	**0.53**	0.13-0.3	0.28	-	0.08	0.5-1.5	0.54	3-15	5.0	30-200	185.0	15-300	54.0	15-60	36.0
96 DAP	YL	2.75-3.5	2.56	0.25-0.45	0.16	1.75-2.25	1.46	0.25-0.5	0.48	0.13-0.3	0.28	-	0.07	0.5-1.5	0.39	3-15	8.0	30-200	**210.0**	15-300	41.0	15-60	24.0
96 DAP	YL	2.75-3.5	2.79	0.25-0.45	0.22	1.75-2.25	1.93	0.25-0.5	**0.54**	0.13-0.3	0.30	-	0.10	0.5-1.5	0.51	3-15	8.0	30-200	**201.0**	15-300	33.0	15-60	35.0
96 DAP	YL	2.75-3.5	3.08	0.25-0.45	0.24	1.75-2.25	1.98	0.25-0.5	0.44	0.13-0.3	0.27	-	0.08	0.5-1.5	0.54	3-15	8.0	30-200	**201.0**	15-300	35.0	15-60	36.0

DAP - Days after planting	Norm - Normal
YL – Young leaves	Meas - Measured

Table B24. Plant analysis data of Peas sampled at New Vaal, winter 2003.

Date	Site	N (%)		P (%)		K (%)		Ca (%)		Mg (%)		Na (%)		SO_4 (%)		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})	
		Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas
26 DAP	N1	3.1-4.8	3.70	0.25-0.35	0.30	1.5-3.0	2.80	1.15-2.5	0.95	0.25-0.4	0.43	-	0.15	0.2-0.4	1.00	4-10	6.0	220-245	87.0	35-100	59.0	25-61	110.0
26 DAP	N2	3.1-4.8	3.80	0.25-0.35	0.30	1.5-3.0	2.61	1.15-2.5	1.02	0.25-0.4	0.47	-	0.12		1.16	4-10	18.0	220-245	162.0	35-100	74.0	25-61	128.0
26 DAP	N3	3.1-4.8	4.20	0.25-0.35	0.30	1.5-3.0	2.79	1.15-2.5	0.86	0.25-0.4	0.47	-	0.22		0.78	4-10	5.0	220-245	212.0	35-100	72.0	25-61	156.0
77 DAP	N1	2.7-4.8	4.10	0.25-0.35	0.30	1.5-3.0	1.56	1.15-2.5	1.41	0.25-0.4	0.51	-	0.17		1.78	4-10	8.0	220-245	228.0	35-100	60.0	25-61	137.0
77 DAP	N2	2.7-4.8	4.20	0.25-0.35	0.30	1.5-3.0	1.62	1.15-2.5	1.22	0.25-0.4	0.46	-	0.13		1.77	4-10	6.0	220-245	162.0	35-100	56.0	25-61	128.0
77 DAP	N3	2.7-4.8	4.20	0.25-0.35	0.30	1.5-3.0	1.57	1.15-2.5	1.26	0.25-0.4	0.46	-	0.10		1.98	4-10	8.0	220-245	120.0	35-100	54.0	25-61	113.0
89 DAP	N1	2.7-4.8	4.50	0.25-0.35	0.30	1.5-3.0	2.37	1.15-2.5	1.59	0.25-0.4	0.44	-	0.10		3.03	4-10	20.0	220-245	201.0	35-100	62.0	25-61	71.0
89 DAP	N2	2.7-4.8	4.20	0.25-0.35	0.20	1.5-3.0	2.31	1.15-2.5	1.58	0.25-0.4	0.43	-	0.10		2.93	4-10	15.0	220-245	90.0	35-100	59.0	25-61	53.0
89 DAP	N3	2.7-4.8	4.30	0.25-0.35	0.20	1.5-3.0	2.86	1.15-2.5	1.61	0.25-0.4	0.56	-	0.14		3.07	4-10	15.0	220-245	80.0	35-100	90.0	25-61	123.0

Norm - Normal
Meas - Measured

Table B25. Plant analysis data of Sweetcorn New Vaal, summer 2003/2004.

Date	Site	N (%)		P (%)		K (%)		Ca (%)		Mg (%)		Na (%)		SO_4 (%)		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})	
		Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas
41 DAP	N3 Acc cub	2.6-3.38	2.50	0.14-0.56	0.30	1.8-3.64	2.29	0.15-2.5	0.48	0.15-0.8	0.43	-	0.14		1.39	8-12	15.0	60-160	447.0	20-100	44.0	20-40	23.0
41 DAP	N1	2.6-3.38	2.70	0.14-0.56	0.30	1.8-3.64	1.77	0.15-2.5	0.54	0.15-0.8	0.46	-	0.04		1.47	8-12	17.0	60-160	213.0	20-100	32.0	20-40	42.0
41 DAP	N2	2.6-3.38	2.80	0.14-0.56	0.30	1.8-3.64	2.14	0.15-2.5	0.41	0.15-0.8	0.39	-	0.04		1.44	8-12	12.0	60-160	213.0	20-100	32.0	20-40	41.0
41 DAP	N3	2.6-3.38	2.80	0.14-0.56	0.30	1.8-3.64	1.89	0.15-2.5	0.47	0.15-0.8	0.40	-	0.02		1.10	8-12	15.0	60-160	180.0	20-100	48.0	20-40	41.0
41 DAP	N1Acc cub	2.6-3.38	2.50	0.14-0.56	0.30	1.8-3.64	2.31	0.15-2.5	0.50	0.15-0.8	0.48	-	0.15		1.49	8-12	15.0	60-160	447.0	20-100	44.0	20-40	29.0
41 DAP	N2 Acc cub	2.6-3.38	2.50	0.14-0.56	0.30	1.8-3.64	2.25	0.15-2.5	0.52	0.15-0.8	0.48	-	0.12		1.34	8-12	12.0	60-160	432.0	20-100	44.0	20-40	24.0
71 DAP	N1	2.6-3.38	6.00	0.14-0.56	0.80	1.8-3.64	3.99	0.15-2.5	2.34	0.15-0.8	0.56	-	0.00		0.43	8-12	17.0	60-160	566.0	20-100	59.0	20-40	84.0
71 DAP	N2	2.6-3.38	5.20	0.14-0.56	0.70	1.8-3.64	3.13	0.15-2.5	4.95	0.15-0.8	0.87	-	0.00		0.22	8-12	26.0	60-160	1007.0	20-100	66.0	20-40	75.0
71 DAP	N3	2.6-3.38	4.00	0.14-0.56	0.50	1.8-3.64	3.96	0.15-2.5	3.33	0.15-0.8	0.8	-	0.00		0.45	8-12	21.0	60-160	563.0	20-100	69.0	20-40	72.0
93 DAP	N1	2.6-3.38	3.90	0.14-0.56	0.40	1.8-3.64	2.83	0.15-2.5	1.64	0.15-0.8	0.46	-	0.01		0.59	8-12	6.0	60-160	650.0	20-100	92.0	20-40	69.0
93 DAP	N2	2.6-3.38	3.70	0.14-0.56	0.60	1.8-3.64	2.38	0.15-2.5	2.06	0.15-0.8	0.48	-	0.00		0.47	8-12	6.0	60-160	504.0	20-100	83.0	20-40	53.0
93 DAP	N3	2.6-3.38	3.80	0.14-0.56	0.50	1.8-3.64	2.71	0.15-2.5	1.43	0.15-0.8	0.43	-	0.01		0.64	8-12	9.0	60-160	380.0	20-100	48.0	20-40	54.0

Norm - Normal
Meas - Measured

Table B26. Plant analysis data of Soybean sampled at New Vaal, summer 2004/2005.

Date	Site	N (%)		P (%)		K (%)		Ca (%)		Mg (%)		Na (%)		SO_4 (%)		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})	
		Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas	Norm	Meas
31 DAP	S1	3.5-5.5	5.9	0.3-0.6	0.02	1.7-2.5	2.58	1.1-2.2	0.89	0.03-0.6	0.46	-	0.00	0.25-0.60	0.80	4-30	47.0	20-300	215.0	17-100	54.0	21-80	77.0
31 DAP	S2	3.5-5.5	5.3	0.3-0.6	0.2	1.7-2.5	2.21	1.1-2.2	0.99	0.03-0.6	0.53	-	0.00	0.25-0.60	0.69	4-30	38.0	20-300	204.0	17-100	54.0	21-80	39.0
31 DAP	S3	3.5-5.5	2.5	0.3-0.6	0.2	1.7-2.5	1.68	1.1-2.2	0.92	0.03-0.6	0.39	-	0.00	0.25-0.60	1.55	4-30	42.0	20-300	174.0	17-100	62.0	21-80	32.0
40 DAP	S1	3.5-5.5	4.8	0.3-0.6	0.2	1.7-2.5	2.12	1.1-2.2	0.88	0.03-0.6	0.42	-	0.00	0.25-0.60	1.46	4-30	33.0	20-300	222.0	17-100	78.0	21-80	38.0
40 DAP	S2	3.5-5.5	5.6	0.3-0.6	0.3	1.7-2.5	2.01	1.1-2.2	0.95	0.03-0.6	0.45	-	0.00	0.25-0.60	1.26	4-30	39.0	20-300	215.0	17-100	36.0	21-80	30.0
40 DAP	S3	3.5-5.5	4.0	0.3-0.6	0.3	1.7-2.5	2.36	1.1-2.2	1.09	0.03-0.6	0.46	-	0.00	0.25-0.60	1.38	4-30	45.0	20-300	221.0	17-100	45.0	21-80	83.0
51 DAP	S1	3.5-5.5	2.2	0.3-0.6	0.1	1.7-2.5	2.35	1.1-2.2	0.92	0.03-0.6	0.43	-	0.01	0.25-0.60	1.38	4-30	9.0	20-300	213.0	17-100	54.0	21-80	92.0
51 DAP	S2	3.5-5.5	2.3	0.3-0.6	0.1	1.7-2.5	2.26	1.1-2.2	1.23	0.03-0.6	0.49	-	0.01	0.25-0.60	1.00	4-30	8.0	20-300	173.0	17-100	62.0	21-80	74.0
51 DAP	S3	3.5-5.5	1.2	0.3-0.6	0.2	1.7-2.5	1.78	1.1-2.2	1.01	0.03-0.6	0.42	-	0.01	0.25-0.60	1.47	4-30	9.0	20-300	180.0	17-100	50.0	21-80	56.0

Norm - Normal
Meas - Measured

Appendix C

Soil chemical analyses

Table C1. Results of chemical analysis of soil samples from Kleinkopjé (maize crop, begin 2000/2001 summer season, Soil Science Laboratory, University of Pretoria).

						Soluble Cations				Exchangeable cations				
Pivot	Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
Major	M1	0-20	5.3	76	32.59	1.133	0.134	0.152	0.015	1.899	0.319	0.152	0.015	0.065
	M1	20-40	5.3	58	1.54	0.799	0.014	0.196	0.019	4.504	0.105	0.196	0.019	0.089
	M1	40-60	4.5	50	0.72	0.366	0.010	0.244	0.027	1.648	0.083	0.244	0.027	0.056
	M1	60-80	4.6	51	1.29	0.420	0.016	0.361	0.045	1.490	0.113	0.361	0.045	0.062
	M1	80-100	4.8	64	1.42	0.678	0.013	0.299	0.059	1.940	0.140	0.299	0.059	0.063
Tweefontein	T1	0-20	5.3	50	69.34	0.272	0.064	0.121	0.008	2.426	0.397	0.121	0.008	0.359
	T1	20-40	5.3	59	19.17	0.770	0.021	0.178	0.011	4.493	0.121	0.178	0.011	0.109
	T1	40-60	4.4	53	3.80	0.472	0.013	0.298	0.032	1.422	0.071	0.298	0.032	0.049
	T1	40-60	4.5	44	3.50	0.329	0.020	0.354	0.036	1.645	0.103	0.354	0.036	0.051
	T1	60-80	4.8	67	4.36	0.523	0.029	0.514	0.050	2.914	0.116	0.514	0.050	0.074
	T1	80-100	4.4	58	4.84	0.519	0.023	0.384	0.081	1.091	0.111	0.384	0.081	0.049
	T2	20-40	5.6	9	2.17	0.274	0.006	0.200	0.026	1.616	0.080	0.200	0.026	0.489
	T2	20-40	4.7	42	5.22	0.499	0.008	0.104	0.013	2.299	0.051	0.104	0.013	0.062
	T2	60-80	4.3	44	5.40	0.382	0.015	0.351	0.068	1.058	0.064	0.351	0.068	0.067
Four	F1	0-20	6.8	38	23.16	0.313	0.024	0.136	0.015	6.622	0.217	0.136	0.015	0.100
	F1	20-40	7.0	20	4.29	0.227	0.003	0.107	0.026	5.165	0.078	0.107	0.026	0.432
	F1	60-80	6.5	73	0.67	0.736	0.001	0.579	0.058	3.060	0.049	0.579	0.058	0.102
	F1	40-60	6.4	56	1.36	-0.051	0.000	-0.018	-0.004	6.986	0.064	-0.018	-0.004	-0.003
	F2	0-20	5.3	30	20.90	0.238	0.029	0.128	0.018	2.370	0.291	0.128	0.018	0.550
	F2	40-60	4.5	42	0.80	0.433	0.004	0.293	0.061	1.422	0.057	0.293	0.061	0.033
	F2	60-80	4.6	51	0.90	0.734	0.005	0.358	0.093	1.350	0.059	0.358	0.093	0.055
	F2	80-100	4.3	42	5.01	0.407	0.016	0.141	0.076	0.804	0.073	0.141	0.076	0.042

Table C2. Results of chemical analysis of soil samples from Kleinkopjé, New Vaal and Syferfontein (2001/2002 summer season, Soil Science Laboratory, University of Pretoria).

						Soluble Cations				Exchangeable cations				
Pivot	Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
Tweefontein	T1	0-30	5.9	413	13.20	0.875	0.071	0.727	0.304	7.307	0.360	1.209	0.189	1.220
	T1	30-60	5.9	445	3.63	0.780	0.022	1.556	0.355	2.392	0.130	1.960	0.229	2.310
Four	F1	0-30	4.8	494	67.87	0.758	0.047	0.903	0.402	1.979	0.223	0.835	0.148	1.394
	F1	30-60	4.6	342	4.84	0.630	0.026	0.770	0.334	1.164	0.098	0.729	0.114	1.047
	F1	60-90	4.6	236	1.01	0.556	0.007	0.414	0.128	1.201	0.065	0.641	0.169	0.728
	F1	90-120	4.9	252	0.89	0.610	0.004	0.496	0.255	1.234	0.057	0.863	0.037	1.072
Syferfontein	S1	0-20	5.9	850	2.54	0.069	0.009	0.066	0.295	13.853	0.506	0.066	0.117	0.461
	S1	40-55	6.8	163	0.22	0.527	0.003	0.382	0.350	20.206	0.307	0.382	0.051	0.860
	S1	2^{nd} depth	6.5	221	0.34	0.560	0.004	0.362	0.658	17.828	0.309	0.362	0.658	1.656
	S1	Subsoil	8.6	87	0.32	0.092	0.001	0.099	0.166	22.438	0.136	0.099	0.166	0.337
	S2	20	6.3	151	5.68	0.535	0.007	0.326	0.744	18.128	0.388	0.326	0.744	0.889
	S2	40	6.4	147	0.77	0.625	0.003	0.387	0.435	20.533	0.325	0.387	0.435	1.095
	S2	40-55	7.4	120	0.73	0.391	0.004	0.300	0.216	-0.134	0.383	0.300	0.216	0.735
	S2	55-70	8.2	74	0.63	0.178	0.001	0.160	0.145	0.079	0.217	0.160	0.145	0.400
	S3	0-20	6.7	206	2.67	0.629	0.009	0.342	0.942	19.231	0.457	0.342	0.942	2.230
	S3	20-30	6.5	149	0.54	0.671	0.005	0.397	0.527	22.483	0.399	0.397	0.527	0.781
	S3	30-35	6.7	218	0.85	0.864	0.006	0.551	0.470	-0.585	0.455	0.551	0.470	0.690
	S3	35-55	8.0	147	0.48	0.386	0.003	0.278	0.351	-0.032	0.381	0.278	0.351	0.930
	S4	20	7.4	135	6.51	0.153	0.011	0.136	0.878	15.366	0.422	0.136	0.878	1.176
	S4	20-40	6.8	327	1.31	0.860	0.004	0.626	1.684	20.323	0.214	0.626	1.684	3.753
	S4	40-54	7.4	201	0.60	1.286	0.004	1.869	0.834	20.345	0.257	1.869	0.834	4.520
	S4	54-69	8.3	138	0.35	0.449	0.002	0.513	0.314	22.106	0.217	0.513	0.314	0.913
New Vaal	NV1		4.2	95	1127.60	0.183	0.110	0.080	0.025	1.994	1.785	0.461	0.401	0.028
	NV2		6.1	79	169.84	0.122	0.043	0.190	0.004	3.632	0.693	2.944	0.330	0.088
	NV3		4.1	127	776.59	0.219	0.144	0.075	0.047	1.169	0.723	0.207	0.353	0.081
	NV4		6.3	48	25.92	0.072	0.054	0.036	0.001	1.965	0.439	0.631	0.264	0.012

Table C3. Results of chemical analysis of soil samples from Kleinkopjé (2002) winter season, Soil Science Laboratory, University of Pretoria.

Pivot	Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Soluble Cations				Exchangeable cations				
						Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
Tweefontein	T1	0-20	5.4	222	36.28	0.841	0.081	0.345	0.046	3.883	0.340	0.697	0.089	1.043
	T1	20-40	4.9	256	4.56	0.695	0.042	0.757	0.138	3.779	0.167	1.075	0.067	1.130
	T1	40-60	5.0	234	1.43	0.529	0.022	0.887	0.196	1.600	0.146	1.628	0.156	1.185
	T1	60-80	4.7	150	2.64	0.401	0.006	0.477	0.072	0.830	0.063	1.207	0.128	0.679
	T1	0-30	5.9	413	13.20	0.875	0.071	0.727	0.304	7.307	0.360	1.209	0.189	1.220
	T1	30-60	5.9	445	3.63	0.780	0.022	1.556	0.355	2.392	0.130	1.960	0.229	2.310
	T1	80-100	5.0	135	7.49	0.318	0.002	0.395	0.060	1.512	0.044	1.190	0.066	0.552
Four	F1	0-30	4.8	494	67.87	0.758	0.047	0.903	0.402	1.979	0.223	0.835	0.169	1.394
	F1	30-60	4.6	342	4.84	0.630	0.026	0.770	0.334	1.164	0.098	0.729	0.037	1.047
	F1	60-90	4.6	236	1.01	0.556	0.007	0.414	0.128	1.201	0.065	0.641	0.117	0.728
	F1	90-120	4.9	252	0.89	0.610	0.004	0.496	0.255	1.234	0.057	0.863	0.051	1.072
Major	M	0-20	4.6	304	22.53	0.544	0.082	0.249	0.023	6.067	0.320	0.509	0.161	0.891
	M	20-40	4.6	213	3.83	0.374	0.015	0.096	0.006	4.366	0.127	0.327	0.130	0.568
	M	40-60	4.3	181	2.34	0.280	0.018	0.186	0.010	2.205	0.110	0.541	0.139	0.685
	M	60-80	4.3	219	2.67	0.349	0.012	0.311	0.026	2.890	0.097	1.004	0.184	0.983
	M	80-100	4.5	268	1.94	0.376	0.020	0.412	0.059	3.052	0.134	1.643	0.216	1.062

Table C4. Results of chemical analysis of soil samples from Kleinkopjé (2002/2003) summer season, Soil Science Laboratory, University of Pretoria.

						Soluble Cations				Exchangeable cations				
Pivot	Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
Four	F1	0-20	6.1	196	25.71	0.815	0.062	0.380	0.047	6.848	0.408	1.205	0.087	1.107
	F1	20-40	5.1	214	17.21	0.597	0.025	0.774	0.132	2.430	0.148	1.543	0.090	1.253
	F1	40-60	4.6	216	1.86	0.438	0.036	0.946	0.199	1.247	0.211	1.504	0.123	1.268
	F1	60-80	4.5	214	1.95	0.548	0.012	0.877	0.182	1.012	0.089	1.408	0.105	1.292
	F1	80-100	4.8	181	1.67	0.466	0.002	0.681	0.141	1.199	0.045	1.414	0.146	1.147
	F1	100-120	5.2	217	1.35	0.575	0.002	0.809	0.165	1.684	0.050	1.394	0.092	1.174
	F1	120-140	5.4	301	1.21	0.889	0.001	0.950	0.193	1.001	0.039	1.367	0.076	1.481
	F1	140-160	5.5	252	1.10	0.642	0.001	0.715	0.164	1.073	0.035	1.520	0.127	1.128

Table C5. Results of chemical analysis of soil samples from Kleinkopjé (begin 2003 winter season, Soil Science Laboratory, University of Pretoria).

						Soluble Cations				Exchangeable cations				
Pivot	Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
Four	F1	0-20	5.4	302	37.5	0.894	0.046	0.508	0.058	3.499	0.255	0.690	0.367	0.612
	F1	20-40	5.0	190	3.2	0.292	0.016	0.496	0.061	1.472	0.146	1.377	0.412	0.497
	F1	40-60	4.9	316	4.9	0.319	0.024	1.100	0.183	1.275	0.169	1.570	0.434	1.067
	F1	60-80	5.4	373	2.3	0.371	0.014	1.166	0.325	0.943	0.125	1.710	0.548	1.302
	F1	80-100	5.8	286	1.8	0.415	0.036	0.922	0.169	1.778	0.016	1.732	0.448	0.720
	F1	100-120	5.9	250	1.6	0.462	0.019	0.727	0.153	1.227	0.026	1.417	0.455	0.566
	F1	120-140	5.7	265	1.6	0.620	0.018	0.755	0.181	1.951	0.030	1.356	0.440	0.527
	F1	140-160	5.3	246	2.0	0.599	0.015	0.562	0.118	1.394	0.035	1.179	0.434	0.941
Major	M1	0-20	5.7	332	23.8	0.747	0.008	0.515	0.109	10.109	0.521	1.341	0.986	0.400
	M1	20-40	5.4	261	4.7	0.729	0.008	0.389	0.037	6.434	0.166	0.751	0.349	0.441
	M1	40-60	4.7	152	2.4	0.336	0.010	0.254	0.031	1.138	0.126	0.590	0.321	0.405
	M1	60-80	4.6	158	2.4	0.369	0.009	0.285	0.032	0.925	0.142	0.731	0.358	0.708
	M1	80-100	5.3	162	3.2	0.385	0.046	0.241	0.044	1.398	0.115	0.923	0.372	0.704
	M1	100-120	5.9	132	2.0	0.278	0.033	0.217	0.036	1.720	0.150	1.096	0.420	0.264
	M1	120-140	5.9	137	2.2	0.313	0.029	0.252	0.068	1.580	0.189	1.357	0.440	0.378
	M1	140-160	5.5	109	3.9	0.146	0.018	0.184	0.082	1.333	0.174	1.623	0.439	0.293

Table C6. Results of chemical analysis of soil samples from Kleinkopjé (2003/2004) begin summer season, Soil Science Laboratory, University of Pretoria).

						Soluble Cations				Exchangeable cations				
Pivot	Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
Four	S1	20-40	4.9	300	14.3	0.794	0.032	1.428	0.185	4.433	0.205	0.503	0.005	1.181
	S1	40-60	5.0	371	2.7	0.446	0.018	1.260	0.197	2.026	0.144	2.112	0.241	1.645
	S1	60-80	5.0	335	2.7	0.396	0.010	1.093	0.129	1.935	0.107	2.321	0.148	1.123
	S1	80-100	5.3	297	2.0	0.382	0.004	1.067	0.149	0.961	0.062	1.984	0.127	1.236
	S1	100-120	5.4	162	1.5	0.285	0.002	0.656	0.104	1.483	0.056	2.378	0.208	0.838
	S2	0-20	5.1	324	48.5	0.703	0.087	0.635	0.091	9.519	0.321	1.116	0.063	1.275
	S2	20-40	4.6	354	34.9	0.548	0.022	0.972	0.132	3.541	0.136	1.717	0.154	1.504
	S2	40-60	4.8	398	5.8	0.363	0.042	1.263	0.215	1.216	0.190	2.085	0.183	1.717
	S2	60-80	4.8	227	5.6	0.296	0.021	0.679	0.107	2.445	0.126	1.418	0.100	0.973
	S2	80-100	4.9	238	2.2	0.369	0.010	0.744	0.112	1.508	0.099	1.492	0.082	1.069
	S2	100-120	5.1	321	1.1	0.048	0.003	1.030	0.129	1.894	0.063	1.890	0.108	1.257
	S3	0-20	5.1	328	35.4	0.654	0.067	0.624	0.081	7.122	0.324	1.250	0.104	0.780
	S3	20-40	4.6	490	17.4	0.580	0.036	1.561	0.233	2.416	0.160	1.770	0.196	2.087
	S3	40-60	4.4	416	2.4	0.559	0.037	1.342	0.219	2.282	0.159	1.355	0.114	1.618
	S3	60-80	4.5	531	2.0	0.478	0.016	2.242	0.254	1.485	0.095	2.027	0.154	2.608
	S3	80-100	4.9	459	2.0	0.616	0.006	1.659	0.239	2.410	0.072	1.845	0.164	2.170
	S3	100-120	4.4	416	2.4	0.559	0.037	1.342	0.219	2.282	0.159	1.355	0.114	0.997

Table C7. Results of chemical analysis of soil samples from Kleinkopjé (2003/2004) begin summer season, Soil Science Laboratory, University of Pretoria).

						Soluble Cations				Exchangeable cations				
Pivot	Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
Major	M1	0-20	5.3	285	16.4	0.778	0.037	0.419	0.036	11.489	0.259	1.150	0.053	1.044
	M1	20-40	5.3	349	14.2	0.790	0.043	0.885	0.070	6.587	0.214	1.425	0.063	1.038
	M1	40-60	4.9	294	3.8	0.613	0.028	0.716	0.058	4.109	0.170	1.092	0.062	0.658
	M1	60-80	4.6	242	3.5	0.457	0.029	0.584	0.062	3.532	0.196	1.174	0.071	0.961
	M1	80-100	4.8	392	16.9	0.731	0.043	1.217	0.094	10.988	0.235	1.102	0.087	0.604
	M2	0-20	4.8	392	16.9	0.731	0.043	1.217	0.094	10.988	0.235	1.102	0.087	1.366
	M2	20-40	4.7	315	5.2	0.662	0.027	0.703	0.061	5.018	0.197	1.344	0.159	0.833
	M2	40-60	4.6	210	3.5	0.667	0.028	0.719	0.063	4.544	0.153	0.044	-0.008	0.682
	M2	60-80	5.0	207	2.6	0.539	0.017	0.330	0.025	3.334	0.210	1.116	0.052	0.720
	M2	80-100	5.2	162	1.1	0.410	0.016	0.331	0.034	2.345	0.277	2.177	0.073	0.397
	M3	0-20	4.8	392	9.1	0.700	0.037	0.742	0.061	3.758	0.205	1.280	0.050	1.134
	M3	20-40	4.7	315	3.8	0.674	0.034	0.478	0.055	1.348	0.192	0.738	0.043	0.976
	M3	40-60	4.6	210	2.2	0.559	0.020	0.224	0.033	0.954	0.171	0.506	0.027	0.470
	M3	60-80	4.6	207	2.6	0.355	0.011	0.250	0.023	0.809	0.144	1.163	0.037	0.300
	M3	80-100	4.9	162	2.0	0.364	0.013	0.364	0.034	0.691	0.152	1.404	0.038	0.473

Table C8. Results of chemical analysis of soil samples from Kleinkopjé (2003/2004) begin summer season, Soil Science Laboratory, University of Pretoria).

Pivot	Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Soluble Cations				Exchangeable cations				
						Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
Tweefontein	TWF1	0-20	5.1	292	32.9	0.878	0.057	0.547	0.052	4.433	0.272	1.088	0.055	1.176
	TWF1	20-40	5.3	414	5.1	0.679	0.047	1.200	0.150	9.592	0.285	2.509	0.183	1.646
	TWF1	40-60	5.2	486	2.1	0.515	0.038	1.711	0.247	2.600	0.217	2.600	0.230	2.169
	TWF1	60-80	5.2	333	5.9	0.367	0.026	1.028	0.154	1.745	0.178	2.155	0.166	1.112
	TWF1	80-100	5.3	249	3.4	0.354	0.011	0.636	0.142	1.264	0.132	1.880	0.182	0.793
	TWF2	0-20	5.3	334	52.4	0.880	0.108	0.690	0.078	6.697	0.464	1.562	0.068	1.232
	TWF2	20-40	5.4	547	5.7	0.660	0.072	1.746	0.265	3.718	0.283	2.145	0.194	2.345
	TWF2	40-60	5.0	401	3.6	0.576	0.030	1.294	0.205	2.125	0.182	2.185	0.232	1.370
	TWF2	60-80	5.1	317	4.6	0.432	0.008	1.026	0.151	1.381	0.094	2.692	0.222	1.135
	TWF2	80-100	5.1	337	3.6	0.437	0.003	0.973	0.164	1.984	0.055	2.177	0.182	1.055
	TWF3	20-40	5.1	297	48.5	0.725	0.074	0.532	0.061	8.249	0.308	1.062	0.081	1.044
	TWF3	40-60	5.2	476	8.5	0.652	0.068	1.232	0.173	4.589	0.228	1.465	0.121	1.918
	TWF3	60-80	5.0	526	3.4	0.615	0.042	1.750	0.246	1.607	0.195	2.083	0.179	2.311
	TWF3	80-100	4.9	276	9.2	0.462	0.020	0.691	0.138	0.802	0.110	1.076	0.086	0.978
	TWF3	100-120	4.9	290	8.6	0.447	0.010	0.693	0.130	0.567	0.077	1.198	0.104	0.977

Table C9. Results of chemical analysis of soil samples from Kleinkopjé (2003/2004) end summer season, Soil Science Laboratory, University of Pretoria).

						Soluble Cations				Exchangeable cations				
Pivot	Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
Major	M1	0-20	5.7	377	25.76	0.618	0.038	1.194	0.106	10.455	0.275	2.599	0.109	2.075
	M1	20-40	5.1	341	5.99	0.605	0.024	0.791	0.072	6.525	0.159	1.488	0.044	1.454
	M1	40-60	4.6	220	2.69	0.455	0.015	0.443	0.043	2.718	0.126	0.898	0.016	0.876
	M1	60-80	4.8	160	2.35	0.278	0.009	0.291	0.03	2.072	0.130	1.091	0.033	0.56
	M1	80-100	5.3	149	2.11	0.319	0.013	0.324	0.042	1.816	0.183	1.271	0.026	0.624
	M1	100-120	4.8	88	1.52	0.101	0.006	0.178	0.034	1.052	0.120	1.410	0.042	0.300
	M1	120-140	4.9	74.1	1.33	0.056	0.006	0.131	0.036	0.922	0.110	1.350	0.027	0.228
	M2	0-20	5.0	313	9.44	0.519	0.018	0.782	0.078	8.707	0.160	1.670	0.063	1.296
	M2	20-40	4.6	258	3.34	0.467	0.025	0.459	0.051	3.080	0.176	0.906	0.029	0.987
	M2	40-60	4.5	192	2.92	0.295	0.013	0.292	0.044	2.389	0.157	0.851	0.049	0.728
	M2	60-80	4.7	151	2.51	0.138	0.011	0.259	0.038	1.348	0.151	1.000	0.021	0.517
	M2	80-100	4.9	163	2.52	0.18	0.012	0.276	0.039	1.970	0.176	1.106	0.028	0.625
	M3	0-20	4.8	296	46.66	0.422	0.018	0.667	0.064	6.958	0.129	1.209	0.021	1.216
	M3	20-40	4.6	224	2.77	0.254	0.016	0.503	0.034	4.017	0.116	0.887	-0.002	1.049
	M3	40-60	4.5	168	2.25	0.141	0.009	0.284	0.03	2.039	0.135	0.925	0.024	0.655
	M3	60-80	5.0	280	2.77	0.462	0.013	0.679	0.056	4.198	0.141	1.394	0.021	1.268
	M3	80-100	5.4	268	2.28	0.325	0.012	0.618	0.067	2.529	0.148	1.563	0.044	1.085

Table C10. Results of chemical analysis of soil samples from Kleinkopjé (2003/2004) end summer season, Soil Science Laboratory, University of Pretoria).

						Soluble Cations				Exchangeable cations				
Pivot	Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
Four	S1	0-20	5.2	305	16.14	0.322	0.031	0.666	0.091	7.507	0.205	1.515	0.068	1.141
	S1	20-40	5.1	400	2.88	0.195	0.020	1.254	0.196	2.614	0.142	2.087	0.141	2.213
	S1	40-60	5.0	307	2.66	0.204	0.018	0.895	0.165	2.246	0.129	1.639	0.116	1.380
	S1	60-80	4.9	284	2.02	0.199	0.021	0.784	0.134	1.527	0.154	1.437	0.077	1.092
	S1	80-100	5.2	326	1.07	0.251	0.007	0.933	0.127	1.625	0.099	1.823	0.101	1.442
	S1	100-120	5.3	292	1.68	0.301	0.003	0.735	0.114	1.685	0.069	1.643	0.110	1.175
	S2	0-20	5.0	257	22.84	0.260	0.031	0.421	0.056	9.116	0.224	1.364	0.055	0.733
	S2	20-40	4.8	355	12.36	0.387	0.034	0.860	0.156	3.414	0.161	1.386	0.094	1.260
	S2	40-60	4.9	335	3.26	0.238	0.028	0.963	0.120	1.788	0.180	1.793	0.087	1.401
	S2	60-80	4.8	385	2.12	0.228	0.021	1.408	0.197	2.202	0.154	2.064	0.109	1.833
	S2	80-100	5.1	309	1.20	0.240	0.013	0.867	0.160	1.391	0.109	1.593	0.094	1.171
	S2	100-120	5.2	306	2.17	0.402	0.026	0.583	0.115	1.858	0.180	1.252	0.057	0.865
	S3	0-20	5.2	428	22.79	0.560	0.045	1.038	0.150	7.468	0.189	1.480	0.048	1.620
	S3	20-40	5.0	576	16.95	0.459	0.039	1.905	0.286	2.480	0.172	2.423	0.194	2.771
	S3	40-60	5.2	389	21.07	0.423	0.017	1.065	0.173	2.765	0.130	1.873	0.182	1.816
	S3	60-80	5.2	363	9.25	0.443	0.013	0.907	0.138	1.762	0.105	1.503	0.082	1.538
	S3	80-100	5.1	374	3.23	0.390	0.013	1.087	0.191	1.571	0.106	1.677	0.099	1.601
	S3	100-120	5.4	379	1.70	0.532	0.003	1.042	0.198	1.887	0.039	1.879	0.126	1.723
	S3	120-140	5.4	344	1.30	0.574	0.004	0.974	0.189	2.105	0.046	1.388	0.078	1.620

Table C11. Results of chemical analysis of soil samples from Kleinkopjé (2003/2004) end of summer season, Soil Science Laboratory, University of Pretoria).

Pivot	Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Soluble Cations				Exchangeable cations				
						Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
Tweefontein	TWF 1	0-20	5.5	305	22.06	0.620	0.059	0.595	0.059	8.856	0.326	1.454	0.034	1.208
	TWF 1	20-40	5.5	547	3.37	0.526	0.061	1.832	0.266	7.702	0.308	3.196	0.223	2.590
	TWF 1	40-60	5.4	321	1.26	0.399	0.025	0.938	0.173	1.915	0.171	1.884	0.116	1.457
	TWF 1	60-80	5.0	241	3.24	0.302	0.008	0.523	0.121	1.799	0.090	1.476	0.120	0.574
	TWF 2	0-20	5.0	259	10.67	0.576	0.041	0.565	0.058	4.049	0.205	1.006	-0.004	0.970
	TWF 2	20-40	5.1	450	12.34	0.433	0.042	1.460	0.203	8.094	0.271	3.346	0.225	2.317
	TWF 2	40-60	5.4	478	5.07	0.483	0.036	1.544	0.263	3.743	0.231	2.842	0.235	2.391
	TWF 2	60-80	5.4	430	4.49	0.396	0.016	1.410	0.253	2.268	0.126	2.457	0.188	2.009
	TWF3	0-20	5.6	245	2.67	0.682	0.036	0.414	0.033	12.237	0.241	0.943	-0.018	0.846
	TWF3	20-40	5.6	282	3.55	0.539	0.042	0.593	0.046	4.800	0.242	1.225	-0.001	1.097
	TWF3	40-60	5.1	382	4.45	0.516	0.023	1.105	0.148	4.024	0.126	1.766	0.089	1.705
	TWF3	60-80	4.8	302	5.10	0.300	0.005	0.927	0.162	3.557	0.060	2.463	0.231	1.162

Table C12. Results of chemical analysis of soil samples from Kleinkopjé (begin of winter season 2004, Soil Science Laboratory, University of Pretoria).

Pivot	Site	Depth (cm)	pH	EC mS m-1	P mg kg-1	Soluble Cations				Exchangeable cations				
						$Ca2^{+}$ cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	$Mg2^{+}$ cmol(c) kg-1	Na+ cmol(c) kg^{-1}	$Ca2^{+}$ cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	$Mg2^{+}$ cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	$SO42^{-}$ me $100g^{-1}$
	S1	0-20	5.1	156	0.0	0.861	0.021	0.069	0.008	2.946	0.192	0.318	0.272	0.449
	S1	20-40	4.6	215	0.0	1.070	0.041	0.165	0.017	2.438	0.161	0.073	0.333	0.950
	S1	40-60	4.6	186	0.0	0.490	0.058	0.649	0.049	1.036	0.308	0.668	-0.003	0.787
	S1	60-80	4.6	259	0.0	0.570	0.020	1.040	0.103	0.657	0.139	0.738	0.021	1.004
	S1	80-100	4.7	226	0.0	0.635	0.019	0.922	0.077	0.841	0.129	0.864	0.069	0.999
	S1	100-120	5.0	243	0.0	0.553	0.011	0.946	0.125	1.542	0.109	1.095	0.078	1.089
	S1	120-150	5.0	357	0.0	0.769	0.013	1.584	0.198	1.655	0.110	1.552	0.109	0.600
	S2	0-20	5.2	189	0.0	0.986	0.022	0.098	0.011	3.719	0.111	0.470	0.043	0.321
	S2	20-40	5.0	210	0.0	0.850	0.037	0.285	0.014	2.733	0.236	0.440	0.019	0.433
	S2	40-60	4.9	242	0.0	0.853	0.041	0.665	0.041	1.741	0.228	0.602	0.000	0.697
	S2	60-80	4.8	123	0.0	0.322	0.014	0.426	0.042	1.025	0.166	1.410	0.077	0.157
	S2	80-100	5.1	161	0.0	0.262	0.018	0.595	0.074	0.736	0.138	1.545	0.237	0.424
	S2	100-120	5.3	341	0.0	0.725	0.008	1.435	0.200	0.572	0.085	1.264	0.133	1.088
	S3	0-20	4.9	188	0.0	1.050	0.018	0.062	0.009	3.695	0.158	0.144	0.054	0.503
	S3	20-40	4.4	225	0.0	0.737	0.036	0.485	0.031	1.752	0.189	0.535	0.032	0.583
	S3	40-60	4.7	284	0.0	0.576	0.04	1.026	0.094	0.467	0.216	0.776	0.034	0.843
	S3	60-80	5.0	262	0.0	0.497	0.024	1.047	0.114	0.591	0.173	1.159	0.071	0.733
	S3	80-100	5.2	382	0.0	0.799	0.008	1.684	0.188	0.987	0.089	1.131	0.067	1.243
Four	S3	100-120	5.4	390	0.0	0.732	0.004	1.800	0.220	0.560	0.058	1.591	0.183	1.563

Table C13. Results of chemical analysis of soil samples from Kleinkopjé (begin summer season 2005, Soil Science Laboratory, University of Pretoria).

Pivot	Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Soluble Cations				Exchangeable cations				
						Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
Major	M1	0-20	6.3	319	16.4	0.909	0.068	0.239	0.178	10.019	0.364	0.715	0.157	0.925
	M1	20-40	6.0	359	11.5	0.814	0.024	0.678	0.058	12.011	0.199	1.634	0.094	1.315
	M1	40-60	5.0	284	3.3	0.771	0.02	0.415	0.019	3.495	0.147	0.580	0.086	1.129
	M1	60-80	5.7	291	3.1	0.834	0.021	0.839	0.081	5.154	0.204	1.251	0.063	1.659
	M1	80-100	5.5	294	3.2	0.658	0.031	0.700	0.086	1.947	0.146	1.291	0.067	1.251
	M1	100-120	4.8	218	3.2	0.422	0.026	0.461	0.086	0.825	0.123	1.119	0.041	0.543
	M1	120-140	4.7	142	3.0	0.248	0.039	0.207	0.095	0.456	0.061	0.772	0.053	0.038
	M2	0-20	5.4	369	21.6	1.011	0.084	0.270	0.051	7.522	0.249	0.453	0.037	0.746
	M2	20-40	5.2	370	17.6	1.074	0.041	0.317	0.395	4.276	0.142	0.381	0.000	1.056
	M2	40-60	4.6	374	4.5	0.92	0.063	0.564	0.067	4.430	0.191	0.497	0.064	1.179
	M2	60-80	5.0	328	2.8	0.925	0.050	0.759	0.106	2.509	0.270	1.273	0.082	1.674
	M2	80-100	5.3	260	2.1	0.726	0.030	0.759	0.073	1.614	0.223	1.652	0.063	1.276
	M2	100-120	5.2	251	2.0	0.583	0.028	0.665	0.061	1.094	0.126	1.359	0.066	0.895
	M3	0-20	4.8	264	22.2	0.974	0.041	0.129	0.025	3.143	0.159	0.257	0.014	0.721
	M3	20-40	5.0	283	5.0	0.857	0.034	0.405	0.026	4.422	0.138	0.500	0.074	1.022
	M3	40-60	5.0	485	2.9	0.934	0.134	0.784	0.254	1.925	0.321	0.573	0.142	1.615
	M3	60-80	4.8	323	3.3	0.772	0.069	0.712	0.088	1.669	0.238	0.694	0.108	1.363
	M3	80-100	5.0	393	4.4	0.837	0.097	0.851	0.156	1.474	0.285	0.902	0.127	1.844
	M3	100-120	4.9	375	4.1	0.818	0.100	0.919	0.159	1.373	0.315	1.187	0.124	1.864
	M4	0-20	5.1	346	0.0	1.142	0.114	0.242	0.022	8.539	0.355	0.399	0.083	0.573
	M4	20-40	5.2	387	13.2	1.051	0.143	0.474	0.088	5.785	0.385	0.562	0.108	1.143

M4	40-60	4.7	385	5.4	0.872	0.112	0.568	0.060	3.529	0.351	0.591	0.088	1.468
M4	60-80	4.4	428	3.5	0.936	0.089	0.922	0.060	4.328	0.267	0.657	0.084	1.635
M4	80-100	4.2	396	2.8	0.921	0.074	1.167	0.125	4.364	0.28	1.104	0.062	1.912
M4	100-120	5.2	485	3.2	0.999	0.097	1.133	0.135	1.147	0.293	0.965	0.127	1.615

Table C14. Results of chemical analysis of soil samples from Kleinkopjé (begin summer season 2005, Soil Science Laboratory, University of Pretoria).

Pivot	Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Soluble Cations				Exchangeable cations				
						Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
	S1	0-20	5.3	424	64.0	1.042	0.118	0.566	0.064	6.044	0.313	0.462	0.036	1.071
	S1	20-40	5.2	477	55.8	0.790	0.041	1.776	0.294	1.411	0.200	1.021	0.129	2.291
	S1	40-60	4.8	401	1.3	0.822	0.028	1.156	0.213	0.785	0.149	0.892	0.109	1.937
	S1	60-80	4.8	395	1.3	0.917	0.031	1.494	0.154	0.820	0.159	0.966	0.107	2.261
	S1	80-100	5.2	446	1.2	0.810	0.044	2.052	0.287	0.577	0.202	1.190	0.113	2.816
	S1	100-120	5.3	488	0.8	0.844	0.007	2.134	0.341	0.628	0.090	1.330	0.069	2.711
	S2	0-20	5.3	304	53.8	0.833	0.040	0.468	0.049	6.553	0.229	0.708	0.095	1.093
	S2	20-40	4.8	361	12.3	0.822	0.025	0.775	0.057	2.806	0.152	0.689	0.096	1.507
	S2	40-60	4.6	424	3.8	0.761	0.033	1.203	0.146	1.025	0.157	0.731	0.094	2.058
	S2	60-80	4.6	408	4.2	0.741	0.026	1.013	0.164	0.980	0.146	0.822	0.097	1.707
	S2	80-100	4.8	473	5.2	0.880	0.014	1.437	0.124	0.752	0.107	0.743	0.051	2.091
	S2	100-120	5.3	609	3.6	0.905	0.005	2.456	0.348	1.431	0.072	1.181	0.109	2.676
	S3	0-20	5.8	347	27.4	0.836	0.042	0.670	0.046	7.248	0.301	1.395	0.098	1.428
	S3	20-40	5.9	459	6.3	0.814	0.041	1.250	0.118	4.026	0.264	1.440	0.100	1.921
	S3	40-60	6.0	420	3.8	0.755	0.035	1.027	0.156	2.149	0.252	1.268	0.097	1.820
	S3	60-80	6.1	399	3.0	0.801	0.040	0.826	0.193	3.265	0.278	1.058	0.108	1.686
	S3	80-100	6.0	338	3.3	0.734	0.028	0.781	0.098	1.122	0.220	0.979	0.076	1.386
Four	S3	100-120	5.9	318	2.6	0.870	0.005	0.957	0.073	1.929	0.098	1.150	0.118	1.779

Table C15. Results of chemical analysis of soil samples from Kleinkopjé (begin summer season 2005, Soil Science Laboratory, University of Pretoria).

Pivot	Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Soluble Cations				Exchangeable cations				
						Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
Tweefontein	TWF 1	0-20	6.3	375	48.5	0.952	0.060	0.594	0.058	7.830	0.271	0.952	0.090	1.115
	TWF 1	20-40	5.9	542	9.6	0.606	0.034	1.262	0.255	3.446	0.137	0.861	0.128	1.951
	TWF 1	40-60	5.1	287	4.8	0.502	0.036	0.407	0.057	0.745	0.131	0.416	0.113	0.788
	TWF 1	60-80	4.8	586	5.9	0.515	0.267	0.702	0.333	0.642	0.189	0.318	0.120	1.299
	TWF 1	80-100	4.7	528	7.0	0.596	0.181	0.839	0.222	0.208	0.096	0.000	0.000	1.485
	TWF 2	0-20	5.7	329	30.8	0.893	0.072	0.498	0.050	8.838	0.322	0.917	0.081	1.276
	TWF 2	20-40	5.9	419	5.2	0.759	0.058	1.111	0.130	8.722	0.298	1.365	0.153	1.934
	TWF 2	40-60	5.6	569	7.1	0.647	0.061	1.746	0.231	3.146	0.249	1.291	0.113	2.194
	TWF 2	60-80	5.4	527	3.0	0.662	0.042	1.643	0.224	1.968	0.201	1.722	0.081	2.442
	TWF 2	80-100	5.2	490	8.1	0.630	0.033	1.506	0.222	1.796	0.165	1.332	0.074	2.137
	TWF 2	100-120	5.1	437	6.1	0.606	0.029	1.672	0.249	1.250	0.164	1.521	0.095	2.303
	TWF 3	0-20	6.5	433	15.6	0.869	0.047	1.002	0.116	10.009	0.238	1.639	0.045	1.534
	TWF 3	20-40	6.3	395	5.1	0.000	0.000	0.000	0.000	4.498	0.180	2.180	0.199	0.000
	TWF 3	40-60	5.6	332	4.2	0.640	0.025	0.542	0.068	1.770	0.116	0.511	0.063	1.142
	TWF 3	60-80	5.1	336	5.0	0.610	0.024	0.608	0.074	1.216	0.096	0.585	0.061	1.223
	TWF 3	80-100	5.0	417	4.2	0.541	0.030	1.024	0.173	3.321	0.122	0.893	0.114	1.747

Table C16. Results of chemical analysis of soil samples from Kleinkopjé (begin winter season 2005, Soil Science Laboratory, University of Pretoria).

Pivot	Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Soluble Cations				Exchangeable cations				
						Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
Tweefontein	TWF 1	0-20	6.6	329	23.09	0.999	0.054	0.691	0.094	5.189	0.146	0.473	0.030	1.058
	TWF 1	20-40	6.6	348	20.1	0.984	0.054	0.854	0.093	4.605	0.131	0.532	0.040	1.303
	TWF 1	40-60	5.8	399	6.8	0.978	0.049	1.401	0.168	1.777	0.067	0.050	0.021	1.447
	TWF 1	60-80	4.9	494	7.9	0.943	0.076	2.289	0.385	0.938	0.058	-0.467	-0.104	1.804
	TWF 1	80-100	4.7	460	6.3	0.928	0.049	2.050	0.296	1.023	0.052	-0.335	-0.076	1.654
	TWF 2	0-20	6.1	339	14.1	1.173	0.048	1.035	0.115	5.014	0.160	0.680	0.013	1.313
	TWF 2	20-40	6.0	297	4.6	0.932	0.039	0.623	0.082	2.516	0.154	0.574	0.046	1.031
	TWF 2	40-60	5.9	283	3.2	1.019	0.042	0.567	0.076	3.072	0.151	0.432	0.044	0.853
	TWF 2	60-80	5.5	294	2.9	1.032	0.048	0.651	0.054	3.524	0.143	0.381	0.022	1.011
	TWF 2	80-100	5.0	247	5.1	0.626	0.037	0.492	0.028	0.786	0.072	0.178	0.027	0.591
	TWF 2	100-120	4.8	278	5.0	0.593	0.034	0.621	0.082	0.296	0.049	0.156	0.029	0.653
	TWF 3	0-20	6.0	314	8.0	1.159	0.056	0.673	0.075	13.612	0.200	0.779	0.028	1.174
	TWF 3	20-40	6.1	279	3.6	1.472	0.080	0.543	0.101	8.508	0.141	0.168	-0.012	1.035
	TWF 3	40-60	5.6	272	3.9	1.540	0.064	0.716	0.095	2.108	0.108	0.119	0.007	1.513
	TWF 3	60-80	5.3	264	4.7	0.98	0.053	0.803	0.038	0.947	0.102	0.246	0.021	1.079
	TWF 3	80-100	5.2	264	3.5	0.821	0.064	1.175	0.051	0.771	0.124	0.400	0.008	1.068
	TWF 4	100-120	5.1	247	4.3	0.653	0.069	1.196	0.076	0.400	0.113	0.379	-0.008	0.934

Table C17. Results of chemical analysis of soil samples from Kleinkopjé (begin winter season 2005, Soil Science Laboratory, University of Pretoria).

Pivot	Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Soluble Cations				Exchangeable cations				
						Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
	S1	0-20	5.3	306	45.5	1.054	0.078	0.600	0.074	6.830	0.161	0.456	0.076	1.327
	S1	20-40	5.5	280	6.4	1.070	0.078	0.829	0.070	1.659	0.174	0.319	0.024	1.077
	S1	40-60	5.1	280	3.6	0.702	0.095	0.932	0.058	0.945	0.208	0.339	0.005	1.062
	S1	60-80	5.2	343	3.5	0.831	0.097	1.998	0.167	0.691	0.165	0.055	-0.030	1.744
	S1	80-100	5.5	428	2.7	0.830	0.026	2.945	0.420	1.001	0.075	-0.184	-0.122	2.084
	S1	100-120	5.6	459	2.3	0.841	0.009	3.463	0.584	1.344	0.046	-0.143	-0.199	2.588
	S2	0-20	5.4	324	40.0	1.517	0.077	1.281	0.134	5.269	0.108	0.089	-0.014	1.764
	S2	20-40	5.0	279	10.5	1.313	0.073	0.705	0.107	2.544	0.114	0.171	-0.008	1.160
	S2	40-60	4.8	230	4.2	0.833	0.061	0.583	0.076	0.743	0.116	0.210	0.018	0.863
	S2	60-80	4.8	365	3.7	0.940	0.041	0.876	0.074	0.786	0.090	0.288	0.006	1.025
	S2	80-100	5.2	282	2.7	1.096	0.014	1.851	0.165	0.480	0.056	0.037	-0.049	1.244
	S2	100-120	5.4	379	2.7	1.302	0.005	2.329	0.296	0.670	0.036	-0.030	-0.093	1.967
	S3	0-20	6.2	348	29.1	1.210	0.064	1.142	0.162	5.078	0.175	0.911	-0.003	1.436
	S3	20-40	6.2	370	14.4	1.130	0.046	1.254	0.097	3.561	0.144	0.930	0.010	1.717
	S3	40-60	6.3	384	5.4	1.222	0.074	1.544	0.139	1.807	0.198	0.623	-0.019	1.767
	S3	60-80	6.4	345	2.5	1.017	0.074	1.824	0.251	33.514	2.442	60.069	8.274	1.526
	S3	80-100	6.4	393	3.1	0.673	0.014	1.597	0.284	1.068	0.104	1.410	0.080	1.486
Four	S3	100-120	6.2	412	2.0	0.827	0.005	2.362	0.294	2.925	0.047	0.678	-0.022	1.634

Table C18. Results of chemical analysis of soil samples from Syferfontein (2002) winter season, Soil Science Laboratory, University of Pretoria.

						Soluble Cations				Exchangeable cations				
Pivot	Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
Syferfontein	S1-S5	0-20	6.2	385	4.34	0.888	0.008	1.270	1.755	23.209	0.290	19.581	3.260	3.438
	S1-S5	20-40	6.4	312	1.5	1.083	0.006	1.418	1.127	30.624	0.261	24.618	2.213	2.872
	S1-S5	40-60	7.5	135	1.48	0.327	0.004	0.408	0.650	31.580	0.261	26.781	2.255	0.540
	S1-S5	60-80	8.2	89	1.72	0.156	0.003	0.202	0.524	31.750	0.318	26.410	-0.098	0.671
	S1-S5	0-20	6.2	385	4.34	0.888	0.008	1.270	1.755	23.209	0.290	19.581	3.260	3.438

Table C19. Results of chemical analysis of soil samples from Syferfontein (2002/2003) summer season, Soil Science Laboratory, University of Pretoria.

Pivot	Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Soluble Cations				Exchangeable cations				
						Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
Syferfontein	S1	0-20	7.5	6										
	S1	20-40	7.2	492	2.29	1.323	0.003	1.984	5.025	27.526	0.399	32.081	6.482	5.832
	S1	40-60	7.3	3										
	S1	60-80	7.9	330	2.16	1.113	0.008	1.495	1.165	29.682	0.394	25.327	0.99	2.782
	S2	0-20	7.5	3										
	S2	20-40	6.9	338	1.60	1.091	0.011	0.938	0.000	25.063	0.521	19.299	6.635	3.645
	S2	40-60	7.2	232	1.66	0.964	0.009	0.678	1.319	27.984	0.681	23.016	3.228	1.609
	S2	60-80	8.1	1										
	S2	80-100	8.7	137	1.08	0.29	0.002	0.225	0.784	32.651	0.412	20.506	2.937	0.725
	S3	0-20	7.3	2										
	S3	20-40	7.1	383	2.55	1.029	0.011	0.941	2.538	17.740	0.567	17.896	6.576	3.463
	S3	40-60	7.6	344	1.27	1.766	0.011	1.441	1.066	34.019	0.549	25.381	2.046	3.029
	S4	0-20	7.4	162	4.61	0.173	0.007	0.172	1.166	16.750	0.576	17.103	6.643	0.919
	S4	20-40	6.9	2										
	S4	40-60	7.1	326	1.87	1.111	0.007	1.104	1.325	25.891	0.404	24.071	2.309	
	S4	60-80	7.8	2										2.619
	S4	80-90	8.1	250	1.27	0.786	0.006	0.722	0.624	25.418	0.314	16.634	1.096	
	S5	0-20	7.9	229	6.98	0.021	0.001	0.023	0.108	17.401	0.915	21.037	10.007	1.602
	S5	20-40	7.3	2										0.132
	S5	40-60	7.7	141	2.14	0.386	0.006	0.441	0.736	26.517	0.651	29.837	2.637	
	S5	60-80	8.5	3										1.173
	S5	80-100	7.4	351	2.35	1.068	0.008	1.183	1.783	22.841	0.419	25.145	4.721	
	Out pivot	0-20	7.2	3										3.306
	Out pivot	20-40	7.9	115	1.87	0.364	0.005	0.264	0.536	38.565	0.657	22.031	1.749	
	Out pivot	40-60	8.1	97	1.92	0.317	0.004	0.197	0.476	39.410	0.724	24.155	2.201	0.632
	Out pivot	60-80	8.4	1										0.620

	Out pivot	80-100	8.5	81	1.26	0.139	0.003	0.106	0.469	35.246	0.698	26.304	2.817	

Table C20. Results of chemical analysis of soil samples from Syferfontein (2003) winter season, Soil Science Laboratory, University of Pretoria.

Pivot	Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Soluble Cations				Exchangeable cations				
						Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
Syferfontein	S1	0-20	8.2	176	0.0	0.122	0.006	0.193	1.412	15.376	0.738	24.621	12.907	1.301
	S1	20-40	7.7	377	0.0	0.955	0.008	1.521	3.697	21.280	0.493	30.124	9.535	4.316
	S1	40-60	7.8	371	0.0	1.123	0.006	1.892	1.738	28.546	0.421	33.622	6.362	3.519
	S2	0-20	7.7	229	0.0	0.261	0.010	0.329	1.664	19.129	0.795	21.933	11.786	1.671
	S2	20-40	7.3	335	0.0	1.184	0.010	1.203	2.393	23.645	0.593	23.282	6.750	3.261
	S2	40-60	7.5	190	0.0	0.751	0.006	0.581	1.094	28.919	0.574	26.702	4.917	1.676
	S3	0-20	7.3	304	0.0	0.409	0.011	0.552	2.506	21.027	0.781	23.274	10.291	1.678
	S3	20-40	7.1	295	0.0	1.328	0.011	1.467	1.559	26.396	0.656	28.285	5.279	2.901
	S3	40-60	7.7	183	0.0	0.819	0.008	0.722	0.616	34.290	0.634	28.125	3.438	1.822
	S3	60-80	8.2	136	0.0	0.331	0.004	0.424	0.631	30.586	0.487	33.032	4.249	1.024
	S4	0-20	7.2	233	0.0	0.337	0.009	0.410	1.708	17.007	0.605	20.536	8.261	1.880
	S4	20-40	6.9	261	0.0	0.903	0.009	1.080	1.382	19.684	0.426	23.898	5.064	2.818
	S4	40-60	7.5	215	0.0	0.786	0.005	0.910	0.637	27.387	0.417	24.892	3.373	1.960
	S4	60-80	8.0	209	0.0	0.818	0.005	0.978	0.610	28.003	0.394	23.178	2.661	1.823
	S5	0-20	7.3	270	0.0	0.590	0.010	0.683	1.919	20.048	0.701	25.200	9.399	2.727
	S5	20-40	7.1	264	0.0	0.902	0.005	1.199	1.146	21.532	0.437	29.459	5.300	2.572
	S5	40-60	8.3	166	0.0	0.419	0.004	0.578	0.723	29.65	0.443	31.396	4.114	1.284
	S6	0-20	7.3	173	0.0	0.255	0.006	0.371	1.099	19.534	0.628	26.254	9.697	1.346
	S6	20-40	7.1	263	0.0	0.853	0.007	1.110	1.345	21.431	0.56	29.054	5.971	2.644
	S6	40-60	7.6	185	0.0	0.681	0.006	0.704	0.822	25.545	0.572	31.518	4.493	1.408
	S6	60-80	8.4	111	0.0	0.245	0.004	0.335	0.624	28.127	0.556	32.216	4.343	0.736
	Out pivot	0-20	7.1	26	0.0	0.075	0.002	0.087	0.038	19.265	0.425	23.986	0.192	0.098
	Out pivot	20-40	7.4	26	0.0	0.087	0.003	0.111	0.042	20.501	0.439	27.501	0.319	0.166

Table C21. Results of chemical analysis of soil samples from Syferfontein (2003/2004) summer season, Soil Science Laboratory, University of Pretoria).

Pivot	Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Soluble Cations				Exchangeable cations				
						Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
Syferfontein	S1	0-20	7.4	236	7.1	0.285	0.014	0.374	1.551	17.379	0.494	22.167	8.171	2.195
	S2	20-40	7.1	297	14.3	0.321	0.012	1.025	1.458	14.898	0.323	26.537	4.262	2.669
	S1	40-60	7.2	232	2.1	0.692	0.010	1.034	1.011	22.461	0.330	28.996	2.230	2.580
	S1	60-80	8.0	136	1.9	0.385	0.010	0.505	0.529	25.564	0.407	30.595	3.364	1.114
	S1	80-100	8.7	85	2.0	0.162	0.007	0.240	0.321	23.441	0.514	26.828	3.180	0.571
	S2	0-20	7.7	283	2.8	0.208	0.012	0.413	1.461	21.998	0.466	19.659	10.218	2.583
	S2	20-40	7.2	359	1.6	0.637	0.010	1.325	1.751	12.936	0.302	21.298	5.187	2.573
	S2	40-60	8.4	336	2.8	0.693	0.011	0.899	1.628	23.609	0.367	24.029	6.745	2.597
	S3	0-20	7.8	290	3.3	0.797	0.009	0.867	1.431	16.618	0.307	25.130	5.159	2.669
	S3	20-40	7.7	297	3.1	0.656	0.011	0.570	1.884	11.919	0.357	20.654	7.577	2.736
	S3	40-60	8.3	310	5.1	0.387	0.008	0.756	1.479	21.719	0.373	18.657	5.893	2.400

Table C22. Results of chemical analysis of soil samples from Syferfontein (begin of winter season 2004, Soil Science Laboratory, University of Pretoria).

Pivot	Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Soluble Cations				Exchangeable cations				
						Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
Syferfontein	S1	0-20	7.5	136	4.4	0.139	0.007	0.157	0.793	28.404	0.269	28.389	7.930	0.0
	S1	20-40	8.5	203	1.4	0.312	0.004	0.367	1.311	20.846	0.364	30.731	7.977	0.0
	S1	40-60	8.1	263	0.7	0.590	0.006	0.889	1.542	25.658	0.383	28.069	7.441	0.0
	S1	60-80	8.3	416	0.5	1.287	0.008	1.554	1.670	27.505	0.412	23.206	5.139	0.0
	S1	80-100	9.4	203	0.0	0.120	0.002	0.158	0.593	27.874	0.210	25.590	5.128	0.0
	S1	100-120	9.3	0	0.1	0.000	0.000	0.000	0.000	22.754	0.355	26.983	5.722	0.0
	S1	Parent material	9.2	240	0.2	0.218	0.004	0.343	0.727	28.425	0.397	28.368	4.168	0.0
	S2	0-20	8.0	188	0.4	0.402	0.007	0.420	0.915	30.037	0.813	27.962	6.329	0.0
	S2	20-40	8.0	0	0.5	0.000	0.000	0.000	0.000	41.766	0.736	24.267	6.070	0.0
	S2	40-60	8.0	373	0.6	1.174	0.012	1.223	1.712	40.493	0.604	26.995	7.751	0.0
	S2	60-80	8.4	0	0.6	0.000	0.000	0.000	0.000	42.116	0.417	26.571	6.896	0.0
	S2	Parent material	8.9	395	0.4	1.123	0.008	1.104	1.255	36.402	0.386	28.183	3.379	0.0
	S3	0-20	8.6	81.4	3.8	0.101	0.006	0.070	0.513	18.263	0.782	18.682	10.037	0.0
	S3	20-40	8.4	248	1.4	0.355	0.006	0.360	1.461	22.549	0.531	27.116	5.783	0.0
	S3	40-60	7.9	394	0.3	1.404	0.009	1.752	1.610	31.330	0.508	24.737	5.199	0.0
	S3	60-80	8.4	0	0.4	0.000	0.000	0.000	0.000	39.721	0.404	31.345	3.416	0.0
	S3	Parent material	9.0	253	2.6	0.430	0.003	0.531	0.609	31.007	0.331	25.711	4.460	0.0
	S4	0-20	8.6	124	1.0	0.143	0.005	0.101	0.661	19.218	0.553	22.273	8.366	0.0
	S4	20-40	8.0	296	0.5	0.661	0.006	0.775	1.521	23.591	0.405	22.834	7.071	0.0
	S4	40-60	9.3	198	0.5	0.195	0.003	0.264	0.877	32.440	0.232	25.978	5.497	0.0
	S4	60-80	8.8	295	0.5	0.473	0.003	0.573	0.792	31.912	0.211	23.529	3.581	0.0

	S4	Parent material	9.0	248	1.0	0.433	0.004	0.507	0.657	33.299	0.374	23.266	3.064	0.0
	S5+6	0-20	8.7	104	0.7	0.145	0.007	0.122	0.618	27.550	0.638	19.453	9.801	0.0
	S5+6	20-40	8.2	291	0.9	0.581	0.007	0.715	1.539	24.968	0.438	29.560	7.532	0.0
	S5+6	40-60	8.6	227	0.5	0.439	0.005	0.564	1.241	24.960	0.450	30.617	5.090	0.0
	S5+6	60-80	8.7	345	0.3	1.250	0.008	0.377	1.461	33.081	0.628	39.280	4.217	0.0
	S5+6	80-100	8.8	503	0.2	1.278	0.011	0.312	2.451	28.063	0.577	25.930	6.228	0.0
	S5+6	100-120	8.7	323	0.0	0.985	0.007	1.286	1.193	33.047	0.650	38.290	2.963	0.0
	S5+6	Parent material	8.9	257	0.4	0.590	0.006	0.745	0.848	31.995	0.618	31.176	2.829	0.0

Table C23. Results of chemical analysis of soil samples from New Vaal (2002/2003) summer season, Soil Science Laboratory, University of Pretoria.

	Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Soluble Cations				Exchangeable cations				
						Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
Pivot	NV (Lys)	40cm	6.4	27	8.81	0.014	0.005	0.004	0.023	1.139	0.038	0.359	0.135	0.082
	NV (Lys)	80cm	6.5	26	5.69	0.013	0.003	0.006	0.016	0.816	0.030	0.256	0.176	0.057
	NV (Lys)	100cm	6.7	23	5.08	0.010	0.003	0.003	0.02	0.549	0.026	0.199	0.156	0.068
	NV (Lys 2)	40cm	6.8	36	16.14	0.010	0.003	0.002	0.064	1.342	0.064	0.361	0.285	0.093
	NV (Lys 2)	60cm	6.5	31	6.82	0.013	0.001	0.005	0.031	0.685	0.024	0.271	0.257	0.043
	NV (Lys 2)	100cm	6.5	20	9.05	0.006	0.001	0.002	0.008	0.723	0.039	0.213	0.233	0.069
	NV	0.2m	5.7	121	7.56	0.106	0.006	0.058	0.326	0.990	0.052	0.369	0.118	0.243
	NV	0,4 m	4.9	118	10.69	0.114	0.008	0.076	0.230	0.113	0.032	0.199	0.118	0.163
	NV	0,6 m	5.7	92	3.09	0.111	0.003	0.082	0.169	0.341	0.018	0.410	0.014	0.183
	NV	0,8 m	6.0	58	2.39	0.060	0.002	0.083	0.036	0.217	0.011	0.644	-0.014	0.071

Table C24. Results of chemical analysis of soil samples from New Vaal (2003) winter season, Soil Science Laboratory, University of Pretoria.

Pivot	Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Soluble Cations				Exchangeable cations				
						Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
New Vaal	NV	0-20	4.2	95	1157.6	0.183	0.110	0.080	0.025	1.994	1.785	0.461	0.401	0.028
	NV	20-40	6.1	79	169.84	0.122	0.043	0.190	0.004	3.632	0.693	2.944	0.330	0.088
	NV	40-60	4.1	127	776.59	0.219	0.144	0.075	0.047	1.169	0.723	0.207	0.353	0.081
	NV	60-80	6.3	48	25.92	0.072	0.054	0.036	0.001	1.965	0.439	0.631	0.264	0.012
	NV	0-20	6.9	24	5.85	0.029	0.004	0.008	0.025	0.999	0.054	0.427	0.340	0.093
	NV	20-40	6.7	16	5.32	0.006	0.002	0.005	0.017	0.543	0.027	0.263	0.270	0.090
	NV	40-60	6.2	21	5.39	0.010	0.002	0.007	0.021	0.424	0.022	0.291	0.310	0.085
	NV	60-80	5.8	47	2.93	0.021	0.002	0.018	0.026	0.409	0.017	0.584	0.331	0.086
	NV	80-100	5.9	31	2.09	0.022	0.002	0.014	0.007	0.492	0.018	0.574	0.249	0.013
	NV	100-120	5.9	25	2.41	0.027	0.002	0.010	0.007	0.776	0.024	0.431	0.285	0.024
	NV	120-140	6.1	25	2.76	0.018	0.002	0.008	0.005	0.91	0.018	0.412	0.274	0.018

Table C25. Results of chemical analysis of soil samples from New Vaal (2003/2004) summer season, Soil Science Laboratory, University of Pretoria).

Pivot	Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Soluble Cations				Exchangeable cations				
						Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
New Vaal	NV1	0-20	8.2	99	18.4	0.116	0.011	0.074	0.256	1.121	0.112	0.236	0.531	0.145
	NV1	20-40	8.1	45	12.6	0.031	0.003	0.019	0.078	0.738	0.061	0.193	0.583	0.077
	NV1	40-60	8.0	38	2.5	0.024	0.002	0.014	0.071	0.855	0.052	0.214	0.542	0.074
	NV1	60-80	7.8	69	2.2	0.018	0.001	0.015	0.102	0.750	0.032	0.213	0.629	0.132
	NV1	80-100	7.0	108	2.2	0.044	0.002	0.061	0.187	0.964	0.039	0.578	0.643	0.213
	NV1	100-120	7.0	98	2.6	0.056	0.003	0.063	0.173	0.888	0.046	0.486	0.584	0.217
	NV1	120-140	6.8	49	3.4	0.058	0.002	0.044	0.053	1.713	0.059	0.957	0.482	0.038
	NV1	140-160	7.0	42	3.0	0.044	0.003	0.032	0.022	1.872	0.064	0.854	0.465	0.064
	NV1	160-180	7.0	22	2.9	0.035	0.003	0.023	0.014	1.717	0.061	0.740	0.378	0.039
	NV1	180-200	7.1	18	2.3	0.030	0.002	0.019	0.017	1.897	0.057	0.802	0.379	0.025
	NV2	0-20	7.1	62	51.7	0.040	0.017	0.028	0.180	1.781	0.246	0.603	0.738	0.072
	NV2	20-40	6.9	100	16.6	0.051	0.009	0.049	0.260	2.279	0.108	0.417	0.814	0.203
	NV2	40-60	7.1	93	3.2	0.064	0.006	0.033	0.214	1.398	0.071	0.351	0.587	0.076
	NV2	60-80	7.5	46	3.8	0.047	0.004	0.023	0.145	1.375	0.083	0.757	0.594	0.084
	NV2	80-100	7.4	61	3.9	0.035	0.003	0.029	0.135	1.243	0.099	1.277	0.630	0.096
	NV2	100-120	7.2	77	3.0	0.038	0.004	0.048	0.160	1.474	0.088	1.332	0.609	0.160
	NV3	0-20	7.6	60	17.4	0.054	0.012	0.027	0.145	1.972	0.213	0.678	0.590	0.050
	NV3	20-40	7.3	202	6.8	0.061	0.006	0.078	0.565	2.040	0.068	0.578	0.888	0.479
	NV3	40-60	7.5	149	3.1	0.090	0.002	0.076	0.392	1.821	0.051	1.346	0.921	0.366
	NV3	60-80	7.6	0	1.9	0.117	0.002	0.110	0.287	1.879	0.067	1.229	0.635	0.378
	NV3	80-100	7.2	0	2.7	0.143	0.004	0.161	0.233	1.878	0.062	0.997	0.468	0.393
	NV3	100-120	7.0	0	3.7	0.243	0.005	0.211	0.172	1.888	0.125	1.400	0.528	0.440

Table C26. Results of chemical analysis of soil samples from New Vaal (begin of winter season 2004, Soil Science Laboratory, University of Pretoria).

Pivot	Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Soluble Cations				Exchangeable cations				
						Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
	S1	0-20 1	5.3	104	33.6	0.092	0.026	0.073	0.159	1.425	0.175	0.513	0.086	0.019
	S1	0-20 2	6.3	57	8.3	0.047	0.013	0.031	0.065	0.477	0.096	0.201	0.080	0.103
	S1	0-20 3	60	50	2.8	0.050	0.004	0.030	0.052	0.449	0.039	0.218	0.057	0.112
	S1	0-20 4	5.9	63	2.9	0.052	0.003	0.041	0.075	0.477	0.032	0.314	0.026	0.104
	S1	0-20 5	5.0	52	1.8	0.022	0.002	0.016	0.100	0.532	0.031	0.397	0.110	0.030
	S1	0-20 6	6.3	66	1.7	0.026	0.002	0.025	0.130	0.547	0.025	0.306	0.150	0.123
	S2	0-20 1	6.1	73	41.4	0.065	0.017	0.041	0.095	1.212	0.200	0.422	0.098	0.010
	S2	0-20 2	6.0	51	11.4	0.050	0.013	0.036	0.055	0.468	0.086	0.196	0.050	0.021
	S2	0-20 3	5.6	30	3.9	0.035	0.015	0.020	0.029	0.254	0.071	0.097	0.071	0.010
	S2	0-20 4	5.4	49	2.3	-0.323	-0.041	-0.201	-0.601	0.787	0.089	0.441	0.741	-0.354
	S2	0-20 5	5.6	43	2.0	0.031	0.004	0.026	0.068	0.453	0.037	0.337	0.102	0.014
	S2	0-20 6	5.6	49	1.4	0.023	0.002	0.015	0.102	0.516	0.025	0.300	0.125	0.056
	S3	0-20 1	6.0	90	25.6	0.089	0.017	0.053	0.129	1.129	0.128	0.376	0.103	0.038
	S3	0-20 2	5.1	57	6.7	0.045	0.010	0.031	0.081	0.818	0.104	0.357	0.133	0.014
	S3	0-20 3	5.3	120	2.0	0.074	0.006	0.072	0.198	0.555	0.060	0.415	0.090	0.211
	S3	0-20 4	5.7	134	1.8	0.049	0.004	0.038	0.301	0.615	0.051	0.449	0.187	0.222
	S3	0-20 5	5.9	104	2.1	0.092	0.006	0.077	0.432	0.691	0.052	0.460	0.151	0.382
New Vaal	S3	0-20 6	6.2	199	2.1	0.301	0.006	0.157	0.329	0.552	0.031	0.453	0.167	0.428

Table C27. Results of chemical analysis of soil samples from New Vaal (begin winter 2005, Soil Science Laboratory, University of Pretoria).

Pivot	Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Soluble Cations				Exchangeable cations				
						Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
New Vaal	S1	0-20	6.7	44	27.6	0.108	0.014	0.082	0.128	0.970	0.066	0.333	-0.013	0.011
	S1	20-40	6.7	16	5.7	0.012	0.006	0.006	0.052	0.527	0.087	0.236	0.050	0.015
	S1	40-60	6.5	19	4.3	0.027	0.013	0.022	0.070	0.432	0.049	0.269	-0.015	0.005
	S1	60-80	6.7	18	4.4	0.018	0.010	0.012	0.071	0.461	0.065	0.230	0.015	0.006
	S1	80-100	6.7	35	2.6	0.059	0.010	0.065	0.168	0.919	0.058	0.761	0.000	0.058
	S1	100-120	6.5	63	3.0	0.102	0.009	0.134	0.202	1.175	0.048	0.890	-0.060	0.104
	S2	0-20	6.7	38	23.8	0.046	0.020	0.043	0.037	1.371	0.142	0.511	0.027	0.003
	S2	20-40	5.9	78	8.6	0.066	0.008	0.066	0.188	0.477	0.039	0.209	-0.003	0.154
	S2	40-60	5.6	38	4.1	0.025	0.009	0.018	0.094	0.335	0.056	0.167	0.022	0.063
	S2	60-80	5.7	59	4.2	0.048	0.014	0.045	0.141	0.591	0.081	0.272	0.009	0.097
	S2	80-100	5.6	68	4.6	0.041	0.006	0.061	0.203	0.498	0.038	0.304	-0.044	0.060
	S2	100-120	5.9	109	4.0	0.064	0.007	0.156	0.235	0.555	0.030	0.514	-0.011	0.178
	S3	0-20	7.2	286	26.3	0.089	0.035	0.245	0.715	1.813	0.124	0.491	-0.068	0.165
	S3	20-40	7.1	337	6.6	0.403	0.019	0.332	0.774	0.521	0.054	0.264	-0.058	0.205
	S3	60-80	6.9	250	4.5	0.417	0.008	0.332	0.418	0.501	0.027	0.263	-0.085	0.104
	S3	80-100	6.8	205	3.0	0.383	0.006	0.295	0.296	0.659	0.018	0.351	-0.011	0.051
	S3	100-120	6.8	208	2.4	0.441	0.006	0.308	0.306	0.707	0.018	0.370	-0.033	0.083

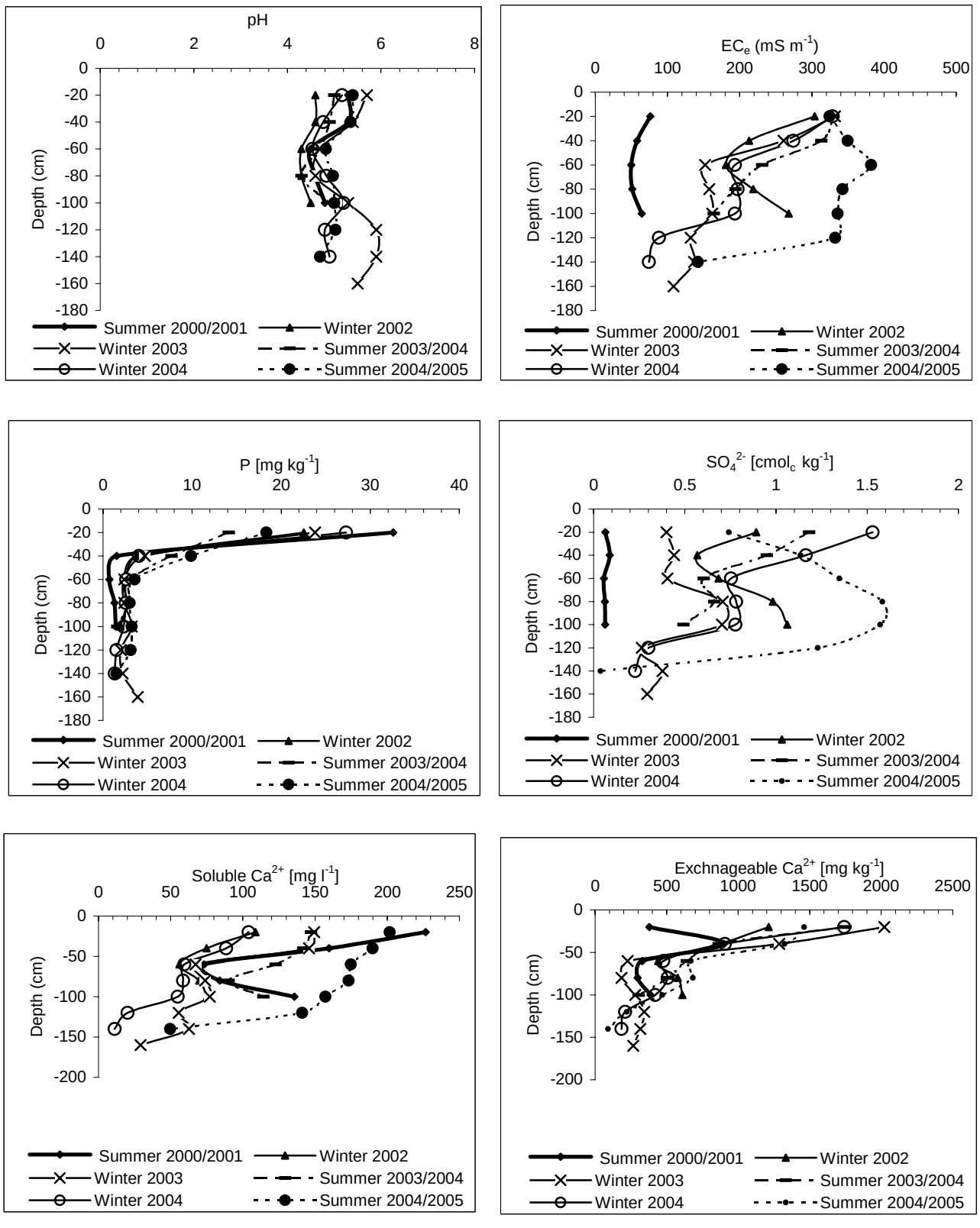
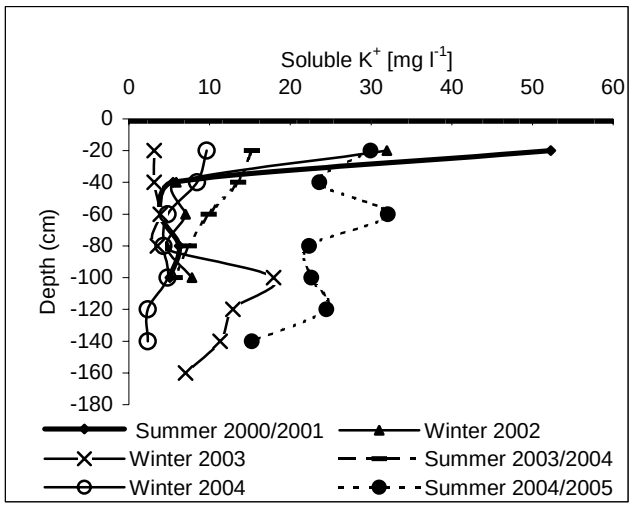
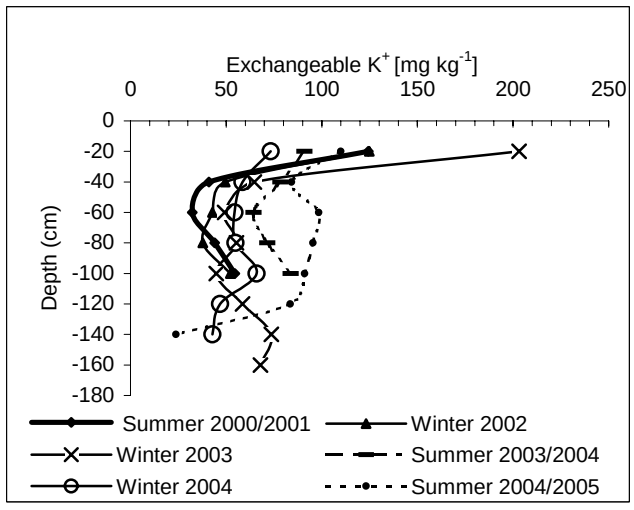
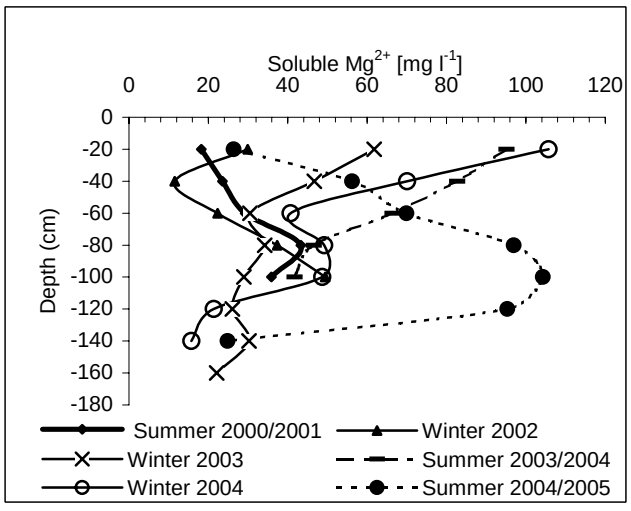
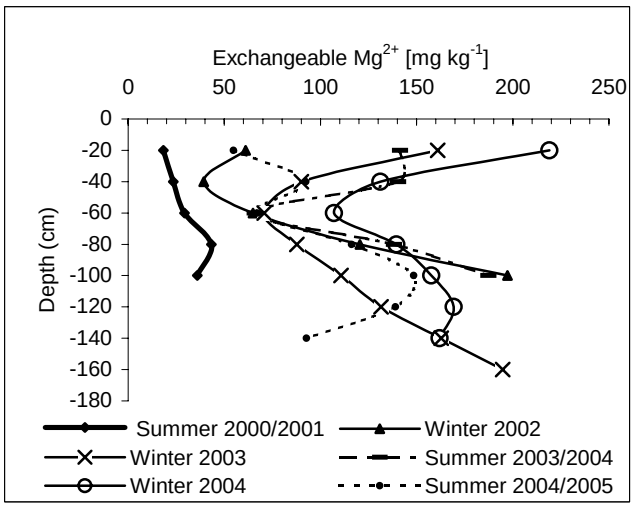


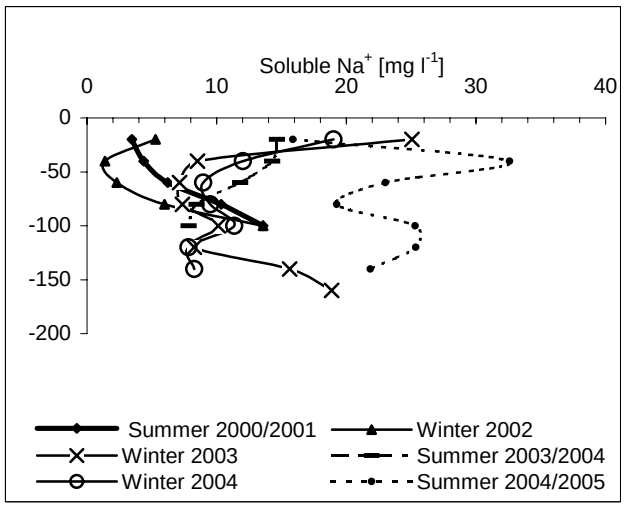
Figure C1. Soil analysis results during crop rotations at Major.











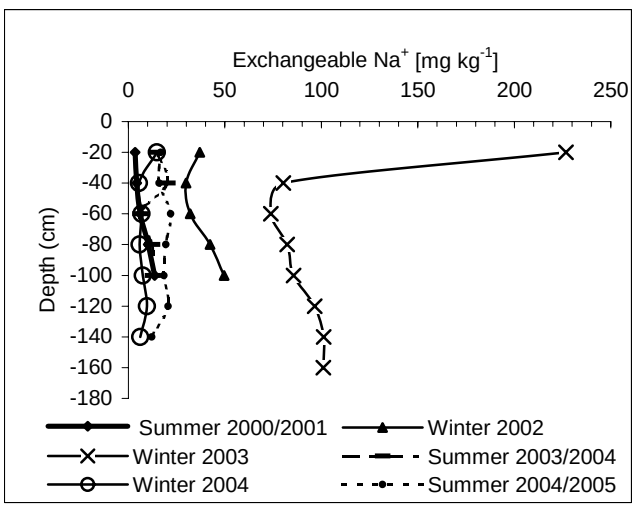


Figure C2. Soil analysis results during crop rotations at Major.

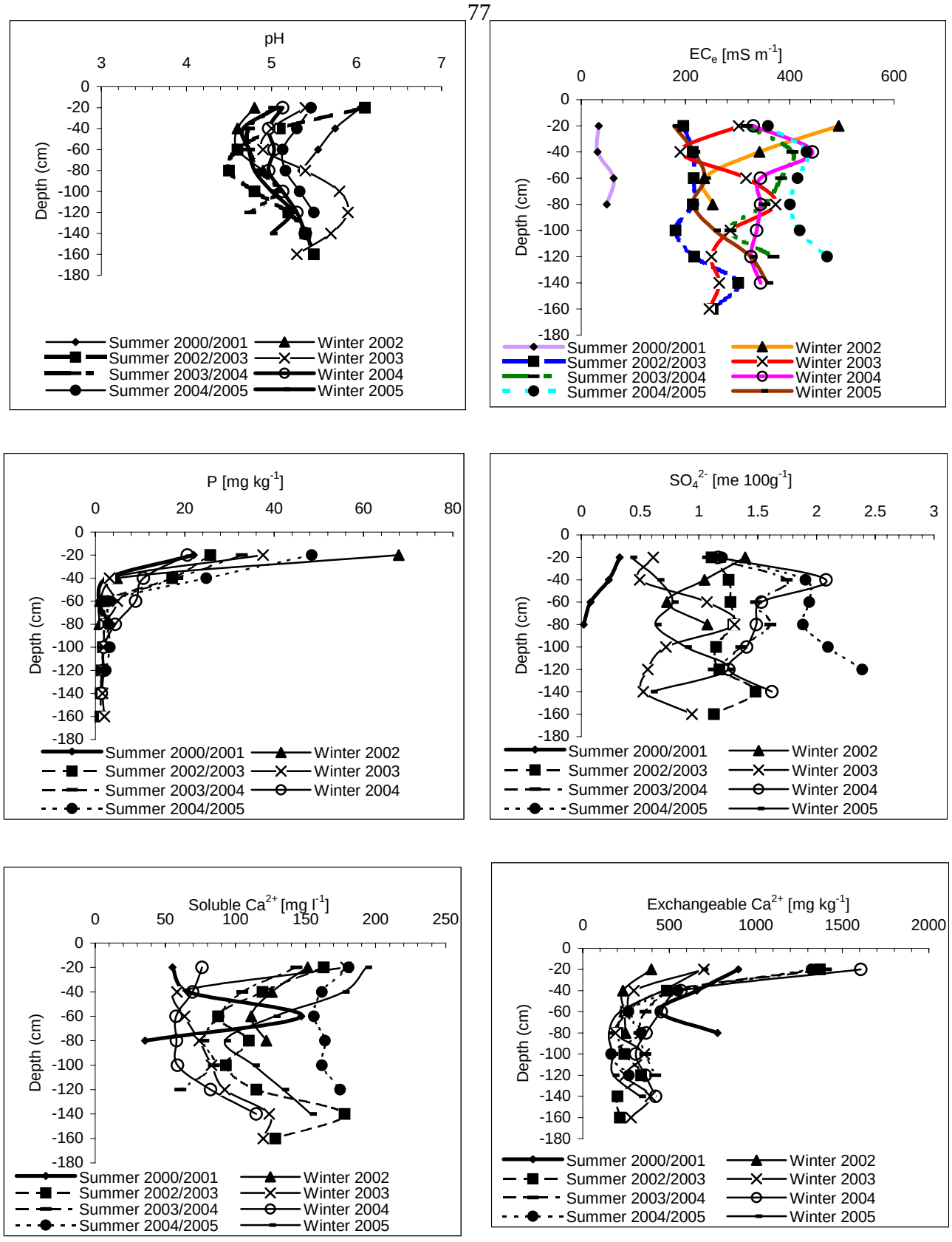
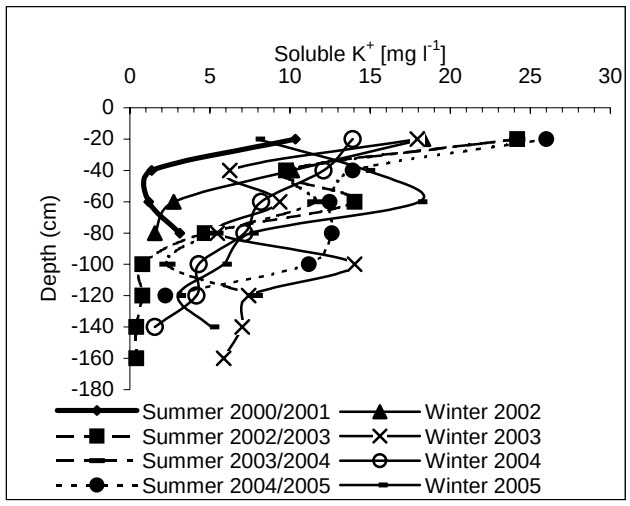
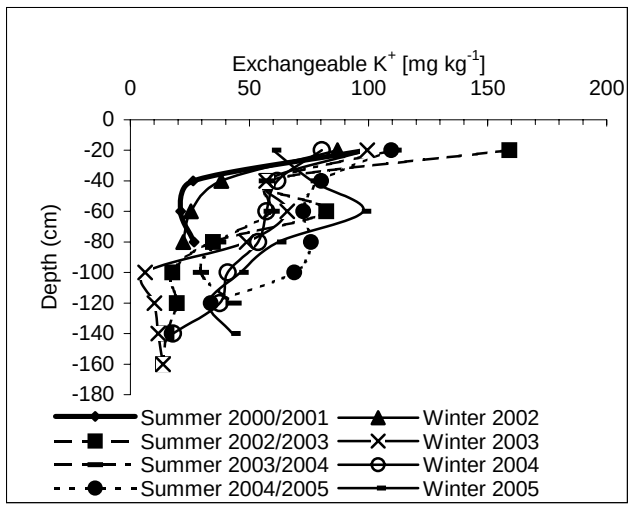
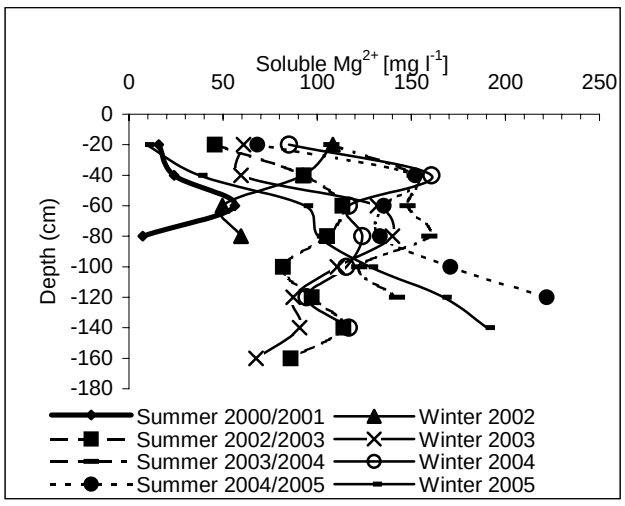
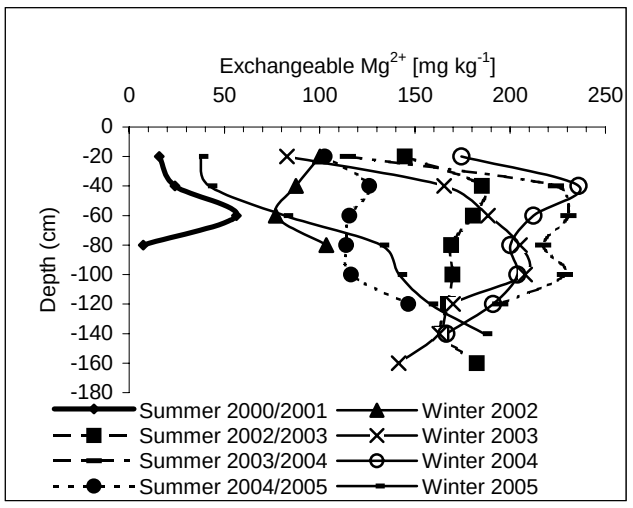


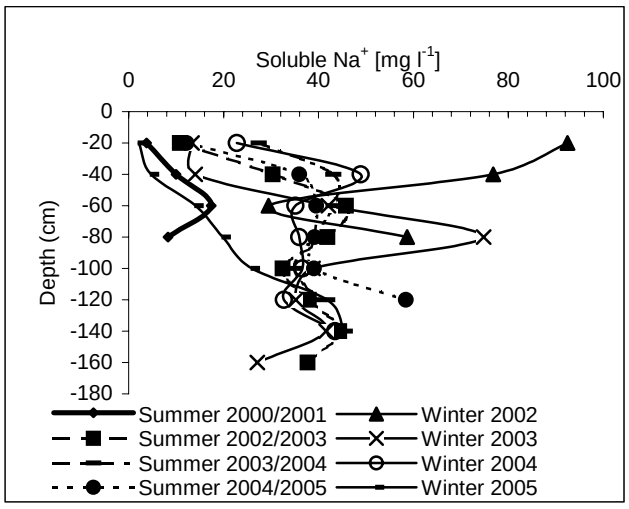
Figure C3 Soil analysis results during crop rotations at Pivot 4











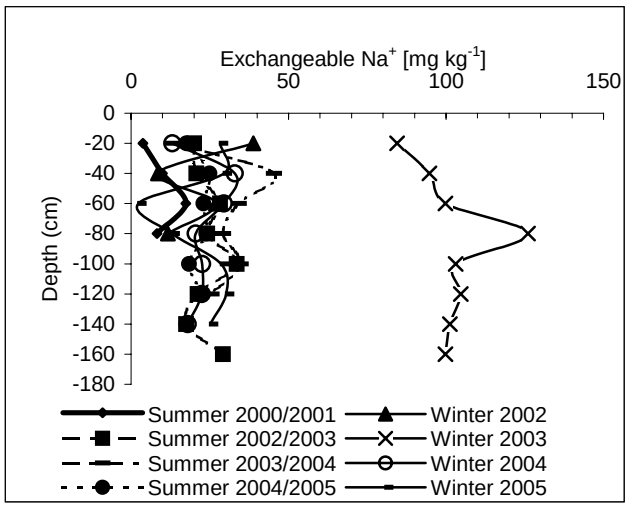


Figure C4 Soil analysis results during crop rotations at Pivot 4

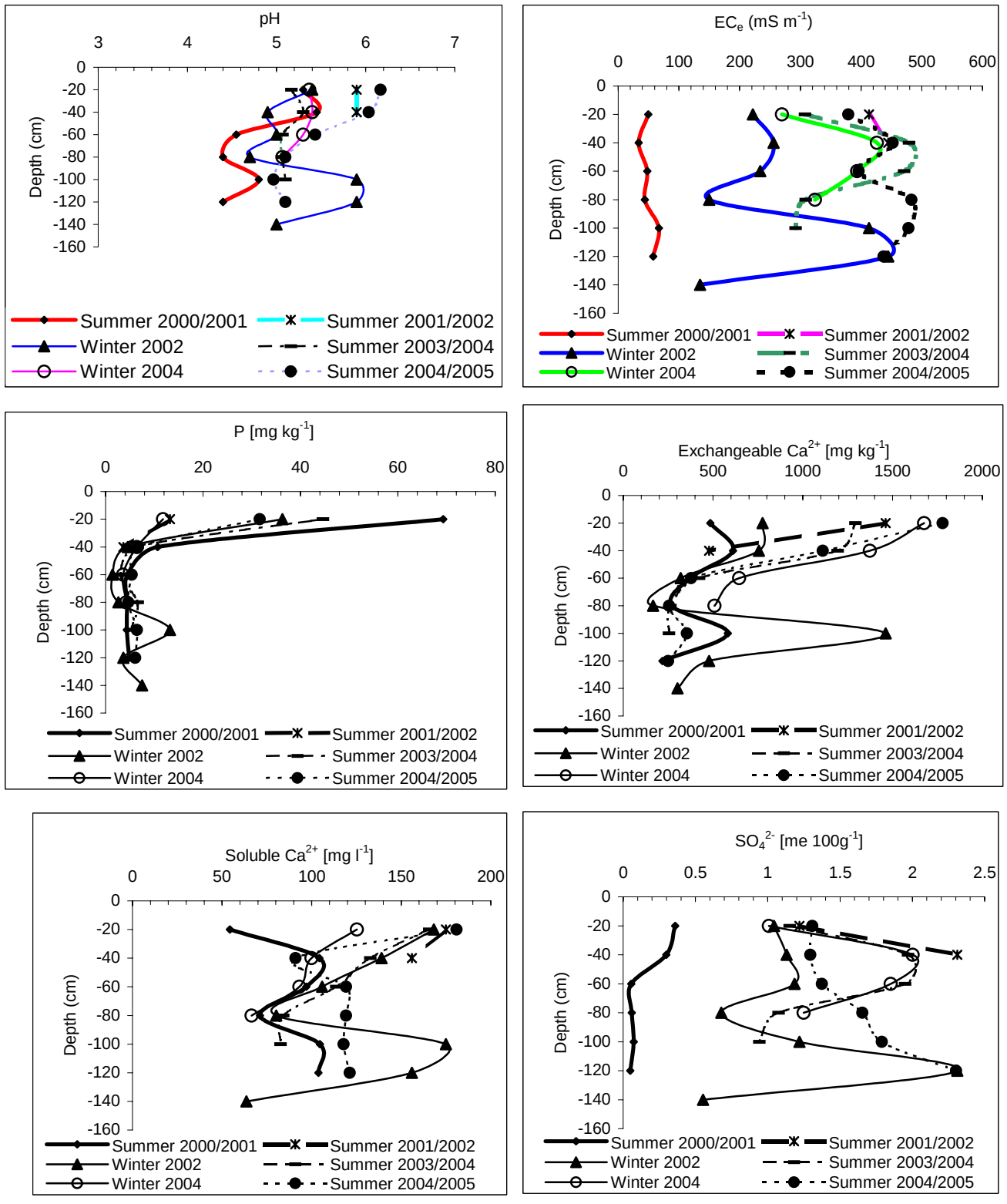


Figure C5. Soil analysis results during crop rotations at TWF.

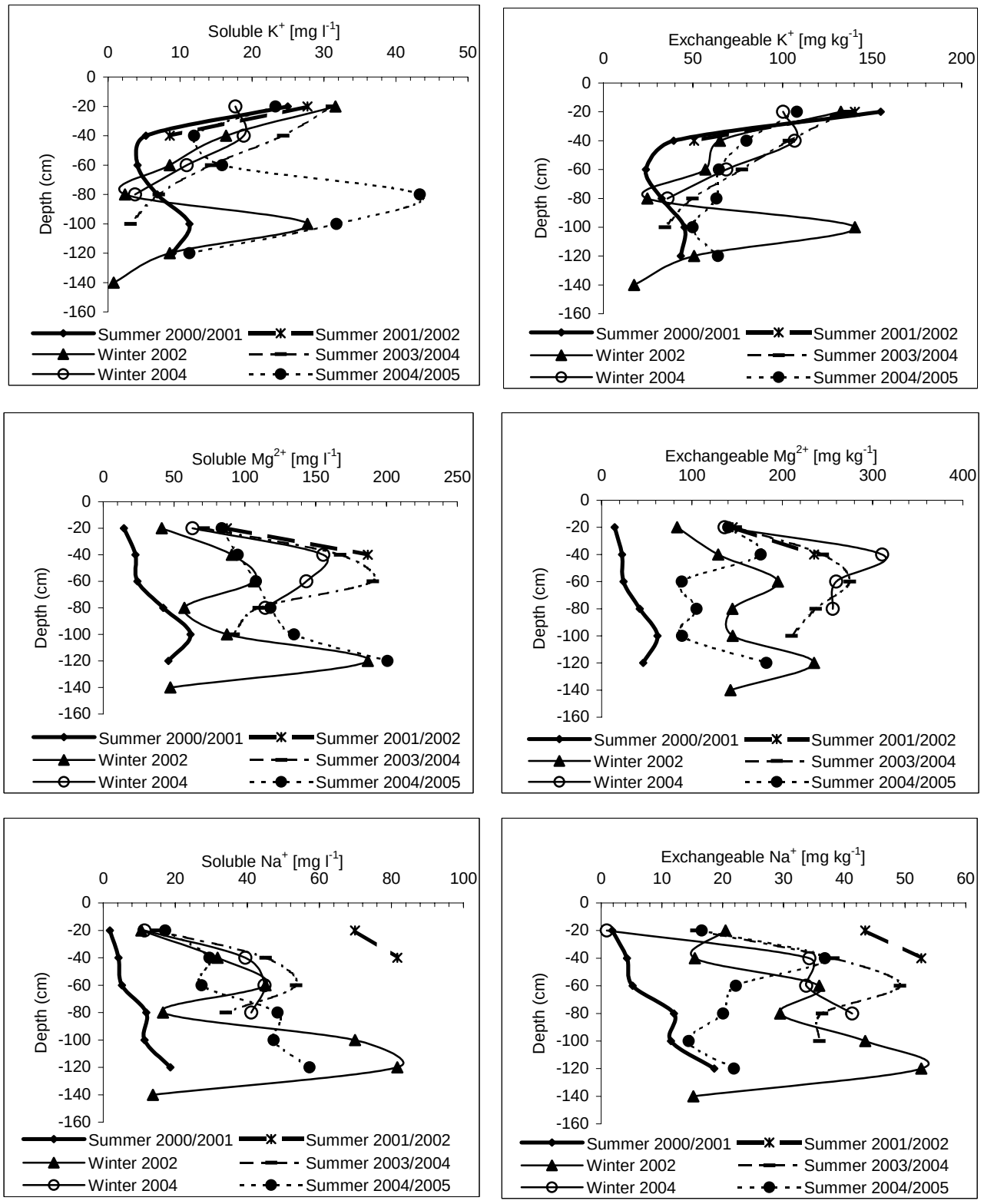


Figure C6. Soil analysis results during crop rotations at TWF.

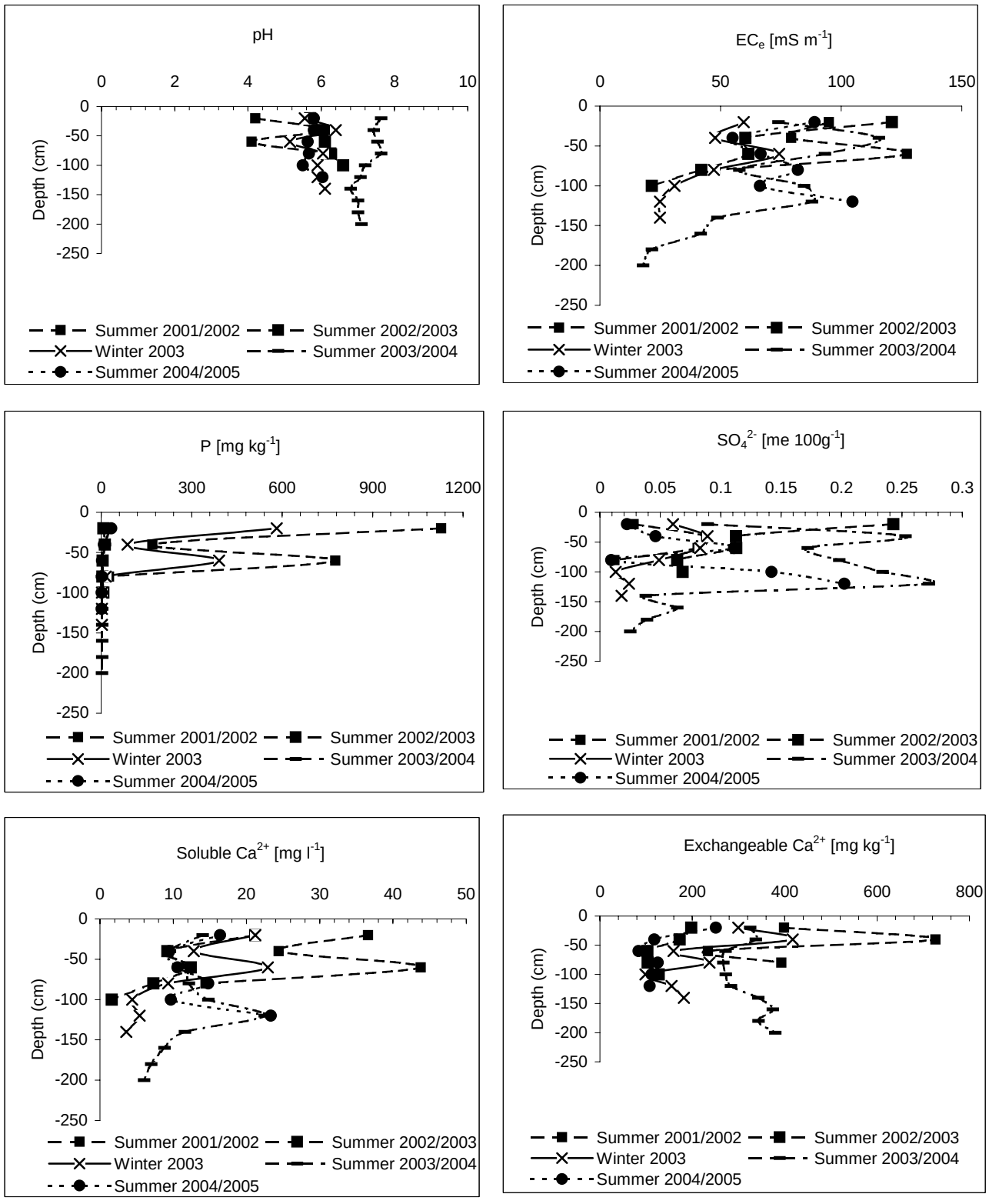


Figure C7. Soil analysis results during crop rotations at New Vaal.

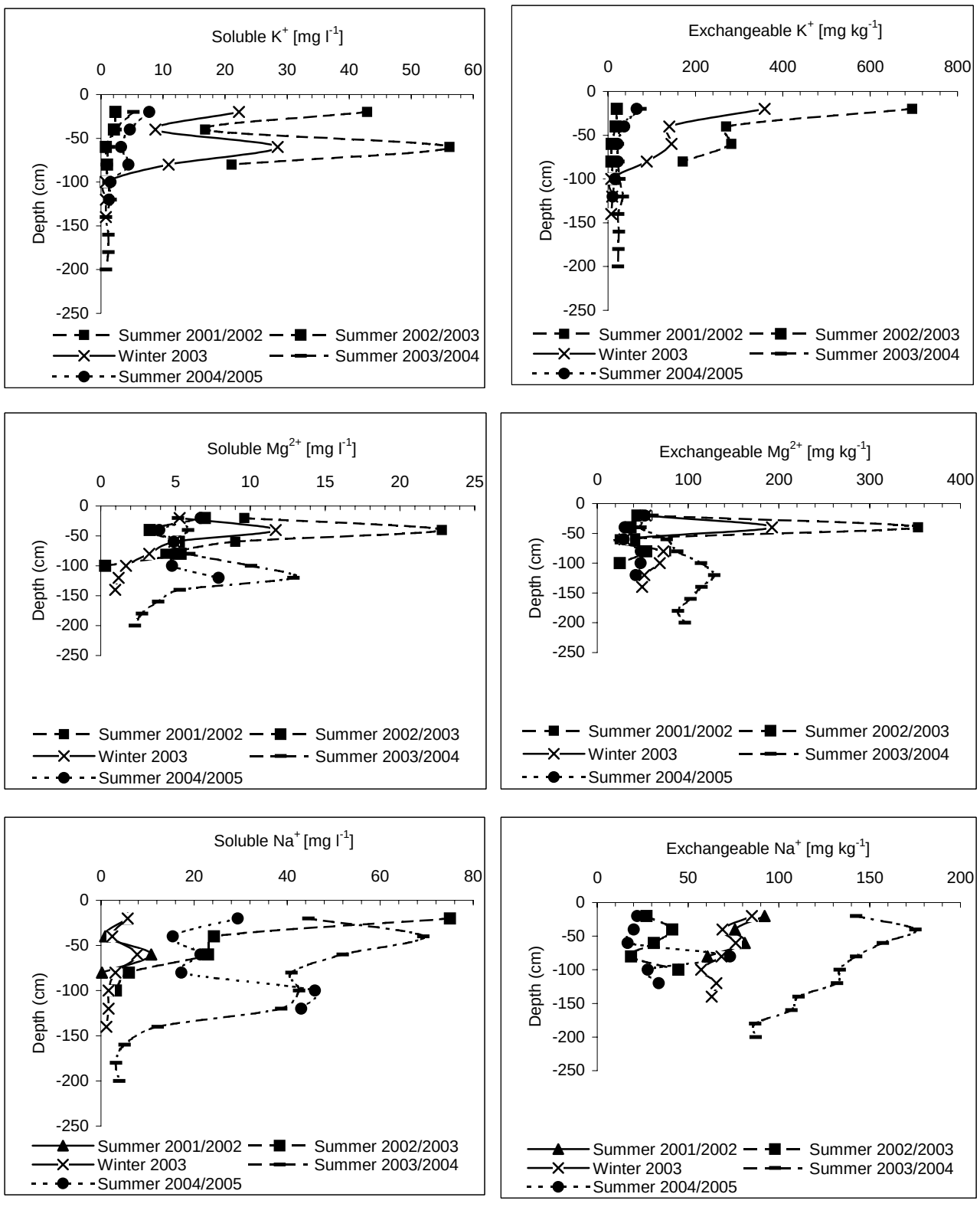


Figure C8 Soil analysis results during crop rotations at New Vaal.

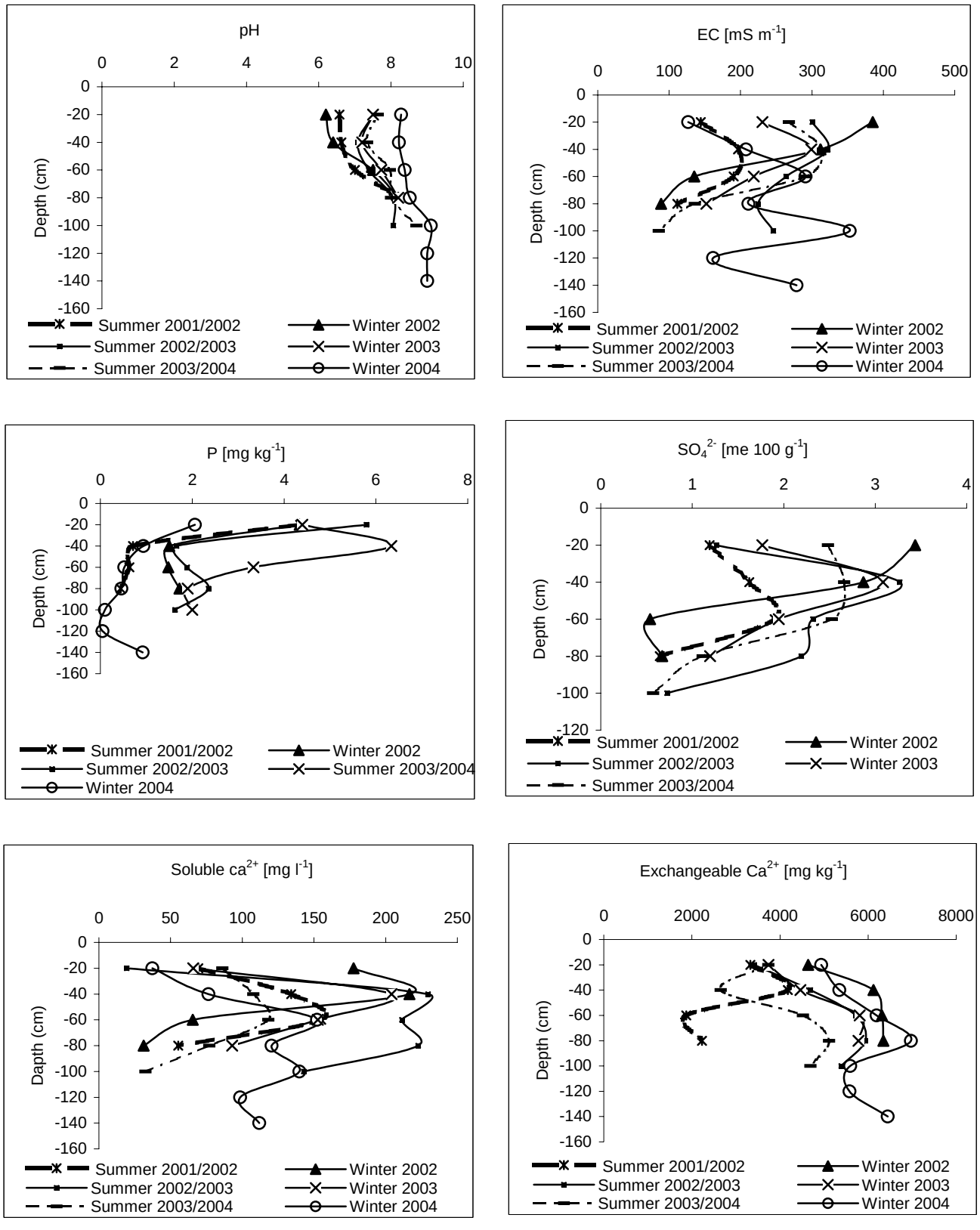


***Figure C9*.** Soil analysis results during the growing period of planted pastures at Syferfontein.

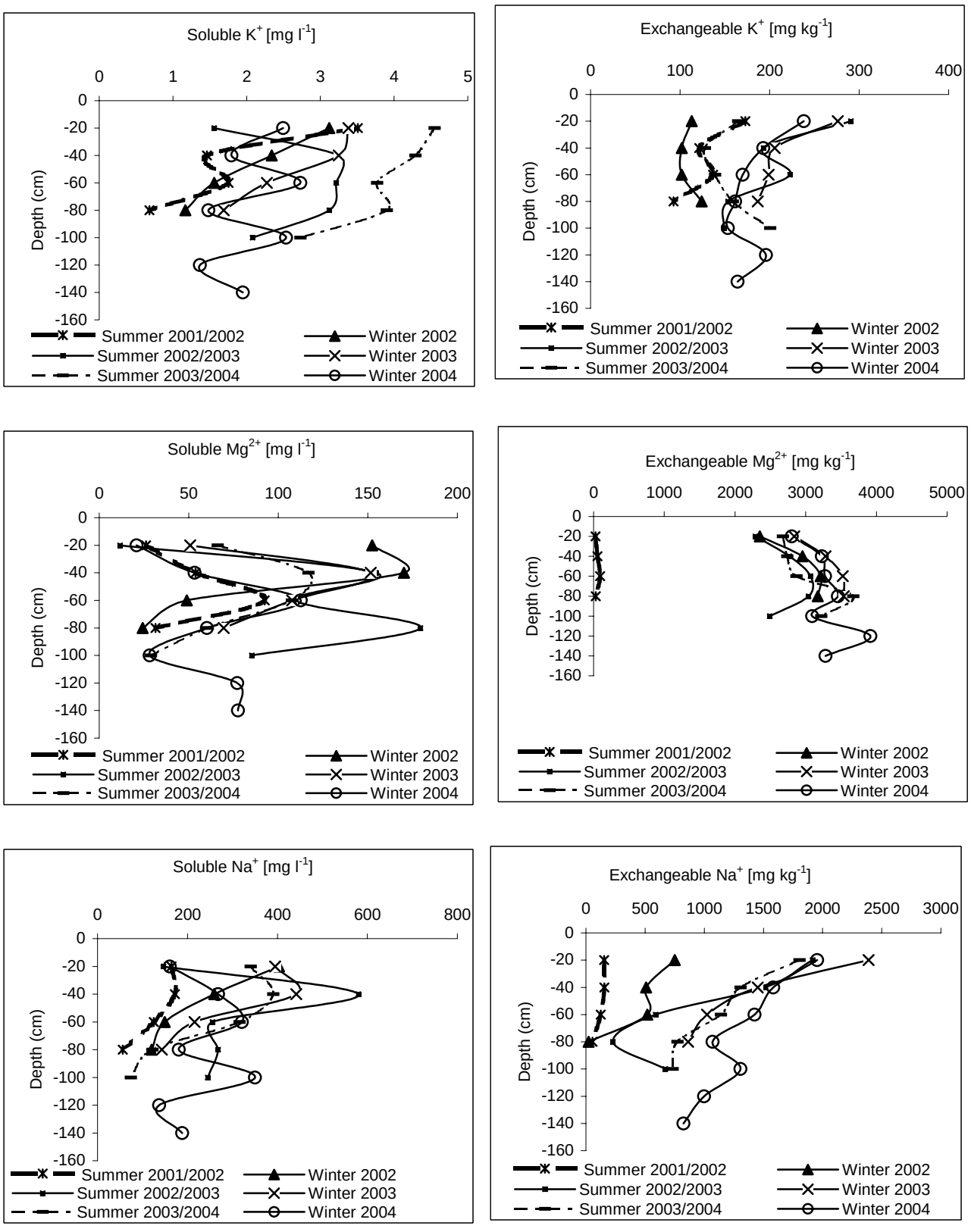


***Figure C.10*.** Soil analysis results during the growing period of planted pastures at Syferfontein.

Appendix D

Soil water and runoff chemical analyses

Table D1. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers (CC) and wetting front detectors (WFD) at Kleinkopjé (maize crop, 2000/2001 summer season, Soil Science Laboratory, University of Pretoria).

Pivot	Date	Site	Instr	Depth (m)	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
Major	01/02/2001	M2	CC	0.4							21.8	719.1
		M2	WFD	0.6							186.3	989.7
	28/02/2001	M2	WFD	0.6	6.3	104	576	6.2	152	38	10.1	1978.9
Tweefontein	28/02/2001	T1	CC	1.0	4.5	183	617	13.6	442	183	53.9	4010.4
		T2	WFD	0.3	5.4	150	879	18.3	280	79	6.0	3892.3
		T2	WFD	0.6	5.3	107	541	17.4	181	55	39.3	1997.0
Four	05/01/2001	F1	CC	1.4	6.1	213	661	5.3	190	72	35.8	1983.3
		F2	CC	1.0	6.4	106	227	17.6	110	42	33.7	976.3
		F2	CC	1.4	6.2	116	289	12.1	84	44	171.2	759.1
		F2	WFD	0.3	5.9	148	282	58.8	106	30	168.2	341.4
	01/02/2001	F1	CC	1.4	6.5	135	654	4.2	215	70	40.3	553.4
		F2	CC	1.0	6.6	90	287	14.1	178	54	28.2	417.7
		F2	CC	1.4	6.0	83	247	10.8	75	45	278.5	804.3
	28/02/2001	F1	CC	1.0	6.8	125	578	12.0	258	64	54.4	2074.8
		F1	CC	1.4	5.5	128	631	3.9	201	64	43.8	2078.8
		F2	CC	1.0	5.1	118	415	10.1	291	70	40.3	2052.3
		F2	CC	1.4	4.1	71	297	6.7	89	54	156.6	877.7
		F1	WFD	0.3	7.0	81	371	22.7	135	42	65.5	2472.5
		F1	WFD	0.6	7.0	117	558	2.7	212	49	22.2	1878.4
		F2	WFD	0.3	6.2	116	540	28.8	195	58	120.3	1988.4
	08/03/2001	F1	CC	1.0	7.9	342	586	10.2	268	68	34.2	2465.3
		F1	CC	1.4	6.5	318	603	2.16	191	59	41.8	2211.2
		F2	CC	1.0	6.8	346	467	6.24	333	76	30.7	2897.8
		F2	CC	1.4	3.4	2	358	3.32	107	61	131.9	1416.5
		F1	WFD	0.3	7.3	168	270	15.4	97	31	23.2	930.8
		F2	WFD	0.3	6.7	246	430	24.8	135	54	20.6	1671.6

Table D2. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers (CC) and wetting front detectors (WFD) at Kleinkopjé (wheat crop, 2001 winter season, Soil Science Laboratory, University of Pretoria).

Pivot	Date	Site	Instr	Depth (m)	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
Tweefontein	8/07/2001	T1	WFD	0.3	5.1	479	618	65.5	394	125	281.0	2665.9
		T2	WFD	0.6	4.7	373	580	34.1	234	87	70.0	2415.7
Four	17/10/2001	F1	CC	0.4	6.5	569	548	182.0	483	153	310.2	3175.5
		F1	CC	1.4	6.1	339	417	10.5	300	73	73.0	2237.6
		F2	CC	0.4	7.2	454	589	54.3	343	102	212.0	2606.3
		F2	CC	1.0	7.4	421	640	10.3	327	87	93.2	2175.5
		F2	CC	1.4	6.7	337	460	5.69	251	66	92.1	2263.0

Table D3. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers (CC) and wetting front detectors (WFD) at Kleinkopjé (maize crop, 2001/2002 summer season, Soil Science Laboratory, University of Pretoria).

Pivot	Date	Instr	Depth (m)	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
Major	10/01/2002	CC	1.4	6.6	284	390	2.71	224	86	101.2	1240.6
	07/02/2002	CC	1.4	7.1	34	35	1.98	15	8	13.6	1051.8
		CC	1.0	8.1	53	55	1.17	32	16	7.6	64.5
	07/02/2002	WFD	0.3	7.3	48	32	0.26	34	9	14.6	24.6
		WFD	0.6	7.4	40	30	0.22	31	7	13.6	12.0
	26/02/2002	WFD	0.6			644	40.4	717	266	183.3	3647.5
		CC	0.4	6.6	194	97	19.4	72	54	36.3	739.3
	12/03/2002	CC	0.4	7.2	371	528	38.9	389	133	45.3	2532.5
		CC	1.0			426	35.6	327	114	72.5	2089.4
		CC	1.4	5.3	171	163	18.7	124	69	0.0	694.4
	26/03/2002	CC	1.4	6.1	177	353	17.3	254	156	36.3	905.2
	12/04/2002	CC	1.0	5.0	173	283	16.9	244	123	40.3	959.4
	22/04/2002	CC	0.4	6.0	416	1038	36.0	809	198	40.8	25.3
		CC	1.4	5.1	146	265	16.8	223	51	36.3	768.2
Tweefontein	26/02/2002	CC	0.4	8.0	433	530	55.4	408	109	52.4	2612.6
	12/03/2002	WFD	0.3	6.7	344	518	26.3	364	103	37.3	3132.5
	12/04/2002	CC	0.4	6.1	483	1049	55.4	1005	303	54.4	757.0
	22/04/2002	CC	0.4	6.1	466	1054	55.0	978	294	52.4	632.1

Table D4. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers (CC) and wetting front detectors (WFD) at Kleinkopjé (maize crop, 2002/2003 summer season, Soil Science Laboratory, University of Pretoria).

Pivot	Date	Instr	Depth (m)	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})
Major	18/11/2002	WFD	0.3	5.1	390	692	254	85	94.6	
	15/01/2003	WFD	0.6	4.5	352	599	32.4	374	134.0	
	15/01/2003	CC	1.0	4.7	489	612	13.1	623	209.0	
Four	05/11/2002	WFD	0.6	5.3	371	592	65.8	295	42.0	
	05/11/2002	WFD	0.3	545	904	45	5482.2	298	166.2	
	05/11/2002	WFD	0.6	7.1	672	460	53.6	950	273.0	
	05/11/2002	CC	1.4	7.2	369	605	2.55	282	93.0	
	15/01/2003	CC	1.0	6.5	515	697	697.0	576	1440.0	
	23/01/2003	CC	1.0	7.5	5	644	3.8	573	208.0	
	25/02/2003	CC	0.3	7.1	6	750	89.5	549	208.0	
	12/03/2003	WFD	0.6	8.1	424	642	41.5	514	332.0	
	06/03/2003	WFD	0.6	6.9	507	670	39.4	553	251.0	
Tweefontein	15/01/2003	WFD	1.0	7.4	5	522	525.0	155	277.0	
	12/03/2003	WFD	0.3	8.1	515	614	90.2	722	273.0	
	12/03/2003	WFD	0.6	6.3	560	697	5.52	633	251.0	
	04/02/2003	WFD	0.6	4.7	5	660	671.0	8.41	158.0	
	04/02/2003	CC	1.0	5.0	5	649	619.0	17.4	136.0	

Table D5. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers (CC) and wetting front detectors (WFD) at Kleinkopjé (2003 winter season, Soil Science Laboratory, University of Pretoria).

Pivot	Date	Site	Instr	Depth (m)	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
Major	05/07/2002	M	CC	1.4	5	143	101	15.8	87	54		
	23/08/2002	M	CC	1.4	5.5	348	464	10.9	236	77		
	18/08/2003	M	CC	0.4	6.8	457	523	68.8	391	92	121.9	2387.3
	21/08/2003	M	CC	0.3	6.3	442	531	69.6	373	103	124.9	4316.6
	21/08/2003	M	CC	0.9			535	52.8	329	108		3557.9

Table D6. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers (CC) at Kleinkopjé (2003/04 summer season, Soil Science Laboratory, University of Pretoria).

Pivot	Date	Site	Instr	Depth (m)	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
Major	30/04/03	M1	CC	1.0	7.1	577	680	4.2	730	213.0	130.9	4214.0
	17/10/03	M1	CC	1.4	6.3	370	511	16.4	288	395.0	15.6	3073.7
	17/09/03	M2	CC	1.4	7.0	275	381	21.4	188	67.0	46.8	1428.3
	17/09/03	M3	CC	1.0	7.0	275	381	21.4	188	67.0	46.8	1428.3
	01/10/03	M	CC	1.4	6.3	181	213	13.6	121	53.0	39.8	408.6
	01/12/03	M	CC	0.4	7.8	198	191	14.2	131	72.0	51.4	1113.1
	24/12/03	M1	CC	1.4	8.2	433	578	25.1	407	71.0	25.2	3292.9
	24/12/03	M2	CC	1.4	8.3	352	525	17.7	296	46.0	14.6	2296.0
	24/12/03	M3	CC	1.4	8.3	361	527	17.3	283	46.0	16.1	2486.9
	07/01/04	M1	CC	0.9	7.1	423	469	24.6	357	85.0	118.8	2671.7
	26/02/04	M	CC	0.3	6.5	561	547	10.16	660	115.0	42.3	3825.3
	26/02/04	M	CC	1.0	6.1	530	536	13.9	520	123.0	218.5	3382.0
	11/03/04	M	CC	0.6	6.9	491	502	14.5	558	108.0	136.5	3158.1
	11/03/04	M	CC	1.0	7.1	597	494	5.8	818	148.0	205.4	4359.7
	29/03/04	M	CC	0.3	7.6	434	480	12.0	471	57.0	11.6	2910.5
	29/03/04	M	CC	0.6	7.7	579	495	7.5	767	131.0	223.6	3765.8
	29/03/04	M	CC	1.0	7.7	484	509	25.3	476	102.0	178.3	2946.3
Tweefontein	17/10/03	TWF	CC	0.9	6.6	430	550	41.2	390	725.0	61.9	4196.8
	26/02/04	TWF	CC	0.9	6.5	718	453	9.9	985	351.0	50.4	4086.6
Four	30/04/03	F	CC	1.0	7.1	577	680	4.2	730	213.0	130.9	4214.0
	17/10/03	F	CC	1.0	7.6	475	639	38.1	441	700.0	61.9	4376.5
	17/09/03	F	CC	1.2	6.4	526	478	4.04	573	197.0	143.5	3874.5
	26/02/04	F	CC	1.0	6.8	447	406	21.4	339	128.0	177.7	2462.0
	11/03/04	F	CC	1.0	6.6	483	531	8.0	494	267.0	236.7	2911.9
	26/03/04	F	CC	1.4	7.6	621	601	3.1	664	243.0	343.4	3746.4

Table D7. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers (CC) at Kleinkopjé (2004/05 summer season, Soil Science Laboratory, University of Pretoria).

Pivot	Date	Instr	Depth (m)	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
Major	08/12/2004	CC	0.3	7.2	301	579	21.2	637	32	22.2	1641.0
		CC	1.4	7.8	375	658	21.0	994	50	32.2	2385.0
		WFD	0.6	7.3	276	524	20.1	837	94	15.6	1930.3
	14/08/2004	CC	1.0	6.7	261	476	17.4	294	63	61.4	1639.0
		CC	1.4	6.7	261	476	17.4	294	60	61.4	1171.4
		CC	1.4	6.4	290	440	17.7	294	51	71.0	1963.2
	02/10/2004	CC	1.0	6.5	398	659	10.1	494	71	45.8	2962.6
	16/10/2004	CC	1.0	6.6	1147	707	9.5	2960	350	148.5	11674.7
	21/10/2004	CC	1.0	6.5	553	689	19.1	990	120	69.0	3833.4
	06/11/2004	CC	1.0	7.1	440	662	25.6	627	84	48.8	2756.2
		WFD	1.0	0.0	284	697	35.9	649	106		2963.7
	15/05/2005	CC	1.0	6.6	346	498	44.4	432	50	47.8	2443.5
Four	24/09/2004	WFD	0.3	7.1	270	489	40.3	285	80		2162.3
		WFD	0.6	6.7	270	494	54.4	353	110		2500.8
		WFD	0.9	6.4	313	617	99	307	87		2801.4
	24/09/2004	CC		6.7	996	647	6.2	2165	414	173.7	8360.2
	02/10/2004	CC		6.5	1118	687	3.1	2565	480	228.1	9914.5
	16/10/2004	CC	1.0	6.8	1319	728	3.8	3345	511	360.0	12387.7
	26/02/2005	CC	0.9	6.6	94	488	52.7	1600	298	177.2	7392.6
	14/08/2004	CC	0.6	5.4	706	608	76.7	1	237	196.9	5696.2
		CC	0.6	7.4	838	722	88.6	1620	272	215.0	6038.7
	24/09/2004	CC	0.3	0.0	0	786	48.3	1210	266	0.0	5935.8
		CC	0.9	7.5	859	708	76.3	1575	268	202.4	6429.2

Tweefontein		CC	0.6	7.3	949	739	66.2	1975	317	233.6	8673.0
	16/10/2004	CC	0.9	7.4	1061	721	50.7	2495	387	247.7	9315.6
	06/11/2004	CC	0.9	8.4	19000	699	131.0	5530	880	565.5	16541.3
	15/05/2005	CC	1.0	6.7	911	500	95.3	1410	49	281.0	7688.3

Table D8. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers (CC) and wetting front detectors (WFD) at New Vaal (Maize, 2001/2002 summer season, Soil Science Laboratory, University of Pretoria).

Pivot	Date	Instr	Depth (m)	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
New Vaal	10/01/2002	WFD	0.6	6.9	61	58	4.16	28	19.0	24.2	31.0
		CC	1.0	6.9	43	42	1.88	17	12.0	8.6	121.0
		CC	1.4	6.7	44	37	5.15	16	10.0	15.6	110.4
	24/01/2002	CC	1.0	7.2	45	39	1.27	15	26.0	6.0	15.1
		CC	1.4	6.7	36	38	4.22	11	48.0	11.6	63.3
	19/02/2002	WFD	0.3	6.8	547	250	3.96	193	908.0	39.3	2508.2
		WFD	0.3	7.1	245	77	1.34	46	407.0	19.1	752.6
		CC	1.4	7.7	312	193	1.53	194	30.0	42.3	1599.6
	29/02/2002	CC	1.4	5.8	33	31	3.82	14	9.0	1173.7	130.0
		CC	1.0	6.8	33	35	1.24	18	8.0	8.6	45.9
		WFD	0.3	6.9	49	38	0.46	35	8.0	30.2	103.7
	05/03/2002	WFD	0.3	7.6	46	43	0.58	28	2.0	105.2	157.1
		CC	1.0	7.8	48	49	1.67	23	9.0	0.0	50.0
		CC	1.4	7.8	36	30	1.52	14	8.0	8.1	13.7
	02/04/2002	CC	0.4	8.5	40	39	1.18	17	8.0	12.1	46.2
		CC	1.4	8.2	35	41	1.25	14	12.0	11.1	50.3

Table D9. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers (CC) and wetting front detectors (WFD) at New Vaal (2002/2003 summer season, Soil Science Laboratory, University of Pretoria).

Pivot	Date	Site	Instr	Depth (m)	PH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
New Vaal	30/04/2002	NV	CC	0.6	7.8	32	45	1.28	7	5	59.4	38.8
	30/04/2002	NV	CC	0.9	7.7	32	39	1.50	5	1	104.3	25.7
	14/05/2002	NV	CC	1.0	6.5	39	40	1.07	16	12	68.1	16.6
	14/05/2002	NV	CC	1.4	6.6	35	37	1.31	14	10	94.8	16.6
	04/05/2003	NV	CC	1.2	6.6	228	255	1.49	112	80	129.4	408.1
	04/05/2003	NV	WFD	0.3	8.0	576	273	7.07	110	1190	193.4	2665.5
	28/10/2002	NV	CC	1.4	6.0	64	58	33.00	5.58	9	128.3	18.6
	23/01/2002	NV	CC	1.4	7.8	5	565	234.00	6.98	1190	2980.5	57.9
	06/02/2003	NV	CC	1.4	5.9	2	348	129.00	2.21	58	400.6	86.1
	06/02/2003	NV	CC	0.3	7.0	5	504	175.00	2.03	930	2447.4	151.6
	17/02/2003	NV	CC	1.0	7.0	5	512	34.00	5.19	1290	2595.3	190.8

Table D10. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers (CC) and wetting front detectors (WFD) at New Vaal (2003 winter season, Soil Science Laboratory, University of Pretoria).

Pivot	Date	Site	Instr	Depth (m)	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
New Vaal	05/08/2002	NV	CC	1.4	7.8	39	38	3.15	180	11	15.1	18.1
	20/08/2002	NV	CC	1.2	5.3	35	32	16	6.63	6	33.3	23.2
	08/08/2003	NV	CC	0.9	7.2	167	151	9	63	118	119.3	331.5
	15/08/2003	NV	CC	1.4	6.7	168	148	4	63	114	92.1	364.9
	29/08/2003	NV	CC	0.9	6.6	240	76	15.8	54	354	104.7	

TABLE D11. RESULTS OF CHEMICAL ANALYSIS OF SOIL WATER SAMPLES EXTRACTED WITH THE CERAMIC CUP SOIL WATER SAMPLERS (CC) AT NEW VAAL (SWEETCORN, 2003/04 SUMMER SEASON, SOIL SCIENCE LABORATORY, UNIVERSITY OF PRETORIA).

Pivot	Date	Site	Instr	Depth (m)	PH	EC ($Ms\ m^{-1}$)	Ca^{2+} ($mg\ \ell^{-1}$)	K^{+} ($mg\ \ell^{-1}$)	Mg^{2+} ($mg\ \ell^{-1}$)	Na^{+} ($mg\ \ell^{-1}$)	Cl^{-} ($mg\ \ell^{-1}$)	SO_4^{2-} ($mg\ \ell^{-1}$)
	07/11/03	NV	CC	1.4	6.3	260	286	9.0	129	148	451.2	981.0
	21/11/03	NV	CC	1.4	6.7	272	226	4.6	121	179	120.8	789.7
	25/11/03	NV	CC	0.9	6.4	291	105	7.2	54	458	169.2	1023.8
	25/11/03	NV	CC	1.4	6.2	279	152	4.4	119	197	116.8	1075.7
	10/12/03	NV	CC	1.4	6.6	272	201	108.0	4.38	201	113.8	1043.2
	03/12/03	NV	CC	0.9	6.4	269	100	6.0	76	374	154.6	1090.7
New Vaal	03/12/03	NV	CC	1.4	593.0	275	206	4.4	111	195	115.3	1042.2

TABLE D12. RESULTS OF CHEMICAL ANALYSIS OF SOIL WATER SAMPLES EXTRACTED WITH THE CERAMIC CUP SOIL WATER SAMPLERS (CC) AT NEW VAAL (PUMPKIN, 20003/04 SUMMER SEASON, SOIL SCIENCE LABORATORY, UNIVERSITY OF PRETORIA).

Pivot	Date	Site	Instr	Depth (m)	PH	EC ($mS\ m^{-1}$)	Ca^{2+} ($mg\ \ell^{-1}$)	K^{+} ($mg\ \ell^{-1}$)	Mg^{2+} ($mg\ \ell^{-1}$)	Na^{+} ($mg\ \ell^{-1}$)	Cl^{-} ($mg\ \ell^{-1}$)	SO_4^{2-} ($mg\ \ell^{-1}$)
	9/1/2004	NV	CC	0.9	8	346	80	7.3	80	494	216	688.5
	9/1/2004	NV	CC	1.4	7.7	284	232	4	123	208	132.4	769.7
	16/01/04	NV	CC	0.9	6.9	353	164	9.7	86	1805		1362.6
	16/01/04	NV	CC	1.4	6.2	297	295	4.37	117	210	198.4	1109
	26/01/04	NV	CC	0.3	6.5	145	72	9.9	24	175	360.5	194.7
	26/01/04	NV	CC	1.4	5.7	288	248	4.26	111	217	188.8	1098.8
	18/02/04	NV	CC	0.6	6.9	450	157	34.6	88	750	256.8	1676.9
	18/02/04	NV	CC	1.1	6.7	563	231	10.1	192	750	534.8	2382.9
	25/02/04	NV	CC	0.6	7.1	440	161	17.1	72	790	461.7	915.3
New Vaal	25/02/04	NV	CC	1.1	7.6	550	265	8.8	219	765	10.6	2655.6

Table D13. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers (CC) and wetting front detectors (WFD) at New Vaal (maize crop, 2004/2005 summer season, Soil Science Laboratory, University of Pretoria).

Pivot	Date	Instr	Depth (m)	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
New vaal	06/11/2004	CC	1.0	8.8	135	51	9.4	77	166	44.3	162.3
	25/11/2004	CC	0.6	6.8	99	30	3.8	27	149	40.8	240.8
	04/12/2004	CC	1.0	7.6	96	25	3.6	23	148	46.8	185.0
	30/12/2004	CC	1.0	7.8	250	43	0.6	51	433	132.4	726.6
	15/01/2005	CC	0.6	8.5	207	40	0.0	55	442	81.1	793.9
	15/01/2005	CC	0.9	7.9	238	36	0.0	53	415	140.5	740.9
	29/01/2005	CC	0.9	7.7	246	26	0.6	25	523	157.6	734.3
	25/02/2005	CC	0.9	7.6	284	32	0.9	29	630	188.3	768.5
	15/05/2005	CC	1.0	8	175	57	3.9	55	49	63.4	69.8

Table D14. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers (CC) and wetting front detectors (WFD) at Syferfontein (2001/02 summer season, Soil Science Laboratory, University of Pretoria).

Date	Site	Instr	Depth (m)	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
17/10/2001	S1	WFD	0.6	7.5	422	422	1.09	302	298	55.4	2688.2
	S4	WFD	0.6			10.53	0.03	12	13	1.6	27.99
07/01/2002	S1	CC	0.4	7.3	367	249	5.42	172	525	86.6	1564.9
	S1	WFD	0.3	6.9	156	57	1.81	41	235	14.6	300.4
	S2	WFD	0.3	7.3	388	257	7.40	183	780	148.0	1712.0
	S3	WFD	0.3	5.1	641	498	9.01	320	930	52.4	3126.6
	S4	WFD	0.3	7.1	333	95	6.34	87	630	24.2	1147.3
23/01/2002	S1	WFD	0.3	7.2	314	95	6.46	72	2610	44.3	1245.9
	S4	WFD	0.3	7.1	300	95	2.66	61	980	34.2	1402.4
07/03/2002	S3	CC	0.4	8.0	280	192	0.81	148	437	16.6	1515.7
	S4	CC	1.0	8.2	245	289	0.93	203	301	41.3	1375.7
20/03/2002	S1	WFD	0.3	7.4	311	40	4.49	75	580	45.3	473.3
	S2	WFD	0.3	6.6	525	308	3.32	177	862	28.2	2576.9
	S3	WFD	0.3	6.9	289	100	1.09	62	536	8.6	1042.2
	S4	WFD	0.3	6.9	373	142	6.68	89	724	44.3	1479.8
	S3	CC	0.4	6.7	346	172	21.2	103	598	15.1	1416.7
	S4	CC	0.4	7.0	370	224	2.46	129	610	42.8	1180.7
	S4	CC	1.0	7.2	250	139	0.62	77	379	7.6	673.0
04/04/2002	S1	WFD	0.3		0	104	6.22	107	795	41.3	1444.4
	S2	WFD	0.3	8.5	319	106	1.61	73	630	7.6	1350.7
	S3	WFD	0.3	8.5	474	285	1.82	158	850	23.2	1350.0
	S2	CC	0.4	8.6	457	257	0.62	177	820	9.1	1515.6
	S2	CC	1.4	8.6	381	49	0.51	154	680	1.1	1516.9
18/04/2002	S4	CC	0.4	7.8	336	391	1.62	260	615	31.2	560.9
	S1	WFD	0.3	7.9	321	96	12.0	75	625	25.2	223.2
	S2	WFD	0.3	7.7	434	381	1.80	260	760	14.1	147.2

Date	Site	Instr	Depth (m)	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
	S3	WFD	0.3	7.5	446	474	1.91	286	760	17.6	459.4
	S4	WFD	0.3	8.4	273	85	2.48	75	535	9.1	229.1

Table D15. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers (CC) and wetting front detectors (WFD) at Syferfontein (2003 winter season, Soil Science Laboratory, University of Pretoria).

Pivot	Date	Site	Instr	Depth (m)	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
Syferfontein	06/06/2002	S1	WFD	0.6	7.5	314	74	3.38	70.0	660.0	92.1	1049.8
	11/07/2002	S1	WFD	0.6	7.2	459	152	2.09	140.0	845.0	88.1	1926.7
	11/07/2002	S2	WFD	0.6	6.8	481	219	1.07	144.0	495.0	67.5	1104.5
	24/07/2002	S2	WFD	0.6	8.2	484	214	2.65	139.0	825.0	22.2	2038.2
	11/07/2002	S3	WFD	0.6	6.3	219	58	47.00	5.4	880.0	106.7	1844.3
	24/07/2002	S3	WFD	0.6	6.9	514	252	179	1.19	850.0	77.5	2442.1
	11/0720/02	S4	WFD	0.6	6.7	430	174	11.9	124.0	925.0	78.0	510.2
	24/07/2002	S4	WFD	0.6	7.8	469	172	2.48	141.0	825.0	71.0	1809.1

Table D16a. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers (CC) and wetting front detectors (WFD) at Syferfontein (2002/03 summer season, Soil Science Laboratory, University of Pretoria).

Pivot	Date	Site	Instr	Depth (m)	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
Syferfontein	18/04/02	S1	WFD	0.6	7.9	321	96	12.0	75.0	625.0	25.2	223.2
	16/05/02	S1	WFD	0.6	8.2	318	91	1.45	75.0	710.0	53.4	210.8
	24/12/02	S1	WFD	0.6	6.7	405	281	4.84	267.0	2360.0	63.9	1854.7
	09/01/03	S1	WFD	0.6	7.7	295	58	1.60	53.0	1410.0	11.1	702.8
	30/01/03	S1	WFD	0.6	8.1	225	58	2.69	40.0	970.0	7.0	996.6
	28/02/03	S1	WFD	0.6	6.5	209	69	11.9	65.0	460.0	36.3	865.0
	11/03/03	S1	WFD	0.6	7.2	458	160	7.09	106.0	1230.0	240.2	2063.4
	01/04/03	S1	WFD	0.6	7.5	405	189	3.20	96.0	1360.0	57.4	2614.1

Table D16b. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers (CC) and wetting front detectors (WFD) at Syferfontein (2002/03 summer season, Soil Science Laboratory, University of Pretoria).

Pivot	Date	Site	Instr	Depth (m)	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
Syferfontein	18/04/02	S2	WFD	0.6	7.7	434	381	1.80	260.0	760.0	14.1	147.2
	16/05/02	S2	WFD	0.6	8.2	362	145	1.71	94.0	730.0	22.2	627.0
	15/11/02	S2	WFD	0.6	6.5	354	142	19.90	75.0	1.0	129.4	1367.2
	24/12/02	S2	WFD	0.6	7.2	304	87	6.23	59.0	1370.0	47.8	1212.1
	09/01/03	S2	WFD	0.6	7.4	341	279	4.51	92.0	1670.0	17.1	1521.7
	30/01/03	S2	WFD	0.6	6.9	4.5	236	3.18	107.0	1290.0	12.6	2983.6
	28/02/03	S2	WFD	0.6	6.8	543	311	6.83	172.0	1720.0	94.7	3045.9
	11/03/03	S2	WFD	0.6	7.0	547	245	5.10	131.0	1360.0	53.4	2706.5

Table D16c. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers (CC) and wetting front detectors (WFD) at Syferfontein (2002/03 summer season, Soil Science Laboratory, University of Pretoria).

Pivot	Date	Site	Instr	Depth (m)	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
Syferfontein	18/04/02	S3	WFD	0.6	7.5	446	474	286.0	1.91	760.0	17.6	459.4
	16/05/02	S3	WFD	0.6	8.2	451	156	117.0	12.0	950.0	21.1	952.6
	15/11/02	S3	WFD	0.6			164	160.0	11.0	0.80	101.7	3426.1
	24/12/02	S3	WFD	0.6	8.6	405	277	99.0	3.78	1730.0	44.3	1877.9
	09/01/03	S3	WFD	0.6	7.2	338	248	92.0	1.04	1630.0	27.2	1472.6
	28/02/03	S3	WFD	0.6	6.8	148	56	31.0	2.56	372.0	12.6	573.8
	11/03/03	S3	WFD	0.6	7.1	340						
	01/04/03	S3	WFD	0.6	7.4	462	158	140.0	3.79	1510.0	63.4	2303.5

Table D16d. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers (CC) and wetting front detectors (WFD) at Syferfontein (2002/03 summer season, Soil Science Laboratory, University of Pretoria).

Pivot	Date	Site	Instr	Depth (m)	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
Syferfontein	18/04/02	S4	WFD	0.6	8.4	273	85	2.48	75.0	535.0	9.1	
	16/05/02	S4	WFD	0.6	8.5	365	188	0.56	121.0	685.0	0.0	229.1
	15/11/02	S4	WFD	0.6	6.8	504	204	3.47	152.0	1.0	104.2	2019.7
	24/12/02	S4	WFD	0.6	8.7	345	103	2.53	76.0	1570.0	58.4	1951.2
	09/01/03	S4	WFD	0.6	7.8	326	238	1.97	88.0	1600.0	50.9	1041.0
	30/01/03	S4	WFD	0.6	7.6	2.6	75	2.07	46.0	900.0	24.2	1177.7
	28/02/03	S4	WFD	0.6	7.1	293	82	3.23	52.0	1240.0	31.2	1258.0
	11/03/03	S4	WFD	0.6	7.0	495	18	3.97	94.0	1360.0	27.2	1425.0
	01/04/03	S4	WFD	0.6	7.4	408	177	2.76	100.0	1370.0	48.3	1512.9

Table D16e. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers (CC) and wetting front detectors (WFD) at Syferfontein (2002/03 summer season, Soil Science Laboratory, University of Pretoria).

Pivot	Date	Site	Instr	Depth (m)	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
Syferfontein	15/11/02	S5	WFD	0.6	6.7	490	362	9.50	279.0	0.75	140.5	2021.8
	24/12/02	S5	WFD	0.6	7.8	635	921	2.39	824.0	1900.0	323.8	3736.3
	09/01/03	S5	WFD	0.6	7.6	304	219	0.94	98.0	1420.0	30.2	1334.6
	30/01/03	S5	WFD	0.6	7.8	2	77	0.96	51.0	505.0	9.1	1318.0
	28/02/03	S5	WFD	0.6	7.1	438	223	2.86	159.0	1360.0	48.8	2360.7
	11/03/03	S5	WFD	0.6	7.5	453	108	2.39	93.0	1150.0	67.0	2423.3
	01/04/03	S5	WFD	0.6	7.3	458	205	0.60	138.0	1450.0	57.4	2596.8

Table D16f. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers (CC) and wetting front detectors (WFD) at Syferfontein (2002/03 summer season, Soil Science Laboratory, University of Pretoria).

Pivot	Date	Site	Instr	Depth (m)	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
Syferfontein	15/11/02	S6	WFD	0.6	6.7	476	354	3.66	282.0	0.72	96.7	2027.8
	24/12/02	S6	WFD	0.6	6.8	408	424	1.36	363.0	1680.0	52.4	2252.0
	09/01/03	S6	WFD	0.6	7.7	329	283	1.33	238.0	1530.0	34.7	1403.9
	30/01/03	S6	WFD	0.6	8.4	3	96	1.59	70.0	545.0	20.6	1438.7
	28/02/03	S6	WFD	0.6	7.1	447	228	2.69	169.0	1390.0	54.9	2304.4
	01/04/03	S6	WFD	0.6	7.3	475	254	0.81	175.0	1430.0	77.0	2908.1

Table D17a. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers (CC) and wetting front detectors (WFD) at Syferfontein (2003 summer season, Soil Science Laboratory, University of Pretoria).

Pivot	Date	Site	Instr	Depth (m)	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
Syferfontein	14/08/2003	S2	WDF	0.6	7.5	562	220	17.70	163.0	1.0	56.4	3470.7
	14/08/2003	S2	CC	0.6	7.6	500	144	6.65	138.0	1.0	55.4	3068.6
	14/08/2003	S3	WFD	0.6	7.5	506	186	2.18	141.0	1.0	55.4	2965.0
	14/08/2003	S4	WFD	0.6	7.6	640	169	6.12	140.0	1.0	131.4	2644.6
	14/08/2003	S6	CC	0.3	7.7	610	188	0.74	172.0	1.0	63.9	2292.8
	14/08/2003	S6	CC	0.6	8.0	564	310	0.26	257.0	0.82	77.5	2789.1

Table D17b. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers (CC) and wetting front detectors (WFD) at Syferfontein (2003/04 summer season, Soil Science Laboratory, University of Pretoria).

Pivot	Date	Site	Instr	Depth (m)	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
Syferfontein	29/09/03	S1	WFD	0.6	7.8	731	284	5.30	192.0	1225.0	86.1	2250.6
	11/02/03	S2	WFD	0.6	7.9	544	145	14.10	111.0	1205.0	168.7	2134.6
	25/11/03	S2	WFD	0.6	7.8	936	285	87.70	221.0	2.0	430.0	3652.5
	25/11/03	S2	CC	0.3	8.1	660	143	9.90	150.0	1.0	167.2	2951.4
	01/12/03	S2	WFD	0.6			162	193.00	75.0	1170.0	495.5	4693.3
	15/01/04	S2	WFD	0.6	7.1	678	200	23.80	131.0	1460.0	350.0	3186.6
	29/01/04	S2	WFD	0.6			77	50.00	7.5	675.0		1348.2
	16/02/04	S2	CC	0.6	7.3	117	29	6.48	5.0	215.0	192.9	59.8
	22/02/04	S2	CC	0.6	6.7	158	19	5.22	6.0	210.0	20.6	353.0
	04/03/04	S2	CC	0.6	7.2	314	75	0.78	51.0	0.64	62.4	1302.0

Table D17c. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers (CC) and wetting front detectors (WFD) at Syferfontein (2003/04 summer season, Soil Science Laboratory, University of Pretoria).

Pivot	Date	Site	Instr	Depth (m)	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
Syferfontein	29/09/2003	S3	WFD	0.6	7.9	622	210	0.57	143.0	1025.0	65.5	1768.3
	21/10/2003	S3	WFD	0.6	7.3	752	230	8.50	183.0	1160.0	106.7	2598.1
	12/11/2003	S3	WFD	0.6	7.5	690	172	7.40	45.0	1860.0	85.1	3605.4
	25/11/2003	S3	WFD	0.6	7.6	305	67	1.50	44.0	548.0	23.2	1209.6
	09/12/2003	S3	WFD	0.6	7.3	560	224	175.00	5.61	1220.0	75.5	2870.4
	09/12/2003	S3	WFD	0.6	7.2	467	72	82.00	1.69	1045.0	39.3	2027.4
	30/12/2003	S3	WFD	0.6	8.1	266	47	1.30	39.0	541.0	17.1	1245.4

Table D17d. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers (CC) and wetting front detectors (WFD) at Syferfontein (2003/04 summer season, Soil Science Laboratory, University of Pretoria).

Pivot	Date	Site	Instr	Depth (m)	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
Syferfontein	29/09/2003	S6	CC	1.0	7.7	623	383	0.05	332.0	670.0	75.0	2001.7
	29/09/2003	S6	CC	1.0	7.7	632	435	0.01	356.0	740.0	74.5	2087.3
	29/09/2003	S6	CC	0.4	7.5	598	275	1.04	226.0	900.0	70.5	1820.2
	25/11/2003	S6	WFD	0.6	7.9	375	74	1.60	61.0	0.78	22.7	1296.6
	25/11/2003	S6	CC	0.3	7.7	444	31	4.20	122.0	0.84	40.3	1700.3
	30/12/2003	S6	WFD	0.6	8.5	400	92	2.20	74.0	882.0	54.9	1418.1
	16/02/2004	S6	WFD	0.6	7.7	181	22	0.62	8.0	355.0	50.9	201.6
	04/03/2004	S6	WFD	0.6	7.9	156	20	0.63	7.0	312.0	46.3	117.7
	20/03/2004	S6	CC	0.3	8.6	316	96	0.50	70.0	544.0	84.6	955.5

Table D17e. Results of chemical analysis of soil water samples extracted with the wetting front detectors (WFD) at Syferfontein (2003/04 summer season, Soil Science Laboratory, University of Pretoria).

Pivot	Date	Site	Instr	Depth (m)	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
Syferfontein	25/11/2003	S4	WDF	0.6	7.6	582	46	6.6	120.0	1.0	58.9	3037.8
	09/12/2003	S4	WFD	0.6	7.3	674	117	152.0	5.56	1390.0	65.0	3349.7
	30/12/2003	S4	WFD	0.6			103	124.0	5.40	2688.4	55.9	1206.0
	15/01/2004	S4	WFD	0.6	7.4	555	171	4.88	115.0	1185.0	99.2	2793.1
	29/01/2004	S4	WFD	0.6	8.7	352	55	2.10	45.0	670.0	41.3	1254.7
	16/02/2004	S4	WFD	0.6	7.1	185	19	2.36	4.0	348.0	28.2	474.6
	04/03/2004	S4	WFD	0.6	7.5	258	34	1.18	26.0	511.0	62.4	715.1
	20/03/2004	S4	WFD	0.6	8.8	272	53	1.10	31.0	545.0	33.7	259.7

Table D17f. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers (CC) and wetting front detectors (WFD) at Syferfontein (2003/04 summer season, Soil Science Laboratory, University of Pretoria).

Pivot	Date	Site	Instr	Depth (m)	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
Syferfontein	21/10/2003	S5	CC	0.4	7.4	574	209	0.35	173.0	770.0	142	1249.7
	25/11/0203	S5	CC	0.3	7.9	425	106	2.00	93.0	0.87	18.1	1511.1
	25/11/2003	S5	CC	0.6	7.6	457	58	0.80	141.0	0.87	29.2	1810.4
	30/12/2003	S5	WFD	0.6	8.3	189	31	0.30	33.0	361.0	33.7	700.6
	16/02/2004	S5	WFD	0.6	7.5	182	20	0.69	7.0	347.0	52.4	196.2
	22/02/2004	S5	WFD	0.6	6.9	4	2	0.19	0.57	2.0	4.5	3.4
	04/03/2004	S5	CC	0.6	8.0	433	153	2.2	127.0	0.81	32.2	2175.6

Table D17g. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers (CC) and wetting front detectors (WFD) at Syferfontein (2003/04 summer season, Soil Science Laboratory, University of Pretoria).

Pivot	Date	Site	Instr	Depth (m)	PH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
Syferfontein	08/10/2003	S2	WFD	0.6	7.3	648	223	6.20	131.0	1620.0	66.5	3495.5
	12/11/2003	S2	WFD	0.6	7.3	400	84	3.40	13.0	1020.0	39.8	1925.6

Table D18. Results of chemical analysis of soil water samples extracted with the wetting front detectors (WFDs) at optimum (2004 summer season, soil science laboratory, university of Pretoria).

Pivot	Date	Site	Instr	Depth (m)	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
Optimum	19/03/04	S1	WFD	0.6	7.0	384	387	43.6	357.0	135.0	7.0	2117.8
	19/03/04	S2	WFD	0.6	6.9	254	300	6.0	223.0	39.0	12.6	819.0
	01/04/04	S1	WFD	0.6	5.9	231	214	27.3	193.0	75.0	20.6	833.4
	01/04/04	S2	WFD	0.6	6.8	106	83	2.9	67.0	23.0	6.5	411.0

Table D19. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers (CC) at Optimum (2004/05 summer season, Soil Science Laboratory, University of Pretoria).

Pivot	Date	Instr	Depth (m)	pH	EC (mS m^{-1})	Ca^{2+} (mg ℓ^{-1})	K^{+} (mg ℓ^{-1})	Mg^{2+} (mg ℓ^{-1})	Na^{+} (mg ℓ^{-1})	Cl^{-} (mg ℓ^{-1})	SO_4^{2-} (mg ℓ^{-1})
Optimum	14/08/2004	WFD	0.3	6.0	195	343	8.8	201	33	29.2	738.9
	14/08/2004	WFD	0.3	6.0	578	594	49.8	409	86	0.0	5385.5
	04/09/2004	WFD	0.3	7.0	277	473	37.8	331	67	48.3	2056.8
	16/10/2004	CC	0.3	7.0	454	688	35.4	550	144	45.3	3009.9
	21/10/2004	CC	0.3	6.5	442	648	15.0	568	127	77.0	2237.7
	18/12/2004	WFD	0.6	6.2	368	424	12.9	875	141	42.3	2203.9
		WFD	0.6	6.7	553	559	37.4	1450	272	24.7	3722.1
	20/04/2005	WFD	0.6	6.9	292	346	33.6	240	50	55.9	1235.5

Table D20. pH of runoff water samples collected with ISCO sampler at Syferfontein (2003/ 2004 summer season, ARC, RSA).

Pivot	Number of bottles	Oct-03	Nov-03	Dec-03	Jan-04	Feb-04	Mar-04	Mar-04	Apr-04	Apr-04	May-04
Syferfontein	1	8.8	9.2	6.7	6.8	6.9	6.9	-	6.8	8.0	7.6
	2	8.9	7.1	-	6.6	6.9	6.8	6.4	7.0	7.8	7.7
	3	8.5	9.1	-	6.7	6.6	7.0	6.2	6.6	7.8	7.6
	4	8.4	9.1	-	6.9	7.1	6.8	6.3	6.7	7.9	7.9
	5	8.6	-	-	6.9	7.0	7.0	6.2	6.6	7.8	-
	6	8.6	-	7.0	7.0	7.0	7.0	6.4	6.7	7.9	-
	7	8.6	-	6.9	7.0	6.9	7.2	6.2	6.7	-	-
	8	-	-	6.9	7.0	7.1	7.0	6.3	6.7	-	-
	9	-	-	7.4	7.3	7.4	6.9	6.4	6.7	-	-
	10	-	-	7.5	7.1	7.0	6.9	6.8	6.8	7.8	-
	11	-	-	7.1	7.3	7.0	7.0	6.7	6.7	-	-
	12	-	-	7.0	7.2	7.2	7.1	6.7	6.8	-	-
	13	-	-	7.3	7.3	7.0	7.3	6.6	6.8	-	-
	14	-	-	7.0	7.3	7.2	7.2	6.8	6.8	-	-
	15	-	-	-	-	7.3	7.2	6.6	6.8	-	-
	16	-	-	-	-	7.1	7.2	6.7	6.9	7.8	-
	17	-	-	-	-	7.1	7.5	6.6	7.2	7.9	-
	18	--	-	-	-	7.2	7.6	6.9	6.8	8.0	-
	19		-	-	-	7.2	7.7	7.0	6.8	8.2	-
	20	-	-	-	-	7.2	7.8	6.6	6.7	8.2	-
	21	-	-	-	-	7.2	-	6.8	6.9	7.9	-
	22	-	-	-	-	7.1	7.5	6.7	6.8	8.0	-
	23	-	-	-	-	7.2	7.3	6.8	6.9	7.9	-
	24	-	-	-	-	7.4	7.3	6.7	7.0	7.9	-

Table D21. EC (mS m^{-1}) of runoff water samples collected with ISCO sampler at Syferfontein (2003/ 2004 summer season, ARC, RSA).

Pivot	Number of bottles	Oct-03	Nov-03	Dec-03	Jan-04	Feb-04	Mar-04	Mar-04	Apr-04	Apr-04	May-04
Syferfontein	1	495	645	103	62	37	29	-	66	47	137
	2	503	633	82	58	37	29	28	65	39	136
	3	533	646	84	61	37	30	22	66	37	136
	4	537	646	84	64	37	30	22	66	39	142
	5	493	-	103	68	37	32	21	68	42	-
	6	505	-	118	85	38	33	21	68	43	-
	7	520	-	122	78	37	34	22	67	-	-
	8	-	-	125	86	37	34	22	66	-	-
	9	-	-	125	88	36	34	23	65	-	-
	10	-	-	124	93	37	35	23	64	42	-
	11	-	-	-	97	37	35	24	63	-	-
	12	-	-	52	-	37	35	24	63	-	-
	13	-	-	41	-	46	32	24	62	-	-
	14	-	-	47	-	43	36	24	53	-	-
	15	-	-	-	-	42	35	24	53	-	-
	16	-	-	-	-	40	34	24	54	43	-
	17	-	-	-	-	39	38	24	54	43	-
	18	-	-	-	-	39	47	24	55	44	-
	19	-	-	-	-	39	48	24	58	44	-
	20	-	-	-	-	40	51	24	60	45	-
	21	-	-	-	-	40		24	62	45	-
	22	-	-	-	-	39	33	25	64	46	-
	23	-	-	-	-	39	29	25	66	46	-
	24	-	-	-	-	38	28	25	65	46	-

Table D22. TDS of runoff water samples collected with ISCO sampler at Syferfontein (2003/ 2004 summer season, ARC, RSA).

Pivot	Number of bottles	Oct-03	Nov-03	Dec-03	Jan-04	Feb-04	Mar-04	Mar-04	Apr-04	Apr-04	May-04
Syferfontein	1	3746	5382	646	251	229	174		405	279	1072
	2	3865	5107		205	221	176		407	204	1056
	3	4134	5331		254	221	177	155	408	218	1018
	4	4134	5306		339	217	179	152	418	230	1076
	5	3717	-		303	218	188	153	427	248	-
	6	3785	-	496	317	215	194	151	428	254	-
	7	3963	-	493	336	216	204	158	412	-	-
	8	-	-	493	364	216	204	166	420	-	-
	9	-	-	627	486	212	206	172	403	-	-
	10	-	-	754	422	212	208	170	403	255	-
	11	-	-	773	487	210	206	172	394	-	-
	12	-	-	792	-	210	209	173	392	-	-
	13	-	-	803	-	298	199	173	387	-	-
	14	-	-	800	-	265	213	176	324	-	-
	15	-	-	-	-	252	218	178	324	-	-
	16	-	-	-	-	232	200	168	326	258	-
	17	-	-	-	-	231	222	173	347	261	-
	18	-	-	-	-	225	283	171	351	259	-
	19	-	-	-	-	231	282	176	369	259	-
	20	-	-	-	-	231	290	177	382	266	-
	21	-	-	-	-	228	-	177	385	271	-
	22	-	-	-	-	226	194	174	413	272	-
	23	-	-	-	-	223	170	175	431	273	-
	24	-	-	-	-	226	141		415	274	-

Table D23. Sulphate (mg ℓ^{-1}) of runoff water samples collected with ISCO sampler at Syferfontein (2003/ 2004 summer season, Institute for soil climate and water - ARC, RSA).

Pivot	Number of bottles	Oct-03	Nov-03	Dec-03	Jan-04	Feb-04	Mar-04	Mar-04	Apr-04	Apr-04	May-04
Syferfontein	1	2177.63	3043.3	270.9	67.86	46.21	37.45		193.03	119.13	643.44
	2	2221.09	2907.4	-	69.92	44.32	38.23	50.18	195.01	65.30	630.01
	3	2435.28	3091.6	-	117.50	44.18	38.20	38.50	193.13	61.39	608.91
	4	2421.71	3037.3	-	162.47	43.98	39.19	34.70	197.93	57.74	639.17
	5	2157.19		-	135.38	42.75	40.00	36.35	202.68	59.05	-
	6	2115.53		250.1	137.32	42.16	41.24	36.67	201.03	58.80	-
	7	2218.49		203.4	140.07	41.73	42.04	35.73	194.01	-	-
	8	-	-	210.9	151.86	41.22	42.71	35.90	191.84	-	-
	9	-	-	277.9	202.91	41.02	42.51	36.81	180.43	-	-
	10	-	-	350.8	199.88	39.96	42.97	37.55	183.12	61.97	-
	11	-	-	356.6	205.89	40.46	43.03	35.94	178.18	-	-
	12	-	-	364.6	203.95	40.11	45.93	37.85	175.23	-	-
	13	-	-	364.2	229.65	116.40	64.27	38.31	172.19	-	-
	14	-	-	360.8	230.31	90.90	63.92	36.90	130.58	-	-
	15	-	-	-	-	77.96	65.56	36.61	141.77	-	-
	16	-	-	-	-	65.45	51.96	36.10	148.71	56.70	-
	17	-	-	-	-	58.57	61.21	36.78	152.95	56.38	-
	18	-	-	-	-	56.85	76.51	36.93	162.96	56.71	-
	19	-	-	-	-	54.55	76.69	36.56	174.64	56.14	-
	20	-	-	-	-	54.66	84.01	37.64	175.37	56.36	-
	21	-	-	-	-	52.67		37.03	178.80	55.61	-
	22	-	-	-	-	50.24	55.39	37.28	190.97	56.03	-
	23	-	-	-	-	48.91	40.75	36.91	199.55	57.91	-
	24	-	-	-	-	48.92	19.15	37.45	190.90	57.52	-

Table D24. Bicarbonate (mg ℓ^{-1}) of runoff water samples collected with ISCO sampler at Syferfontein (2003/ 2004 summer season, INSTITUTE FOR SOIL, climate and water - ARC, RSA).

Pivot	Number of bottles	Oct-03	Nov-03	Dec-03	Jan-04	Feb-04	Mar-04	Mar-04	Apr-04	Apr-04	May-04
Syferfontein	1	664.9	939.4	280.6	195.20	155.55	97.60		112.85	106.75	170.8
	2	738.1	915		134.20	155.55	100.65	122.00	109.80	100.65	176.9
	3	780.8	927.2		118.95	152.50	97.60	98.82	115.90	115.90	158.6
	4	780.8	902.8		125.05	155.55	97.60	95.77	112.85	137.25	176.9
	5	677.1			137.25	158.60	109.80	89.06	115.90	149.45	
	6	786.9		170.8	146.40	155.55	106.75	86.62	118.95	149.45	
	7	805.2		231.8	164.70	158.60	125.05	87.23	115.90		
	8	-	-	213.5	176.90	161.65	125.05	87.84	118.95		
	9	-	-	219.6	231.80	158.60	122.00	97.60	128.10		
	10	-	-	250.1	164.70	158.60	128.10	99.43	118.95	152.50	
	11	-	-	262.3	219.60	158.60	128.10	104.31	122.00		
	12	-	-	268.4	234.85	158.60	125.05	100.04	122.00		
	13	-	-	280.6	244.00	143.35	106.75	98.21	122.00		
	14	-	-	274.5	231.80	146.40	109.80	98.82	131.15		
	15	-	-			149.45	118.95	101.87	109.80		
	16	-	-			146.40	115.90	102.48	106.75	167.75	
	17	-	-			149.45	134.20	92.11	103.70	170.80	
	18	-	-			149.45	170.80	96.99	94.55	167.75	
	19	-	-			158.60	176.90	96.99	97.60	170.80	
	20	-	-			161.65	167.75	101.87	100.65	176.90	
	21	-	-			161.65		103.70	103.70	183.00	
	22	-	-			158.60	115.90	107.36	106.75	186.05	
	23	-	-			158.60	97.60	103.70	103.70	186.05	
	24	-	-			158.60	94.55	101.26	106.75	186.05	

Table D25. Nitrate (mg ℓ^{-1}) of runoff water samples collected with ISCO sampler at Syferfontein (2003/ 2004 summer season, Institute for soil, climate and water - ARC, RSA).

Pivot	Number of bottles	Oct-03	Nov-03	Dec-03	Jan-04	Feb-04	Mar-04	Mar-04	Apr-04	Apr-04	May-04
Syferfontein	1	5.37	98.53	0	2.46	3.20	7.39		2.90	4.76	7.93
	2	7.53	76.87		4.56	3.41	7.32	8.26	3.08	3.88	6.15
	3	12.49	91.61		2.20	3.90	7.79	7.12	3.15	3.78	7.05
	4	9.13	120.49		2.51	3.66	6.88	7.09	4.00	3.92	5.99
	5	11.42			2.86	3.00	6.89	6.44	4.26	4.26	
	6	5.65		1.22	2.96	3.22	6.56	5.37	3.67	5.50	
	7	6.78		0.41	2.76	2.93	6.42	4.35	3.17		
	8			0.91	1.53	2.78	5.72	8.90	3.36		
	9			0.00	2.68	2.83	6.11	6.85	1.51		
	10			0.78	1.08	3.22	5.45	10.08	4.17	4.49	
	11			0.00	1.50	3.39	4.99	4.79	3.08		
	12			0.26	1.18	3.35	4.59	6.37	1.48		
	13			0.00	2.03	1.93	2.69	6.20	2.17		
	14			0.27	2.40	2.44	3.14	8.17	3.56		
	15					2.37	3.27	7.81	3.12		
	16					1.76	2.28	6.96	2.79	4.32	
	17					2.87	2.83	8.30	4.07	4.57	
	18					3.14	1.56	8.21	2.27	4.34	
	19					3.09	1.27	8.16	3.09	4.58	
	20					2.56	2.40	7.69	2.65	4.40	
	21					2.39		8.24	1.91	4.90	
	22					2.85	4.65	6.65	4.00	4.93	
	23					2.92	6.19	3.61	4.84	5.02	
	24					3.62	6.94	6.78	4.39	5.67	

Table D26. Chloride (mg ℓ^{-1}) of runoff water samples collected with ISCO sampler at Syferfontein (2003/ 2004 summer season, Institute for soil, climate and water - ARC, RSA).

Pivot	Number of bottles	Oct-03	Nov-03	Dec-03	Jan-04	Feb-04	Mar-04	Mar-04	Apr-04	Apr-04	May-04
Syferfontein	1	48.19	139.18	12.65	6.34	7.54	7.71		11.01	12.39	23.49
	2	49.72	85.17		3.81	7.77	8.47	9.11	13.39	10.25	22.15
	3	48.00	93.31		5.09	7.72	9.36	9.37	11.14	13.32	22.39
	4	57.03	93.15		9.31	7.82	10.00	8.61	11.14	14.16	23.27
	5	50.07			8.02	7.59	11.05	10.23	11.59	17.63	
	6	54.97		8.89	9.51	7.58	11.9	10.47	10.35	18.92	
	7	82.53		9.54	9.81	7.52	12.55	11.23	10.82		
	8			10.52	10.35	7.58	13.07	12.10	12.48		
	9			15.40	13.22	7.74	13.12	13.41	10.57		
	10			17.56	14.11	7.42	13.48	13.82	10.69	16.75	
	11			20.30	16.59	7.46	12.69	13.67	9.32		
	12			19.82	16.17	7.44	13.03	14.60	10.08		
	13			20.81	15.36	9.49	6.71	14.66	10.03		
	14			20.92	15.11	8.34	9.54	14.16	7.41		
	15					8.10	7.89	14.89	7.33		
	16					7.82	6.90	15.12	7.58	15.83	
	17					7.98	8.89	13.13	8.73	14.63	
	18					8.22	12.15	15.48	10.14	14.51	
	19					8.22	11.60	16.41	10.41	14.70	
	20					8.38	11.39	16.34	10.07	14.39	
	21					8.24		15.88	10.97	14.82	
	22					8.20	5.20	15.94	10.18	14.88	
	23					8.18	5.88	16.37	11.47	16.16	
	24					8.10	7.05	17.10	11.25	15.16	

Table D27. Sodium (mg ℓ^{-1}) of runoff water samples collected with ISCO sampler at Syferfontein (2003/ 2004 summer season, Institute for soil, climate and water - ARC, RSA).

Pivot	Number of bottles	Oct-03	Nov-03	Dec-03	Jan-04	Feb-04	Mar-04	Mar-04	Apr-04	Apr-04	May-04
Syferfontein	1	928.09	1306.32	178.56	48.43	74.06	48.92		105.68	70.65	254.46
	2	949.31	1238.61		40.68	67.64	47.19	45.50	108.04	57.00	257.85
	3	979.96	1253.87		49.42	67.66	49.88	36.61	112.14	62.89	250.17
	4	1011.87	1238.37		76.24	64.92	51.37	37.05	116.90	68.95	265.01
	5	912.52			67.63	66.17	52.29	34.55	123.94	72.85	
	6	958.09		115.39	72.72	65.64	55.79	37.64	126.35	75.72	
	7	975.72		128.55	79.45	66.46	57.70	37.18	120.41		
	8			130.85	86.97	66.58	57.25	38.12	120.72		
	9			182.94	122.45	63.85	59.89	41.23	116.88		
	10			219.31	93.67	65.07	60.36	42.32	117.99	75.52	
	11			225.36	119.83	61.82	59.89	44.25	116.97		
	12			231.15	115.13	61.94	61.21	44.14	118.65		
	13			236.24	129.18	75.99	49.45	45.31	115.79		
	14			238.52	135.3	68.66	59.06	44.57	92.01		
	15					67.89	57.03	46.29	94.09		
	16					63.28	55.65	47.93	90.90	77.96	
	17					66.19	56.05	45.50	96.87	79.08	
	18					62.21	78.73	45.80	100.48	80.01	
	19					64.91	78.37	43.36	106.03	78.32	
	20					63.71	83.31	46.46	110.61	81.82	
	21					64.22		47.79	111.48	83.40	
	22					64.53	46.61	47.00	123.40	83.72	
	23					63.87	45.59	48.36	129.64	82.48	
	24										

Table D28. Potassium (mg ℓ^{-1}) of runoff water samples collected with ISCO sampler at Syferfontein (2003/ 2004 summer season, Institute for soil, climate and water - ARC, RSA).

Pivot	Number of bottles	Oct-03	Nov-03	Dec-03	Jan-04	Feb-04	Mar-04	Mar-04	Apr-04	Apr-04	May-04
Syferfontein	1	15.70	27.27	2.75	1.48	3.15	3.71		3.53	1.51	
	2	19.13	28.36		1.51	2.60	3.96	2.34	3.44	1.85	
	3	18.97	29.30		1.46	2.73	3.70	2.74	3.68	2.12	
	4	20.73	29.14		2.23	2.55	3.74	2.78	3.38	2.44	
	5	18.17			1.87	2.63	3.30	2.67	3.48	2.46	
	6	20.81		2.47	1.86	2.65	3.40	2.74	3.56	2.56	
	7	20.24		2.43	2.37	2.59	3.40	2.72	3.13		
	8			2.53	2.94	2.51	3.26	2.71	3.05		
	9			2.87	3.22	2.40	3.47	2.73	2.58		
	10			3.54	2.20	2.41	3.41	2.73	2.92	3.09	
	11			3.63	3.69	2.40	3.39	2.79	2.54		
	12			4.61	3.47	2.41	3.53	2.78	2.78		
	13			4.81	3.86	2.60	1.95	2.82	2.78		
	14			4.75	4.67	2.80	2.17	2.83	1.95		
	15					2.56	2.74	2.70	1.98		
	16					2.50	2.99	2.94	2.05	3.35	
	17					2.86	3.66	2.75	2.16	3.24	
	18					2.59	4.22	2.60	2.53	3.42	
	19					2.57	3.89	2.63	3.15	3.33	
	20					2.49	3.83	2.65	3.09	3.36	
	21					2.47		2.62	2.99	3.35	
	22					2.61	2.58	2.59	3.32	3.52	
	23					2.52	3.02	2.62	3.55	3.32	
	24					2.81	3.34	2.58	3.33	3.39	

Table D29. Calcium (mg ℓ^{-1}) of runoff water samples collected with ISCO sampler at Syferfontein (2003/ 2004 summer season, Institute for soil, climate and water - ARC, RSA).

Pivot	Number of bottles	Oct-03	Nov-03	Dec-03	Jan-04	Feb-04	Mar-04	Mar-04	Apr-04	Apr-04	May-04
Syferfontein	1	74.98	89.21	21.78	9.63	8.96	9.27		9.00	9.17	24.77
	2	88.92	91.21		8.83	8.83	8.79	8.67	9.43	7.58	21.49
	3	99.13	101.31		8.92	8.75	8.62	9.23	9.54	8.15	20.78
	4	77.10	101.48		11.10	8.17	8.60	9.21	11.14	7.47	23.28
	5	84.29			9.32	7.85	8.83	8.72	10.22	8.75	
	6	76.03		18.08	8.95	7.84	8.98	8.94	10.09	8.51	
	7	88.23		17.85	8.92	7.51	9.10	8.72	10.03		
	8			16.57	9.37	7.42	9.00	8.88	12.10		
	9			17.67	12.37	7.09	8.70	8.53	12.01		
	10			19.05	12.95	7.16	8.51	8.97	11.07	7.71	
	11			18.83	14.42	7.00	8.10	9.06	11.09		
	12			20.06	12.45	7.21	8.87	9.00	10.63		
	13			19.75	12.52	9.80	9.76	8.82	10.97		
	14			19.29	13.15	9.15	9.81	8.44	12.13		
	15					9.28	10.41	8.93	11.15		
	16					8.97	10.56	8.55	10.76	7.78	
	17					8.84	9.92	8.08	14.43	7.79	
	18					8.80	11.08	7.82	11.30	7.52	
	19					9.21	10.38	7.65	10.88	7.52	
	20					9.07	10.23	7.48	12.29	7.49	
	21					8.69		7.64	12.22	7.67	
	22					9.01	11.15	7.42	12.33	7.45	
	23					8.63	11.35	7.70	13.44	7.32	
	24					6.49	10.41	7.40	12.20	7.24	

Table D30. Magnesium (mg ℓ^{-1}) of runoff water samples collected with ISCO sampler at Syferfontein (2003/ 2004 summer season, Institute for soil, climate and water - ARC, RSA).

Pivot	Number of bottles	Oct-03	Nov-03	Dec-03	Jan-04	Feb-04	Mar-04	Mar-04	Apr-04	Apr-04	May-04
Syferfontein	1	121.07	151.60	15.07	8.21	6.61	9.74		11.15	6.75	23.23
	2	115.61	147.47	-	7.47	7.07	9.56	7.19	9.93	6.00	21.34
	3	123.10	156.96	-	7.46	7.35	8.94	8.47	10.05	6.71	20.54
	4	110.41	160.67	-	9.20	6.94	9.02	7.97	13.23	5.34	21.82
	5	106.98	-	-	8.17	6.77	8.33	8.18	9.91	6.83	-
	6	113.35	-	12.16	7.88	6.85	8.87	7.81	10.25	7.22	-
	7	118.26	-	11.60	8.52	6.23	8.93	7.17	10.23	-	-
	8	-	-	10.89	9.95	5.86	8.37	7.49	13.47	-	-
	9	-	-	11.81	10.51	5.92	8.07	7.06	11.24	-	-
	10	-	-	14.00	10.65	5.83	7.66	7.31	10.73	7.08	-
	11	-	-	14.19	12.39	5.98	7.40	7.48	10.38	-	-
	12	-	-	15.50	12.35	6.10	7.74	7.61	10.06	-	-
	13	-	-	15.38	12.48	8.93	8.44	7.61	10.18	-	-
	14	-	-	14.87	14.24	8.65	8.69	7.61	9.93	-	-
	15		-	-	-	8.03	10.03	7.53	8.78	-	-
	16	-	-	-	-	7.97	10.45	7.56	9.01	6.82	-
	17	-	--	-	-	8.04	10.23	6.96	14.72	7.43	-
	18	-	-	-	-	7.72	10.88	6.65	11.08	7.45	-
	19	-	-	-	-	7.78	10.01	6.61	11.00	7.23	-
	20	-	-	-	-	7.70	9.73	6.36	13.74	7.18	-
	21	-	-	-	-	7.23		6.35	12.94	7.22	-
	22	-	-	-	-	7.60	9.04	6.21	13.10	6.76	-
	23	-	-	-	-	7.31	7.99	6.17	15.32	6.31	-
	24	-	-			6.24	10.50	6.07	13.48	6.85	-

Table D31. pH of runoff water samples collected with ISCO sampler at Tweefontein (2003/2004 summer season, Institute for soil, climate and water - ARC, RSA).

Pivot	Number of bottles	Jan-04	Feb-04	Mar-03	Apr-04
Tweefontein	1	6.7		5.9	7.7
	2	6.7	5.9	6.2	7.9
	3	6.4	5.5	6.2	7.9
	4	6.6	4.8	6.3	7.6
	5	6.6	5.9	6.4	7.6
	6		7.4	6.3	7.7
	7		7.4	6.3	7.8
	8		6.8	6.4	7.9
	9		6.1	6.6	7.9
	10		6.0	6.7	7.9
	11		5.7	7.0	7.9
	12		5.7	7.1	8.0
	13		5.8	7.1	8.0
	14		5.7	7.4	7.9
	15		5.8	7.5	8.0
	16		5.6	7.5	8.0
	17		5.7	7.4	8.0
	18		5.6	7.3	7.9
	19		5.8	7.3	8.0
	20		5.7	7.2	8.0
	21		5.9	7.1	8.0
	22		7.6	7.1	7.9
	23		7.6	6.9	8.0
	24		7.7	5.7	7.9

Table D32. EC (mS m^{-1}) of runoff water samples collected with ISCO sampler at Tweefontein (2003/2004 summer season, Institute for soil, climate and water - ARC, RSA).

Pivot	Number of bottles	Jan-04	Feb-04	Mar-03	Apr-04
Tweefontein	1	80		48	175
	2	77	20	29	201
	3	98	15	31	205
	4	108	21	31	206
	5	89	93	30	209
	6		212	28	211
	7		216	27	216
	8		225	28	220
	9		235	31	222
	10		252	42	225
	11		255	63	228
	12		253	81	231
	13		252	94	233
	14		252	134	234
	15		251	151	235
	16		253	141	236
	17		258	124	235
	18		261	107	233
	19		264	94	230
	20		264	83	229
	21		265	74	228
	22		306	67	228
	23		318	62	227
	24		321	58	226

Table D33. TDS (mg ℓ^{-1}) of runoff water samples collected with ISCO sampler at Tweefontein (2003/2004 summer season, Institute for soil, climate and water - ARC, RSA).

Pivot	Number of bottles	Jan-04	Feb-04	Mar-03	Apr-04
Tweefontein	1	386.33		435.58	1976.35
	2	491.43	127.43	240.67	1976.35
	3	688.90	88.95	265.45	2038.35
	4	793.90	146.43	256.46	2072.35
	5	621.90	842.90	255.19	2134.35
	6		1994.95	233.41	2144.30
	7		2006.85	222.80	2219.30
	8		2131.95	234.28	2263.30
	9		2267.85	264.11	2351.25
	10		2443.95	383.67	2355.25
	11		2540.95	627.92	2395.25
	12		2490.95	864.18	2431.20
	13		2491.90	1021.99	2458.20
	14		2481.95	1498.16	2493.20
	15		2493.95	1780.62	2520.15
	16		2530.95	1723.01	2509.15
	17		2636.95	1369.45	2486.20
	18		2630.95	1113.55	2643.25
	19		2689.95	985.09	2405.20
	20		2677.95	838.01	2388.20
	21		2651.95	728.45	2585.20
	22		3297.65	662.84	2355.25
	23		3400.65	594.06	2368.25
	24		3409.70	545.67	2334.25

Table D34. Sulphate (mg ℓ^{-1}) of runoff water samples collected with ISCO sampler at Tweefontein (2003/2004 summer season, Institute for soil, climate and water - ARC, RSA).

Pivot	Number of bottles	Jan-04	Feb-04	Mar-03	Apr-04
Tweefontein	1	245.12		327.30	1401.74
	2	368.05	78.71	167.95	1401.74
	3	521.42	46.08	186.60	1459.73
	4	605.03	89.36	185.00	1488.86
	5	472.69	615.36	182.76	1533.91
	6		1418.23	166.77	1527.45
	7		1415.03	157.97	1590.22
	8		1509.11	165.22	1625.92
	9		1612.18	191.18	1700.77
	10		1749.94	283.25	1698.66
	11		1822.27	476.45	1724.80
	12		1774.62	674.05	1756.86
	13		1790.52	801.85	1770.21
	14		1770.05	1165.23	1798.02
	15		1776.13	1381.15	1810.68
	16		1803.23	1354.61	1805.73
	17		1873.75	1059.08	1795.37
	18		1883.29	850.42	1963.02
	19		1921.20	770.38	1735.35
	20		1916.38	647.71	1731.12
	21		1887.15	560.51	1798.82
	22		2395.50	506.26	1705.21
	23		2445.34	451.89	1715.88
	24		2454.93	415.31	1686.40

Table D35. Bicarbonate (mg ℓ^{-1}) of runoff water samples collected with ISCO sampler at Tweefontein (2003/2004 summer season, Institute for soil, climate and water - ARC, RSA).

Pivot	Number of bottles	Jan-04	Feb-04	Mar-03	Apr-04
Tweefontein	1	21.35		26.84	79.3
	2	9.15	9.15	28.67	79.3
	3	12.20	6.10	31.11	79.3
	4	12.20	9.15	17.08	79.3
	5	12.20	12.20	25.62	79.3
	6		6.10	23.18	85.4
	7		18.30	24.40	85.4
	8		6.10	27.45	85.4
	9		18.30	23.79	91.5
	10		6.10	28.67	91.5
	11		6.10	34.16	91.5
	12		6.10	39.65	97.6
	13		12.20	50.02	97.6
	14		6.10	53.68	97.6
	15		6.10	70.76	103.7
	16		6.10	71.98	103.7
	17		6.10	67.10	97.6
	18		6.10	54.90	91.5
	19		6.10	37.82	97.6
	20		6.10	35.99	97.6
	21		6.10	31.11	97.6
	22		42.70	32.33	91.5
	23		42.70	29.89	91.5
	24		36.60	28.67	91.5

Table D36. Nitrate (mg ℓ^{-1}) of runoff water samples collected with ISCO sampler at Tweefontein (2003/2004 summer season, Institute for soil, climate and water - ARC, RSA).

Pivot	Number of bottles	Jan-04	Feb-04	Mar-03	Apr-04
Tweefontein	1	3.43		0.00	4.96
	2	1.24	8.24	5.10	4.96
	3	4.68	12.60	6.08	3.83
	4	4.29	12.72	5.76	2.49
	5	5.33	11.38	3.99	2.84
	6		16.19	4.01	1.50
	7		32.58	2.57	2.28
	8		48.23	4.54	2.16
	9		51.62	4.24	2.08
	10		57.76	4.02	1.61
	11		66.19	5.29	2.45
	12		64.94	3.56	2.50
	13		60.55	0.83	2.25
	14		66.71	2.36	1.60
	15		67.00	3.55	2.66
	16		67.77	6.38	3.73
	17		65.20	4.55	3.93
	18		63.30	4.14	1.63
	19		65.12	3.95	1.85
	20		66.35	3.81	1.74
	21		58.32	4.37	1.17
	22		42.67	5.48	1.82
	23		45.01	4.50	2.81
	24		42.86	5.08	1.89

Table D37. Chloride (mg ℓ^{-1}) of runoff water samples collected with ISCO sampler at Tweefontein (2003/2004 summer season, Institute for soil, climate and water - ARC, RSA).

Pivot	Number of bottles	Jan-04	Feb-04	Mar-03	Apr-04
Tweefontein	1	16.77		13.24	18.36
	2	7.78	2.05	7.66	18.36
	3	6.71	2.30	7.43	17.81
	4	9.40	2.25	8.15	18.67
	5	6.83	9.36	8.30	19.64
	6		31.08	6.79	18.53
	7		28.38	7.22	20.63
	8		31.80	6.95	20.35
	9		28.70	7.42	21.54
	10		29.54	12.47	21.75
	11		33.74	16.85	22.73
	12		33.42	16.69	23.45
	13		33.49	16.95	21.97
	14		37.96	32.17	23.31
	15		32.23	34.71	32.58
	16		32.98	40.01	25.53
	17		37.07	28.28	23.10
	18		34.17	25.96	22.35
	19		32.51	17.62	23.21
	20		33.14	16.12	22.28
	21		32.01	14.32	21.89
	22		42.02	15.23	23.07
	23		46.45	12.90	21.43
	24		43.31	11.53	23.38

Table D38. Sodium (mg ℓ^{-1}) of runoff water samples collected with ISCO sampler at Tweefontein (2003/2004 summer season, Institute for soil, climate and water - ARC, RSA).

Pivot	Number of bottles	Jan-04	Feb-04	Mar-03	Apr-04
Tweefontein	1	5.72		5.82	29.34
	2	3.38	2.35	2.94	29.34
	3	5.50	1.67	2.88	32.11
	4	6.81	2.09	2.93	35.34
	5	5.37	11.03	2.78	36.47
	6		37.94	2.54	38.01
	7		36.41	2.44	40.32
	8		39.04	2.42	42.28
	9		40.69	2.60	43.96
	10		45.59	4.09	44.90
	11		44.87	7.44	47.58
	12		44.41	9.72	48.67
	13		43.35	11.05	52.32
	14		42.29	19.63	59.36
	15		41.95	30.96	54.71
	16		44.08	21.24	55.69
	17		45.81	17.14	52.95
	18		45.84	13.53	51.75
	19		44.72	11.02	48.60
	20		45.43	8.88	47.97
	21		45.64	7.23	46.83
	22		61.45	5.98	45.86
	23		66.82	4.89	46.55
	24		65.10	4.59	46.85

Table D39. Potassium (mg ℓ^{-1}) of runoff water samples collected with ISCO sampler at Tweefontein (2003/2004 summer season, Institute for soil, climate and water - ARC, RSA).

Pivot	Number of bottles	Jan-04	Feb-04	Mar-03	Apr-04
Tweefontein	1	4.70		4.54	17.12
	2	4.28	3.84	4.75	17.12
	3	6.37	4.27	4.92	17.95
	4	6.96	5.16	4.68	18.32
	5	6.14	9.56	4.29	17.92
	6		20.03	4.17	18.11
	7		21.86	4.31	18.68
	8		23.80	4.19	18.94
	9		25.08	4.25	18.84
	10		28.91	4.68	18.77
	11		29.18	6.74	19.03
	12		29.07	7.67	18.86
	13		28.67	7.90	19.47
	14		28.22	11.02	19.59
	15		28.16	15.13	19.75
	16		30.81	11.47	20.44
	17		31.22	9.77	19.21
	18		31.30	8.33	18.95
	19		31.80	7.67	18.81
	20		32.00	7.04	18.8
	21		31.82	6.38	19.12
	22		36.11	5.98	18.64
	23		37.84	5.27	18.83
	24		38.01	5.40	18.69

Table D40. Calcium (mg ℓ^{-1}) of runoff water samples collected with ISCO sampler at Tweefontein (2003/2004 summer season, Institute for soil, climate and water - ARC, RSA).

Pivot	Number of bottles	Jan-04	Feb-04	Mar-03	Apr-04
Tweefontein	1	72.13		45.51	325.78
	2	84.09	21.18	26.30	325.78
	3	110.33	14.61	29.72	338.02
	4	121.47	22.57	29.09	336.97
	5	95.17	129.58	28.54	347.53
	6		318.71	26.81	357.03
	7		319.00	25.99	360.40
	8		329.74	26.82	362.22
	9		344.81	29.86	372.15
	10		359.50	40.74	374.85
	11		370.44	61.75	377.79
	12		367.14	85.97	376.17
	13		361.60	104.26	383.95
	14		370.72	151.08	382.98
	15		378.41	174.07	384.40
	16		382.80	156.54	381.55
	17		405.11	133.61	378.78
	18		389.44	118.57	377.07
	19		402.54	103.88	367.31
	20		396.82	93.56	359.32
	21		407.00	84.89	488.11
	22		457.30	77.90	356.66
	23		484.31	73.57	358.39
	24		490.30	66.74	352.71

Table D41. Magnesium (mg ℓ^{-1}) of runoff water samples collected with ISCO sampler at Tweefontein (2003/2004 summer season, Institute for soil, climate and water - ARC, RSA).

Pivot	Number of bottles	Jan-04	Feb-04	Mar-03	Apr-04
Tweefontein	1	24.09		25.79	121.24
	2	17.05	6.05	12.08	121.24
	3	27.77	3.65	13.12	126.05
	4	33.16	6.55	12.52	128.28
	5	24.41	50.40	12.40	131.78
	6		147.33	11.39	133.66
	7		142.72	10.69	137.83
	8		145.60	11.07	140.94
	9		156.33	12.74	145.44
	10		168.71	20.12	147.68
	11		170.61	36.63	151.19
	12		168.74	47.53	154.96
	13		163.64	54.94	158.06
	14		161.22	90.13	157.88
	15		163.30	105.86	161.28
	16		162.74	97.08	162.82
	17		169.94	80.88	162.86
	18		169.42	65.22	161.88
	19		174.94	52.50	158.38
	20		174.51	42.93	159.06
	21		172.73	35.84	160.50
	22		228.00	30.46	156.98
	23		239.33	26.25	157.91
	24		242.41	22.81	156.94

Table D42. Phosphate (mg ℓ^{-1}) of runoff water samples collected with ISCO sampler at Tweefontein (2003/2004 summer season, Institute for soil, climate and water - ARC, RSA).

Pivot	Number of bottles	Jan-04	Feb-04	Mar-03	Apr-04
Tweefontein	1	1.56		0.0	18.64
	2	0.43	0.30	0.0	18.64
	3	0.17	0.64	0.0	4.13
	4	0.82	0.78	0.0	4.48
	5	0.56	0.78	0.0	4.69
	6		2.72	0.0	7.65
	7		2.11	0.0	6.92
	8		1.99	0.0	8.69
	9		0.00	0.8	1.50
	10		1.65	0.0	1.73
	11		0.00	0.0	4.65
	12		3.32	0.0	1.41
	13		0.00	0.0	1.80
	14		0.00	0.0	2.53
	15		1.82	0.0	2.90
	16		2.34	0.0	2.59
	17		0.00	2.59	2.06
	18		3.20	0.0	1.28
	19		4.20	0.0	3.38
	20		2.74	0.0	0.00
	21		1.33	0.0	0.00
	22		3.60	0.0	1.68
	23		3.34	0.0	1.63
	24		0.00	0.58	1.64

Table D43. TSS of runoff water samples collected with ISCO sampler at Tweefontein (2003/2004 summer season, Institute for soil, climate and water - ARC, RSA).

Pivot	Number of bottles	Jan-04	Feb-04	Mar-03	Apr-04
Tweefontein	1	1015		146.0	11.7
	2	622	27.4	115.0	12.9
	3	116	21.1	105.5	18.0
	4	240	4.8	115.5	14.5
	5	135	5.5	96.5	15.4
	6		5.0	101.0	12.6
	7		4.4	94.0	15.7
	8		8.7	82.0	17.4
	9		6.4	81.5	15.7
	10		4.7	78.0	16.0
	11		6.7	60.0	20.9
	12		5.4	51.5	20.0
	13		4.9	62.0	18.4
	14		4.6	57.0	20.9
	15		5.1	67.0	17.8
	16		18.4	65.0	16.3
	17		4.5	53.5	15.4
	18		5.0	51.5	17.7
	19		5.6	46.0	16.6
	20		5.4	54.5	16.6
	21		5.5	52.0	17.7
	22		6.1	58.5	15.4
	23		5.5	58.5	14.6
	24		6.6	57.0	16.9

Appendix E

Fertilizers

Table E1. Type, amount and method of fertilizers application at Kleinkopjé during winter 2000.

Pivot	Crop	Date	Type of fertilizer	Amount (kg ha^{-1})	Application method
Major	Wheat	22/06/2000	4:1:1 (22)	548	Pre-planting
		22/07/2000	2:3:4 (30)	160	With planting
		23/08/2000	3:0:1 (16)	420	Top-dressing
		29/08/2000	$MgSO_4$	30	Top-dressing
		25/09/2000	3:0:1 (16)	420	Top-dressing
		10/10/2000	ANO (21)	166	Top-dressing
Four	Wheat	28/06/2000	4:1:1 (22)	548	Pre-planting
		29/06/2000	2:3:4 (30)	16	With planting
		01/09/2000	3:0:1 (16)	242	Top-dressing
		28/09/2000	3:0:1 (16)	420	Top-dressing
		02/10/2000	ANO (21)	270	Top-dressing
TWF	Wheat	24/06/2000	4:1:1 (22)	548	Pre-planting
		26/06/2000	2:3:4 (30)	160	With planting
		10/09/2000	3:0:1 (16)	420	Top-dressing
		20/09/2000	3:0:1 (16)	420	Top-dressing
		05/10/2000	ANO (21)	100	Top-dressing

Table E2. Type, amount and method of fertilizers application at Kleinkopjé during summer 2000/2001.

Pivot	Crop	Date	Type of fertilizer	Amount (kg ha^{-1})	Application method
Major	Maize	12/12/2000	6:3:2 (22)	360	With planting
Four	Maize	15/12/2000	6:3:2 (22)	360	With planting
TWF	Maize	14/12/2000	6:3:2 (22)	360	With planting

Table E3. Type, amount and method of fertilizers application at Kleinkopjé during winter 2001.

Pivot	Crop	Date	Type of fertilizer	Amount (kg ha^{-1})	Application method
Major	Wheat	18/06/2001	4:1:1 (22)	550	Pre-planting
		18/06/2001	2:3:4 (30)	150	With planting
		01/08/2001	3:0:1 (16)	280	Topdressing
			Omni-boost	3	
		13/08/2001	3:0:1 (16)	280	Topdressing
		20/08/2001	$MgSO_4$	25	
		27/08/2001	3:0:1 (16)	280	Topdressing
		05/09/2001	$MgSO_4$	25	
Four	Wheat	20/06/2001	4:1:1 (22)	550	Pre-planting
		20/06/2001	2:3:4 (30)	150	With planting
		03/08/2001	3:0:1 (16)	280	Topdressing
			Omni-boost	3	
		15/08/2001	3:0:1 (16)	280	Topdressing
		15/08/2001	$MgSO_4$	25	
		29/08/2001	3:0:1 (16)	280	Topdressing
		29/08/2001	$MgSO_4$	25	
		Flag-leaf stage	ANO (21)	100	Topdressing

Table E4. Type, amount and method of fertilizers application at Kleinkopjé during summer 2001/2002.

Pivot	Crop	Date	Type of fertilizer	Amount (kg ha^{-1})	Application method
Major	Maize	12/10/2001	5:3:4 (22)	350	
		25/12/2001	5:0:1 (24)	230	
		15/01/2001	5:0:1 (24)	230	
Four	Maize	11/12/2001	5:3:4 (22)	350	With planting
		20/12/2001	5:0:1 (24)	230	Topdressing (with cultivator)
		20/01/2001	5:0:1 (24)	230	Topdressing (with cultivator)
TWF	Potatoes	20/08/2001	KCl (50)	300	Pre-planting
		20/08/2001	4:3:4 (33)	1200	With planting
		25/10/2001	UAN (32)	200	Topdressing
		16/11/2001	KNO_3	100	Topdressing
		28/11/2001	UAN (32)	100	Topdressing
		07/12/2001	KNO_3	100	Topdressing

Table E5. Type, amount and method of fertilizers application at Kleinkopjé during winter 2002.

Pivot	Crop	Date	Type of fertilizer	Amount (kg ha^{-1})	Application method
Four	Wheat	22/06/2002	4:1:1 (22)	550	uitgespit (?)
		30/07/2002	2:3:4 (30)	150	geplant (planted?)
TWF	Wheat	22/06/2002	4:1:1 (22)	550	uitgespit
		30/07/2002	2:3:4 (30)	150	geplant

Table E6. Type, amount and method of fertilizers application at Kleinkopjé during summer 2002/2003.

Pivot	Crop	Date	Type of fertilizer	Amount (kg ha^{-1})	Application method
Major	Potatoes	16/08/2002	KCl	200	Pre-planting
		17/08/2002	4:3:4 (30)	200	Pre-planting
		09/09/2002	4:3:4 (30)	1000	At planting
		21/10/2002	UAN (32)	100	Topdressing
		04/11/2002	KNO_3	40	Topdressing
		11/11/2002	KNO_3	40	Topdressing
		18/11/2002	UAN (32)	100	Topdressing
		02/12/2002	KNO_3	40	Topdressing
		09/12/2002	KNO_3	40	Topdressing
		17/12/2002	KNO_3	40	Topdressing
Four	Maize	14/12/2002	5:3:4 (22)	300	At planting
			UAN	250	
			UAN	250	
TWF	Maize	13/12/2002	5:3:4 (22)	300	At planting
			UAN	250	
			UAN	250	

Table E7. Type, amount and method of fertilizers application at Kleinkopjé during winter 2003.

Pivot	Crop	Date	Type of fertilizer	Amount (kg ha^{-1})	Application method
Major	Wheat	27/06/2003	4:1:1 (22)	550	Liquid spray
		27/06/2003	Dolomite	3000	Broadcast
		02/07/2003	2:3:2 (22)	167	Pellets with planting
		18/08/2003	3:0:1 (16)	280	Liquid topdressing
		10/09/2003	3:0:1 (16)	280	Liquid topdressing
		19/09/2003	3:0:1 (16)	280	Liquid topdressing
Four	Wheat	21/07/2003	4:1:1 (22)	550	Liquid spray
		25/07/2003	2:3:2 (22)	160	Pellets with planting
		23/09/2003	3:0:1 (16)	280	Liquid topdressing
TWF	Wheat	18/07/2003	4:1:1 (22)	550	Liquid spray
		11/09/2003	2:3:2 (22)	160	Pellets with planting
		15/09/2003	3:0:1 (16)	280	Liquid topdressing
			3:0:1 (16)	280	Liquid topdressing

Table E8. Type, amount and method of fertilizers application at Kleinkopjé during winter 2004.

Pivot	Crop	Date	Type of fertilizer	Amount (kg ha^{-1})	Application method
Major	Wheat	07/07/2004	Lime	3000	Broadcast
		10/07/2004	2:3:2 (22)	310	Pellets with planting
		09/09/2004	5:0:1 (24)	300	Liquid topdressing
Four	Wheat	02/07/2004	2:3:2 (22)	310	Pellets with planting
		06/09/2004	5:0:1 (24)	300	Liquid topdressing
TWF	Wheat	27/06/2004	Lime	3000	Broadcast
		30/06/2004	2:3:2 (22)	310	Pellets with planting
		26/08/2004	5:0:1 (24)	300	Liquid topdressing

Table E9. Type, amount and method of fertilizers application at Kleinkopjé during winter 2005.

Pivot	Crop	Date	Type of fertilizer	Amount (kg ha^{-1})	Application method
Major	Wheat	19/07/2005	2:3:2 (22)	270	Pellets with planting
Four	Wheat	26/07/2005	2:3:2 (22)	285	Pellets with planting
		05/09/2005	5:0:1 (24)	200	Liquid topdressing
TWF	Wheat	23/07/2005	2:3:2 (22)	285	Pellets with planting
		02/09/2005	5:0:1 (24)	200	Liquid topdressing

Appendix F

Herbicide

Table F1. Type, amount and method of herbicides application at Kleinkopjé during winter 2000.

Pivot	Crop	Date	Herbicide	Amount (ℓ ha^{-1})	Application type
Major	Wheat	01/09/2000	Kelp-p-max	4.00	
		01/09/2000	Bromox	1.50	
		01/09/2000	MCPA	0.50	
		01/09/2000	Omniboost	3.00 kg ha^{-1}	
TWF	Wheat	18/08/2000	Kelp-p-max	4.00	
		18/08/2000	Bromox	1.50	
		18/08/2000	MCPA	0.50	
		18/08/2000	Omniboost	3.00 kg ha^{-1}	

Table F2. Type, amount and method of herbicides application at Kleinkopjé during summer 2000/2001.

Pivot	Crop	Date	Herbicide	Amount (ℓ ha^{-1})	Application type
Major	Maize		Wenner	0.60	At planting
			Galleon	0.40	At planting
			Karate	0.04	At planting
			Bladex	2.00	Follow-up
			Bromind	0.45	Follow-up
			Allbuff	0.20	Follow-up
Four	Maize		Wenner	0.60	At planting
			Galleon	0.40	At planting
			Karate	0.04	At planting
			Bladex	2.00	Follow-up
			Bromind	0.45	Follow-up
			Allbuff	0.20	Follow-up
TWF	Maize		Wenner	0.60	At planting
			Galleon	0.40	At planting
			Karate	0.04	At planting

			Bladex	2.00	Follow-up
			Bromind	0.45	Follow-up
			Allbuff	0.20	Follow-up

Table F3. Type, amount and method of herbicides application at Kleinkopjé during winter 2001.

Pivot	Crop	Date	Herbicide	Amount (ℓ ha^{-1})	Application type
Major	Wheat	27/08/2001	MCPA	0.50	
			Campatop	1.50	
			Omniboost	3.00 kg ha^{-1}	
Four	Wheat	27/08/2001	MCPA	0.50	
			Campatop	1.50	
			Omniboost	3.00 kg ha^{-1}	

Table F4. Type, amount and method of herbicides application at Kleinkopjé during summer 2001/2002.

Pivot	Crop	Date	Herbicide	Amount (ℓ ha^{-1})	Application type
Major and Four	Maize		Fastac	0.07	At planting
			Wenner	0.60	At planting
			Fastac	0.12	Follow-up
			Cheeta	1.50	Follow-up
			Frontier	0.75	Follow-up
			2,4-D	0.40	Follow-up
			Allbuff	0.20	Follow-up
TWF	Potatoes	03/09/2001	Relay	1.50	Pre-emergence
			Sencor	1.50	Pre-emergence
			Fastac	1.50	Pre-emergence
		24/10/2001	Vydate	2.00	
			Kelp.p.max	4.00	

			Bravo	2.00	
			Allbuff	0.20	
		31/10/2001	Rimon	0.35	
			Bravo	2.00	
			Allbuff	0.20	
		07/11/2001	Bravo	2.00	
			Rimon	0.35	
			Agrimetcan	0.50	
			Allbuff	0.20	
		14/11/2001	Tanos	0.50 kg ha^{-1}	
			Metaphos	1.00	
			Trimangol	2.00	
			Greengold	0.50	
			Allbuff	0.20	
			Agrimetcan	0.50	
		21/11/2001	Tanos	0.50 kg ha^{-1}	
			Trimangol	2.00	
			Fastac	0.15	
			Allbuff	0.20	
		30/11/2001	Trimangol	3.00	
			Rimon	0.35	
		10/12/2001	Trimangol	3.00	
			Rimon	0.35	
		22/12/2001	Fastac	0.15	
			Chlorpirifos	1.50	
		02/01/2002	Fastac	0.15	
			Chlorpirifos	1.50	

Table F5. Type, amount and method of herbicides application at Kleinkopjé during summer 2002/2003.

Site	Crop	Date	Pesticide	Amount (ℓ ha^{-1})	Application type
Four and TWF	Maize		Suprasien	1.50	
			Turbo maize	3.00	
			2,4-D	0.50	
			Allbuff	0.20	
			Akito	0.12	
Major	Potatoes		Rugby	4.00	
			Eptam	4.00	
			Chlorpirifos	1.50	
		06/11/2002	Kelp.p.max	4.00	
			Allbuff	0.20	
			Vydate	3.00	
			Bravo	2.00	
			Midafos	1.00	
		13/11/2002	Rimon	0.35	
			Allbuff	0.20	
			Agrimectin	0.50	
		20/11/2002	Trimangol	3.00	
			Rimon	0.35	
			Allbuff	0.20	
			Vydate	3.00	
		30/11/2002	Tanos	0.50	
			Trimangol	2.00	
			Rimon	0.35	
			Agrimectin	0.50	
		11/12/2002	Methomyl	1.00	
			Punch C	0.35	
			Trimangol	3.00	

			Allbuff	0.20	
			Agrimectin	0.50	
		19/12/2002	Trimangol	3.00	
			Capitan	0.30	
			Rimon	0.35	
			Allbuff	0.20	
		31/12/2002	Trimangol	3.00	
			Capitan	0.30	
			Rimon	0.35	
			Allbuff	0.20	
		13/01/2003	Trimangol	3.00	
			Punch C	0.30	
			Fastac	0.15	
			Allbuff	0.20	
		23/01/2003	Trimangol	3.00	

Appendix G

Model validations

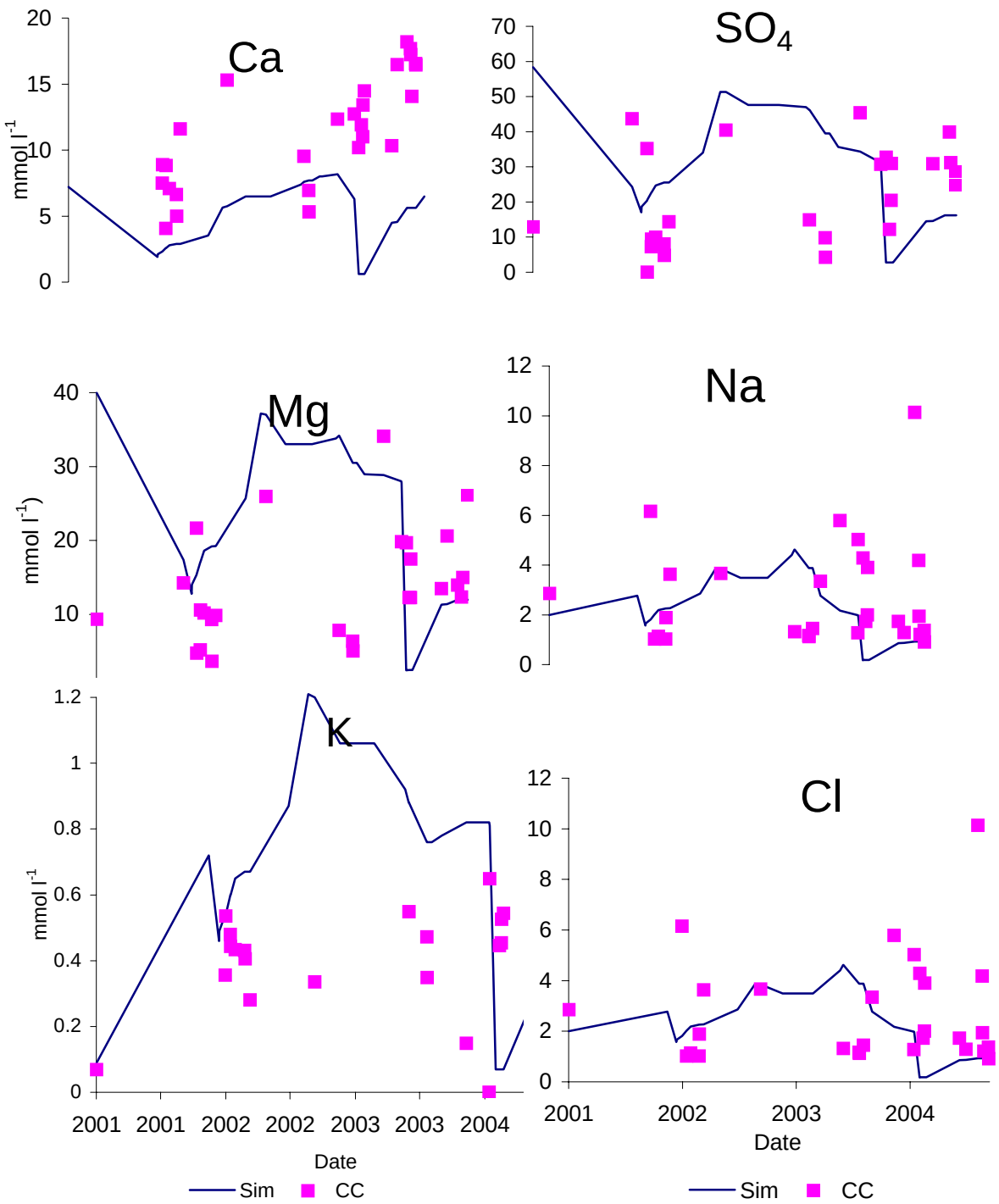


Figure G1. Soil solution sampled at 100cm from CC as compared to model simulations for site Major.

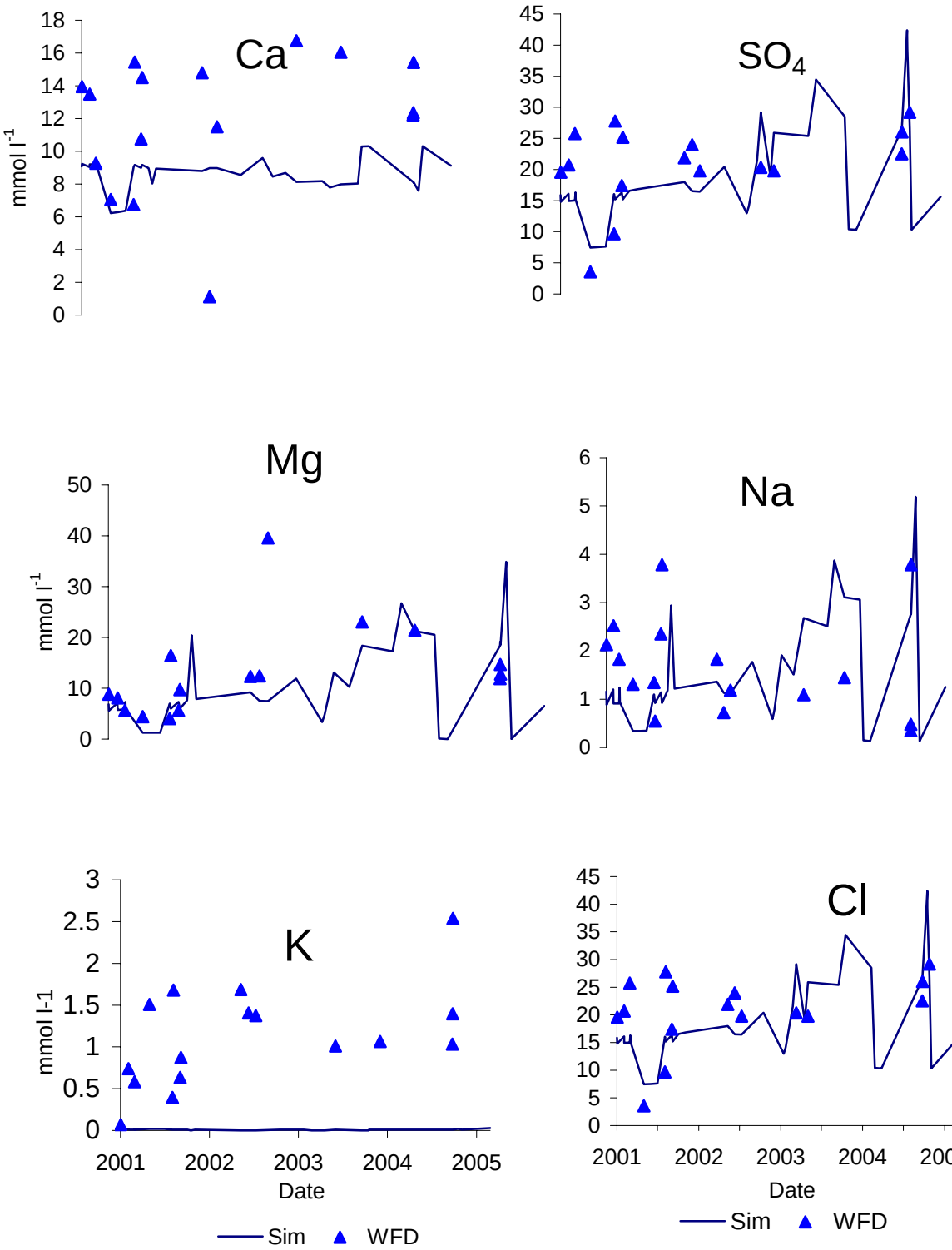


Figure G2. Soil solution sampled at 30 cm from WFD as compared to model simulations for site Pivot 4.

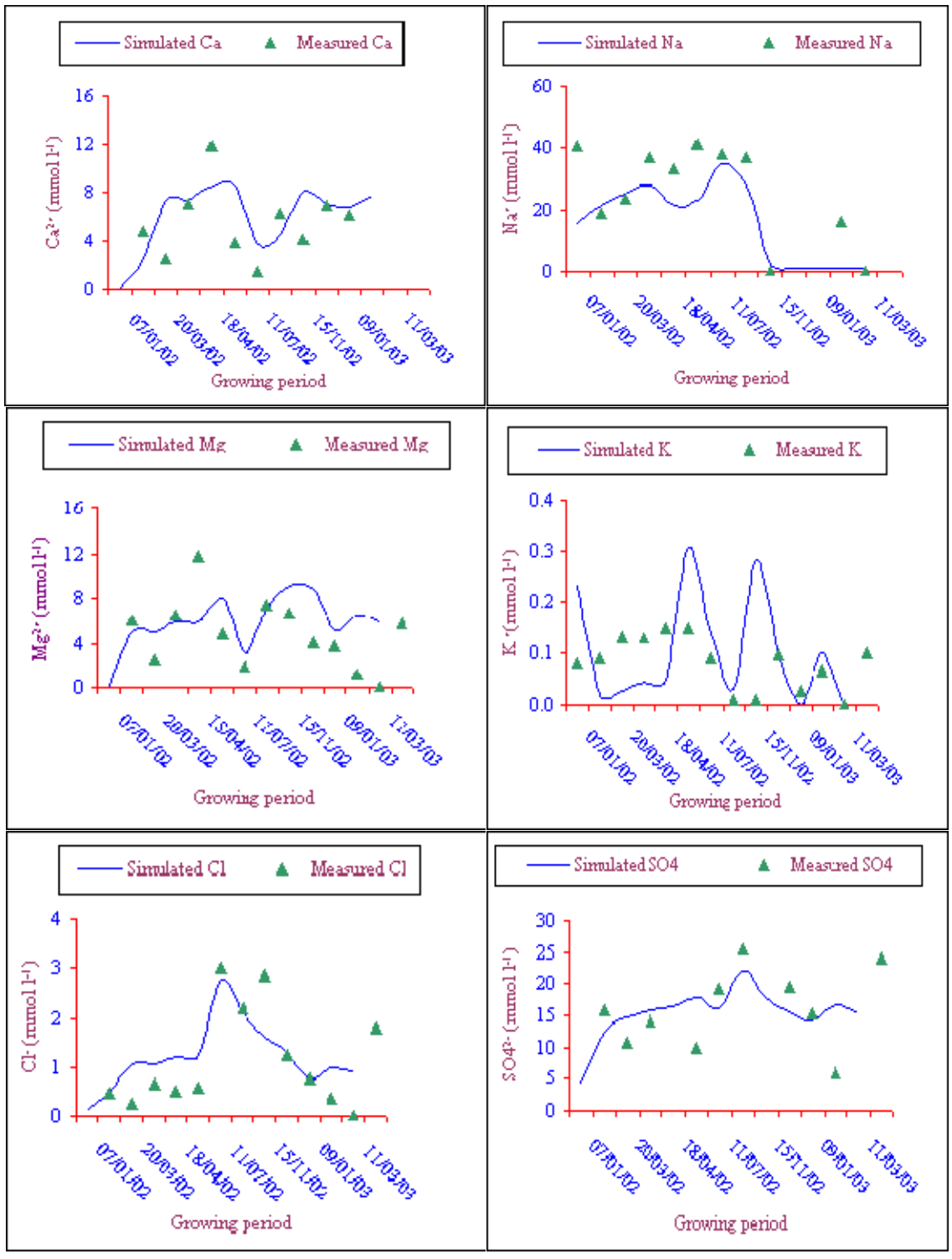


Figure G3. Simulated (solid lines) and measured values (symbols) for concentration of Ca, Na, Mg, K, Cl and SO_4 in the soil solution at a depth of 0.4 m in the Fescue (cv. Demeter) field.

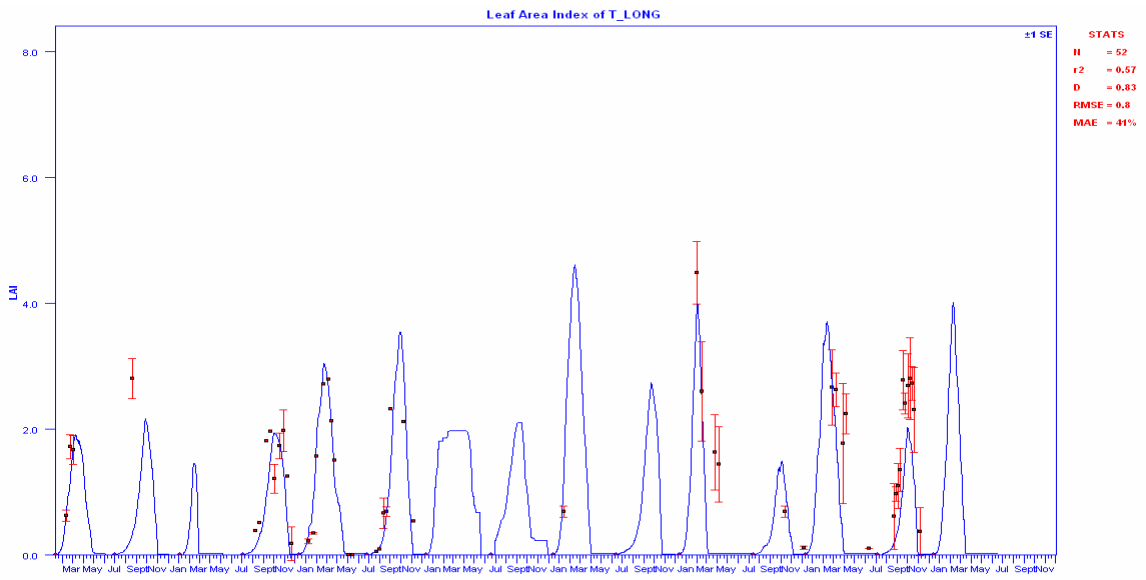


Figure G4. Simulated (solid lines) and measured (symbols) for LAI for Pivot Major.

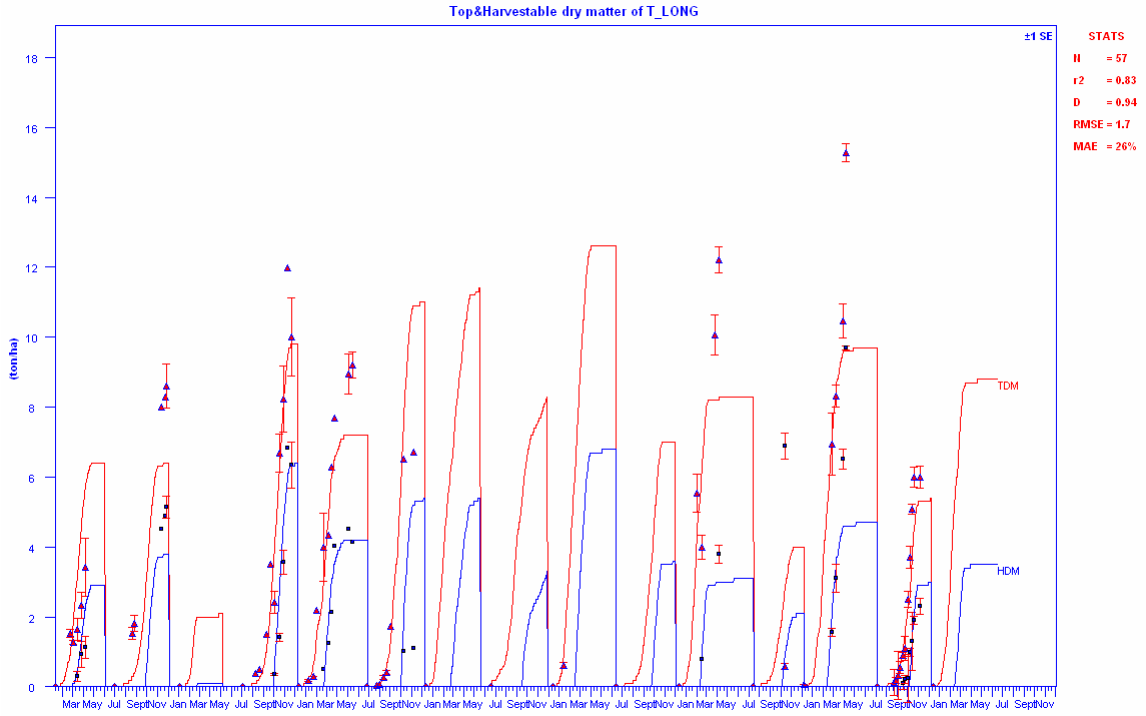


Figure G5. Simulated (solid lines) and measured (symbols) TDM for site TWF.

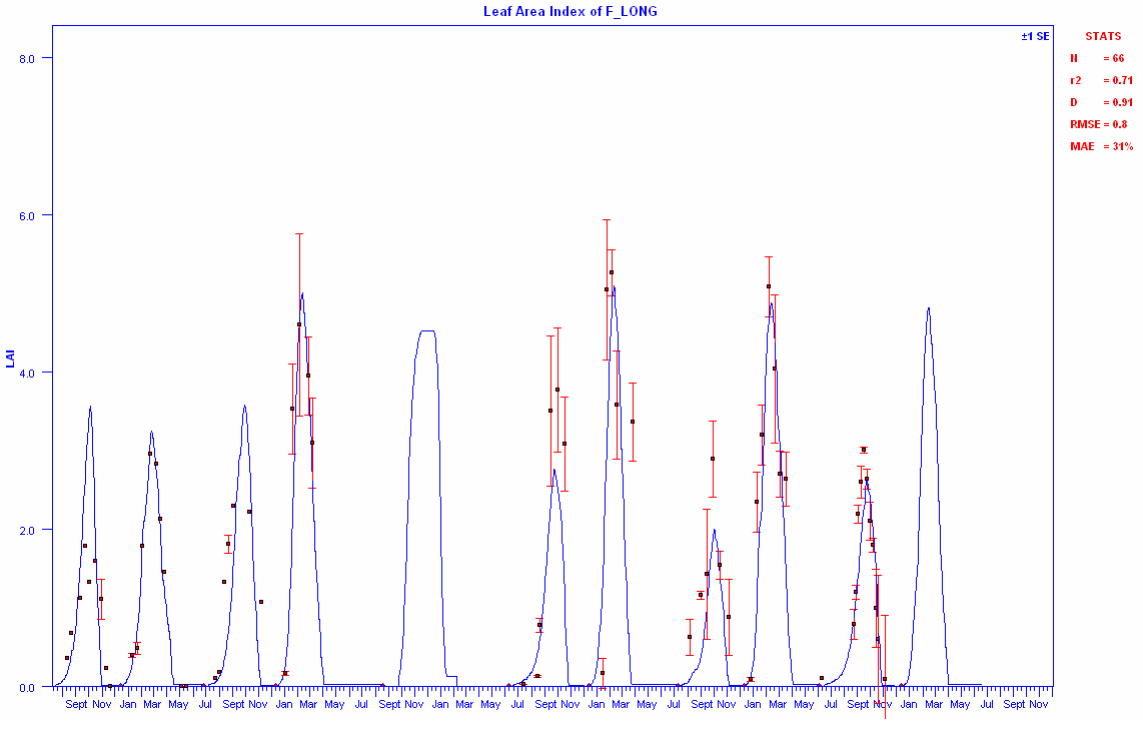


Figure G6. Simulated (solid lines) and measured (symbols) for LAI for Pivot Major.

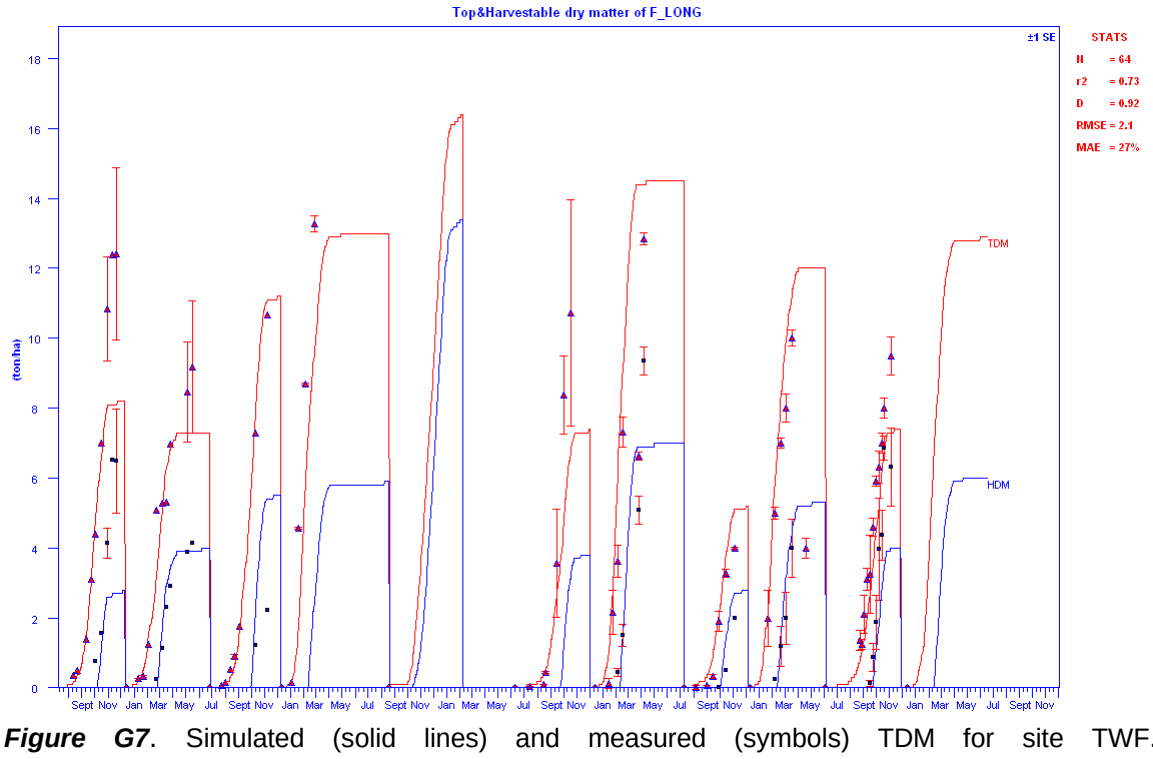


Figure G7. Simulated (solid lines) and measured (symbols) TDM for site TWF.

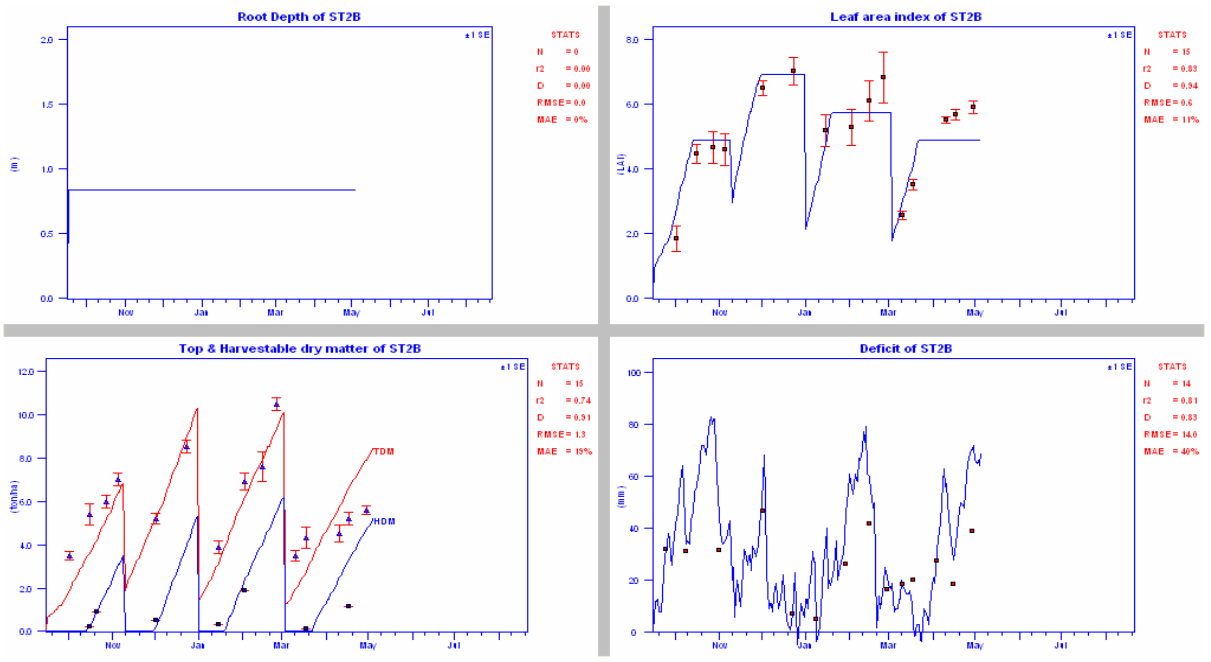


Figure G8. Simulated (solid lines) and measured values (symbols) of root depth (RD), leaf area index (LAI), top dry matter (TDM) and deficit to field capacity Lucerne.

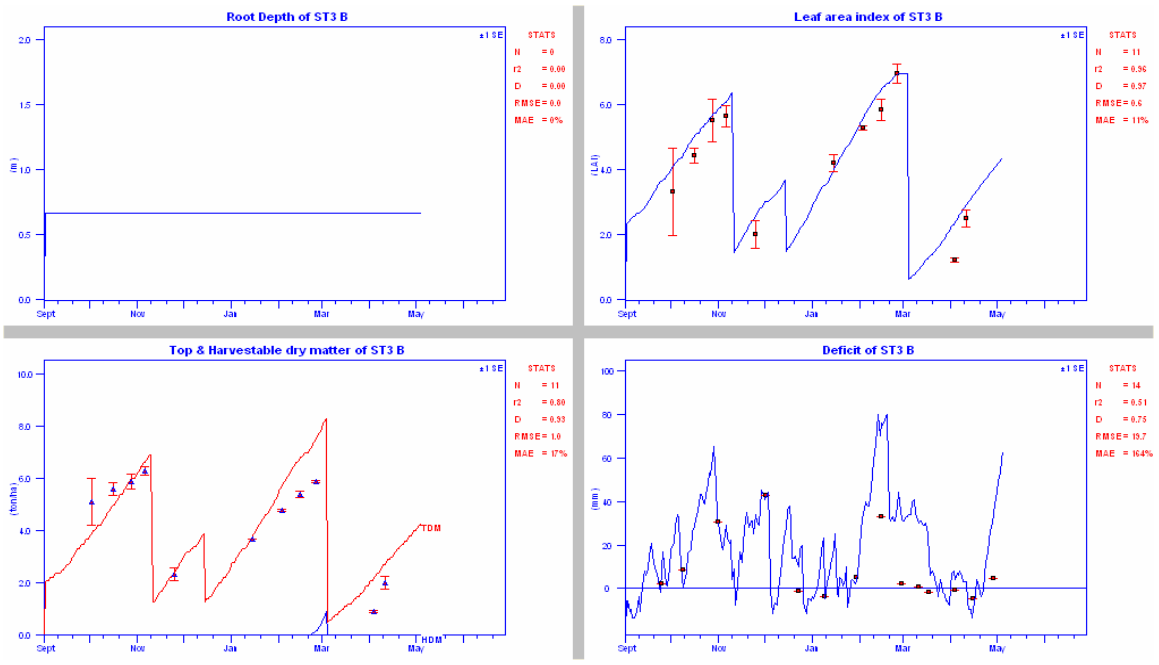


Figure G9. Simulated (solid lines) and measured values (symbols) of root depth (RD), leaf area index (LAI), top dry matter (TDM) and deficit to field capacity Fescue (cv. Demeter).

Appendix H

Potato quality study

THE EFFECT OF IRRIGATION WITH GYPSIFEROUS WATER ON CALCIUM NUTRITION OF POTATO

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ABSTRACT

The potato (*Solanum tubersolum l.*) has fleshy tubers with low levels of endogenous calcium compared with other vegetative parts. Calcium is an essential plant macronutrient in maintaining cell wall stability. Calcium related disorders might be the result of limited calcium transport to the potato tuber due to tuber's displacement from the main transpiration stream and the immobility of calcium in the phloem. Low tuber calcium concentrations have been associated with internal brown spot (IBS) of the potato tuber, which is a physiological disorder associated with the necrosis of the medullary tissue.

In recent investigations, different calcium sources were used to apply additional Ca to the plants, to determine how it affects the amount of Ca accumulated by the tubers. The effluent from coal mines on the Mpumalanga highveld can possibly be used for irrigation as a possible source of Ca. Large volumes of gypsiferous mine wastewater are generated on already scarce water resources. The increasing demand for food and water by a growing population will necessitate careful use of all water resources. An approach recently being investigated is the use of this water for the irrigation of agronomic crops and pastures. The crop response to gypsiferous mine water was investigated in a field trial at Kleinkopjé mines. Irrigating potatoes with gypsiferous water generally resulted in improved quality of the potato tubers.

INTRODUCTION

Potato (*Solanum tubersolum l.)* tubers have low levels of endogenous calcium compared with other vegetative parts. Tuber calcium concentration ranges from 0.009 to 0.06 g Ca/100g dry mater (Collier *et al.,* 1978, Davis and Millard, 1985). Calcium is an essential plant macronutrient in maintaining cell wall stability and integrity (Ilyama *et al*., 1994). Calcium related disorders might be the result of limited calcium transport to the potato tuber because of the organ's displacement from the main transpiration stream and the immobility of calcium in the phloem. This problem may be magnified when potatoes are grown on low CEC, low soil test calcium, sandy soils (Davis and Millard, 1985).

Low tuber calcium concentrations have been associated with internal brown sport (IBS) of the potato tuber, which is a physiological disorder associated with the necrosis of the medullary tissue. Glasshouse and field studies have shown that tubers with IBS symptoms have lower calcium concentrations than unaffected tubers (Colliar *et al*., 1978; Silva *et al.,* 1991). Environmental factors usually correlated with the occurrence of IBS include high temperature and water stress during tuber development. For example at high temperature, an increase in transpiration rate will result in more calcium being transported to vegetative parts and less to the tubers (Silva *et al*., 1991).

In recent research, different calcium sources were used to apply additional calcium to plants to determine how it affects the amount of calcium accumulated by the tubers. The effluent from coalmines on the Mpumalanga Highveld can possibly be used for irrigation as a possible source of Ca. In the mining of mineral resources, large volumes of mine waste water are generated with adverse effects on the already scarce water resources and the increasing demand for food and water by growing population will necessitate careful use of all water resources. This water is

unsuitable for direct uncontrolled discharge into watercourses, where it may become a threat to the environment and problem to potential users.

There are several different approaches to this problem, one alternative approach currently being investigated is the use of this water for irrigation of agronomic crops and pastures. The use of gypsiferous mine water for irrigation of agricultural crops is a promising technology that could add value through agricultural production. Olsen and Rehm (1986), considered application of gypsiferous mine water to the soil beneficial, because gypsum that precipitates in the soil after the application of water high in sulphates is not sufficiently soluble to cause salt damage to a growing plant. This was investigated in a previous Water Research Commission project (Annandale *et. al.* 2001), where crop response to gypsiferous mine water was investigated in a field study at Kleinkopjé Colliery. Commercial potato trials (planted end of August 2001 and 2002) were established at Kleinkopjé mines for monitoring irrigation with gypsiferous water. This was done to determine the impact of irrigation with gypsiferous mine water as a calcium source on potato yield and quality. Irrigating with gypsiferous water may increase the Ca content of the potato tuber and result in improved tuber quality.

MATERIALS AND METHODS

Potato seeds (*Solanum tuberosum* cv. Up-to-date) were planted on Pivot Four at the end of August 2001 and were harvested on January 2002. Two plant rows were spaced 0.4m apart on raised beds to form tram rows (1.7m centre to centre). A plant density of 50 000 seeds ha^{-1} was established. Fertilization was 300 kg ha^{-1} KCl (50) before planting and 1200 kg ha^{-1} 4:3:4 (33) at planting. Potato seeds (cv. Up-to-date) were planted at Pivot Major from end of August 2002 and harvested in January 2003. Centre pivots were used for irrigation with gypsiferous mine water.

Potato plants were sampled every three weeks for growth analysis and twice during the growing season for leaf chemical analysis. Growth analysis was carried out by randomly sampling $1m^2$ of plant material within the pivot (3 replicates per sampling). Leaf area was measured with a LI3100 leaf area meter (Licor, Lincoln, Nebraska, and USA) and leaf area index (LAI) calculated from the data. At the end of the growing season tuber yield, tuber chemical analysis and tuber processing quality (specific gravity and chip colour) were determined. The quality tests were done by ARC-Roodeplaat.

Leaf and tuber chemical analysis were done by measuring dry matter of plant organs after drying in an oven at 60^oC for 4 to 5 days (until constant mass was reached). Dry tuber samples (three replicates) were chemically analysed. Nitrogen and phosphorus were determined with an auto analyser after an H_2SO_4 digestion was performed. For determination of Ca, Mg, K, SO_4, Zn, Cu, Fe and Mn samples were digested using nitric acid and perchloric acid in a digestion block. These nutrients were analysed by atomic absorption spectrometer (according to ALASA, 1998).

Soil sampling was done at the beginning of the cropping season and at the end of the trial for chemical analyses in the laboratory in order to determine changes in chemical composition of the soils at Kleinkopjé mine. Bray-1 extractable P, and ammonium acetate extractable, soluble Ca, Mg, K and Na, exchangeable Ca, Mg, K and soluble SO_4 were determined according to standard methods. The soil pH and EC (as a background reference to indicate possible increases in soil salinity) were also determined (Non-affiliated soil analysis work committee, 1990).

In filed trials at Kleinkopjé Colliery, the soil water and salt balance were monitored continuously during the cropping season. Wetting front detectors were used to measure the movement of water in the soil. Time domain reflectometry (TDR) sensors were used to measure the volumetric water content and salinity. Volumetric water content was also measured with a neutron probe.

The neutron water meter was calibrated for the site and readings taken every three weeks. At the same positions, rain gauges were installed to measure the amounts of irrigation water and rainfall. An automatic weather station was installed to monitor driving variables for evaporation.

RESULTS AND DISCUSSION

Tuber yield

Marketable potato yields of 52 t ha^{-1} (2001 trial) and 62 t ha^{-1} (2002 trial) were produced. This can be regarded as very good yields for the Mpumalanga Highveld. Unfortunately no control fields (irrigated with normal water) were available for comparison.

Growth analysis

Change in leaf areas during the growing season is presented in Figure 1. In 2001, leaf area started increasing from 47 days after planting and a maximum was reached on day 89, hereafter it declined until harvest. For the 2002 trial leaf area started increasing from day 46 and maximum was reached on day 86, where after it declined until harvest. Slightly higher maximum values were obtained in 2001

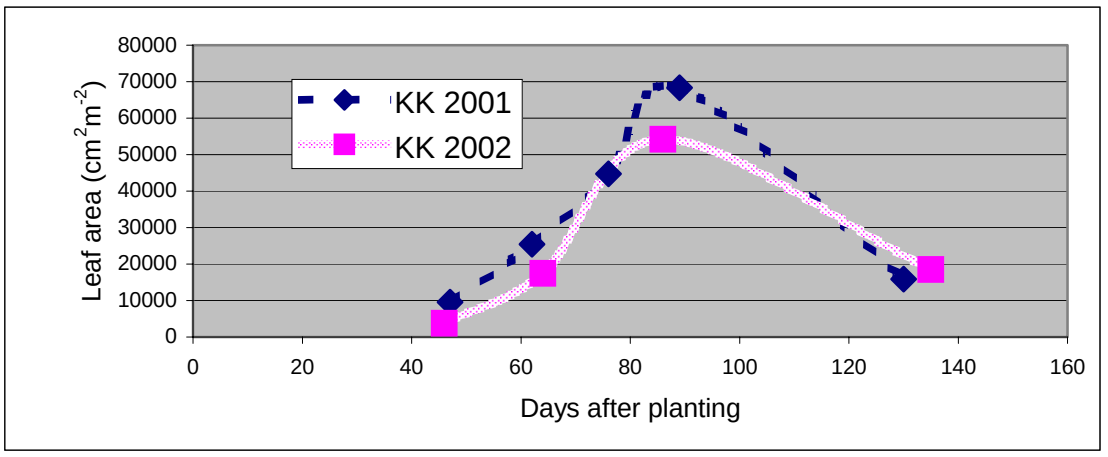

Figure H1. Change in Leaf area during the growing season of a potato crop irrigated with gypsiferous water.

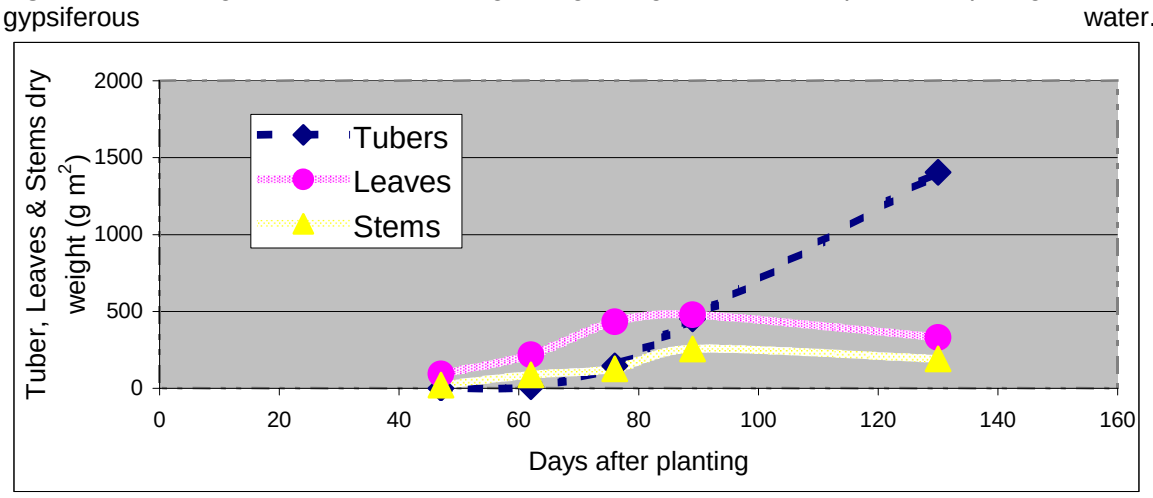

Figure H2a (2001)

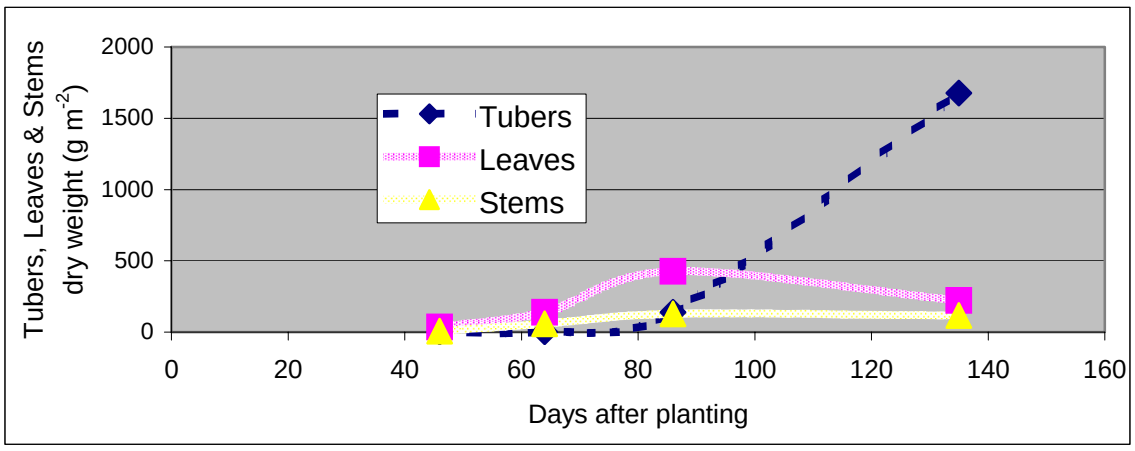

Figure H2b (2002)
Figure H2a & H2b. Tubers, leaves and stems dry mass during potato crop growth.

According to Figure H2a and H2b, leaf dry mass increased more rapidly than stem dry mass. Tubers dry mass increased rapidly with number of days after planting. Increase in dry matter mass for both leaves and stems reached maximum values around day 89 and declined until harvest in 2001. For the 2002 season increase in dry mass for both leaves and stems reached maximum values at around day 86, where after it declined until harvest. Similar trends were observed for both the growing seasons.

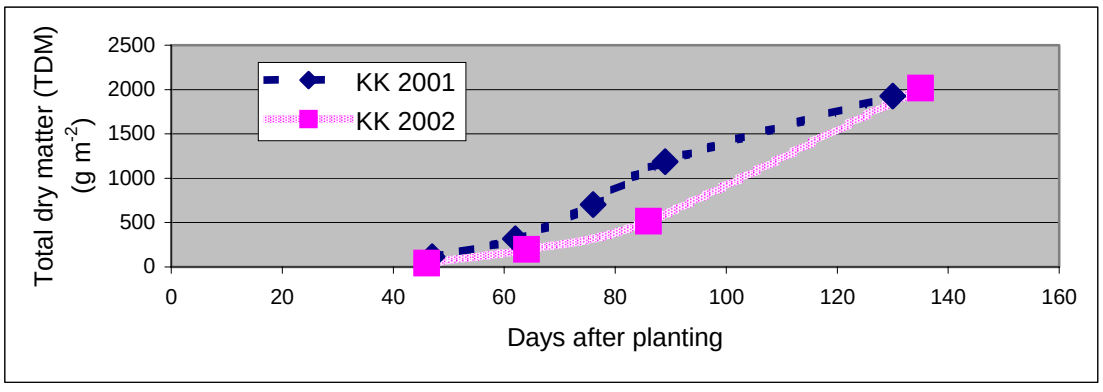

Figure H3. Changes in total dry matter (TDM) during potato crop growth.

Referring to Figure H3, the increase in total dry matter was initially curvilinear and from approximately day 90 the rate became linear. Total dry matter was increasing with number of days after planting until harvest for both the 2001 and 2002 seasons.

Leaf chemical analysis

Leaf chemical analysis was done to determine the effect of calcium on other nutrient levels. Tissue nutrient concentrations were determined for leaf blades sampled on 89 and 130 days and 86 and 130 days after planting for the 2001 and 2002 trials respectively. There was no sign of any nutrient deficiency in leaves on both sampling time points and all the nutrient levels were within acceptable ranges for potatoes (Bennet, 1993) in both seasons.

Table H1a. Potato leaf chemical analysis results on two sampling dates in 2001.

DAP	N %	P %	Ca %	K %	Mg %	Na %	SO_4 %	Cu mg/kg	Fe mg/kg	Mn mg/kg	Zn mg/kg	
89	**5.15**	**0.34**	**1.09**	**4.20**	**4.89**	**0.002**	**1.87**	**10.6**	**620**	**244.8**	**30.4**	
130	**4.7**	**0.3**	**1.27**	**3.75**	**1.01**	**0.018**	**2.8**	**35**	**303.5**	**256.7**	**26**	Norms*
>3	>0.25	>0.15	>1.5	>0.1	>0.025	>5	>50	>40	>20			

* Acceptable ranges from Bennet (1993)

Table H1b. Potato leaf chemical analysis results on two sampling dates in 2002.

DAP	N %	P %	Ca %	K %	Mg %	Na %	SO_4 %	Cu mg/kg	Fe mg/kg	Mn mg/kg	Zn mg/kg	
86	**4.42**	**0.3**	**1.11**	**5.15**	**1.01**	**0.01**	**2.31**	**13**	**489**	**510**	**31**	
130	**2.81**	**0.26**	**0.37**	**1.92**	**1.56**	**0.00**	**1.59**	**19.6**	**306.4**	**70.6**	**46.8**	
Norms*	>3	>0.25	>0.15	>1.5	>0.1	>0.025	>5	>5	>40	>20		

* Acceptable ranges from Bennet (1993)

On the second sampling time point (day 130) nitrogen, phosphorus and potassium levels declined (**N**: 5.15 to 4.73, **P**: 0.34 to 0.3 and **K**: 4.20 to 3.75 during 2001 and **N**: 4.42 to 2.81; **P**: 0.3 to 0.26; **K** 5.15 to 1.92 during 2002). It is normal for nitrogen, phosphorus and potassium levels to decline throughout the growing season, though not rapidly (Lorenz and Tyler, 1983). Calcium increased slightly during the growing season (from 1.09 to 1.27) during 2001. According to Hawkins (1946), there is a tendency for calcium to increase with age in the above-ground parts of the plant. The high calcium levels in irrigation water did not seem to suppress uptake of other essential nutrients.

Tuber chemical analysis

Table H2. Tuber chemical analysis on periderm and medullary tissue 2002 trial, (A – periderm, B – medullary tissue).

Sample	N %	P %	Ca %	K %	Mg %	Na %	SO_4 %	Cu mg/kg	Fe mg/kg	Mn mg/kg	Zn mg/kg
KK A	1.25	0.2	**0.03**	2.59	0.04	0.003	0.35	9.33	39.7	12	31.2
KK B	1.35	0.22	**0.02**	2.99	0.04	0	0.6	7.33	21.7	11.3	35.31
Normal range	**1.16 -1.95**	**0.15 -0.3**	**0.03 -0.09**	**1.0 -4.5**	**0.04 -0.14**	**0.02 -0.3**	**0.1 -0.2**	**4.0 -10.0**	**25.0 -100**	**50 -90**	**8 -30**

* Acceptable ranges from Burton (1989)

Tuber chemical analysis results are presented in Table H2. Tuber calcium content of the periderm (0.03%) was slightly higher than that of the medullary tissue (0.02%). This can be due to the immobility of calcium in the phloem and weakly developed xylem of the stolons and tubers. Generally, nutrient levels were within acceptable ranges for potato tubers Burton (1989).

Tuber internal quality tests

Tuber quality was evaluated by determining specific gravity and chip colour. Both these measurements have no units. Referring to Table H3, during 2001 high specific gravity values were obtained, ranging from 1.085 to 1.090, with an average value of 1.087. An average specific gravity value of 1.075 (range of 1.072 to 1.079) was obtained during 2002. High specific gravity values (>1.075) indicate that tubers are acceptable to the French fry processing industry. Chip colour values of 48.8 to 52.9 and 47.2 to 52.7, with averages of 50.8 and 50.2 were obtained for the 2001 and 2002 trials respectively.

Table H3. Tuber specific gravity and chip colour values.

Season	Specific gravity	Chip colour
2001	1.087	50.8
2002	1.075	50.2

Chip colour values of > 45 are acceptable to the chip processing industry. The results therefore suggest that the tuber quality was generally good. A small percentage of tuber malformation (<5%) was observed at harvesting during 2001. This could be attributed to a lack of irrigation during the late tuber bulking phase (December 2001). There was no irrigation for two weeks in December because of stolen electrical cables.

CONCLUSIONS

Irrigation with gypsiferous mine water had no negative effects on potato crops in terms of growth, leaf nutrient concentration, tuber quality and yield. Irrigating potatoes with gypsiferous mine water resulted in high tuber yields of good quality. Good quality of the potato tubers was indicated by high specific gravity (>1.075) and chip colour (> 45) values, which are acceptable to the chip processing industry.

REFERENCES

ANNANDALE, J.G., JOVANOVIC, N.Z., CLAASSENS, A.S., BENADE, N., LORENTZ, S.A., JOHNSTON, M.A., TANNER, P.D., AKEN, M.E. & HODGSON, F.I.D., 2001. The influence of Irrigation with Gypsiferous mine water on soil properties and drainage water. Water Research Commission Report No. K5/853, Pretoria, South Africa.

BENNET, W.F., 1993. Nutrient deficiencies and toxicities in crop plants. APS. Press.

BURTON, W.G., 1989. The potato. 3rd Ed. Longman Scientific. UK.

COLLIAR, G.F., WURR, D.C.E & HUNTINGTON, V.C., 1978. The effect of calcium nutrition on the Incidence of internal rust spot in the potato. *Journal of Agricultural science 91: 240-243.*

DAVIES, H.V. & MILLARD, P., 1985. Function and distribution of calcium in sprouting and non-sprouting potato tubers. *Annals of Botany 56: 745-754.*

HAWKINS, A., 1946. The rate of absorption and translocation of mineral nutrients by potatoes in Rootstock County, Maine their relation to fertilizer practices. *J. Amer Soc. AGRON. 8: 667-681.*

LORENZ, O.A. & TYLER, K.B., 1993. Plant tissue analysis of vegetable crops. In: Soil and plant tissue testing.

IIYAMA, K., LAM, T.B. & STONE, B.A., 1994. Covalent cross-links in the cell wall. *Plant Physiology 104: 315-320.*

SILVA, G.H., CHASE, R.W., HAMMERSSCHMIDT, R., VITOSH, M.L. & KITCHEN, R., 1991. Irrigation and nitrogen effects on specific gravity and internal defects of Atlantic Potatoes. *Am. potato J. 68:751-765.*

SMITH ORA, 1968. Potatoes production and storing and processing. The AUI publishing company West Port CT. P16.

Appendix I

Groundwater

Borehole logs and Multi- parameter logs New Vaal

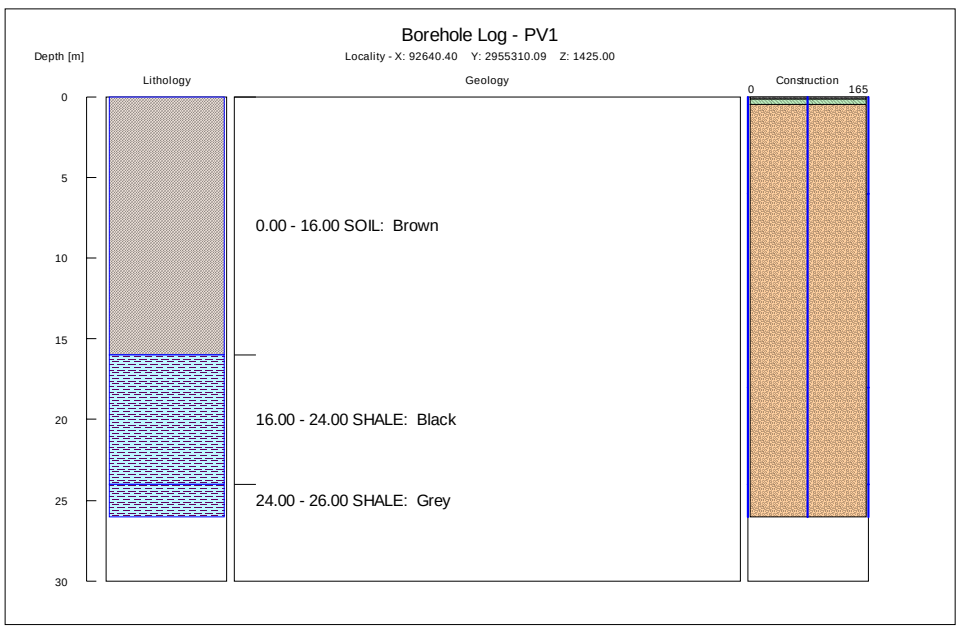

Figure I1. Borehole log illustrating geology and construction of PV1.

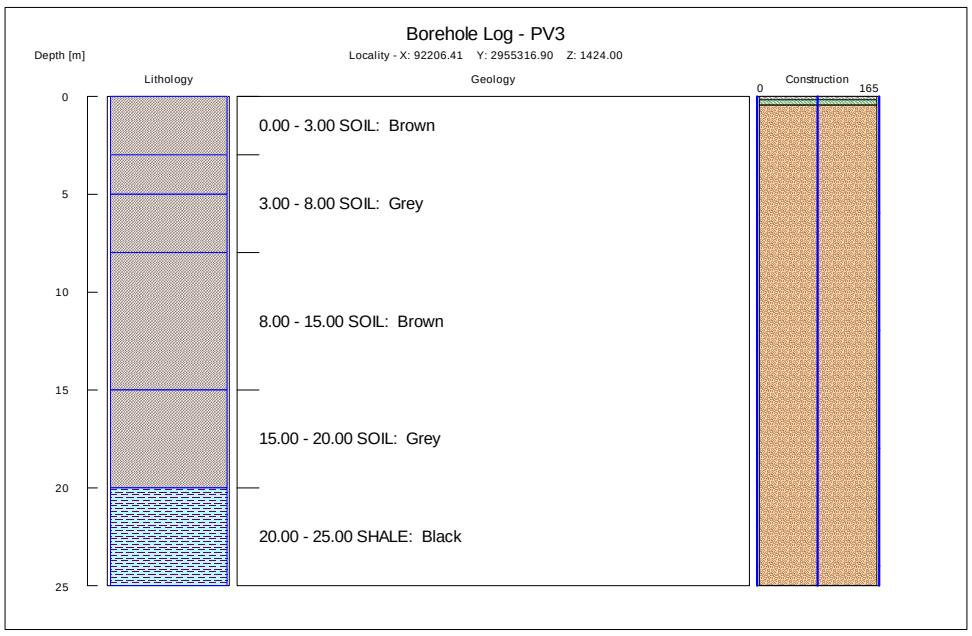

Figure I2. Borehole log illustrating geology and construction of PV3.

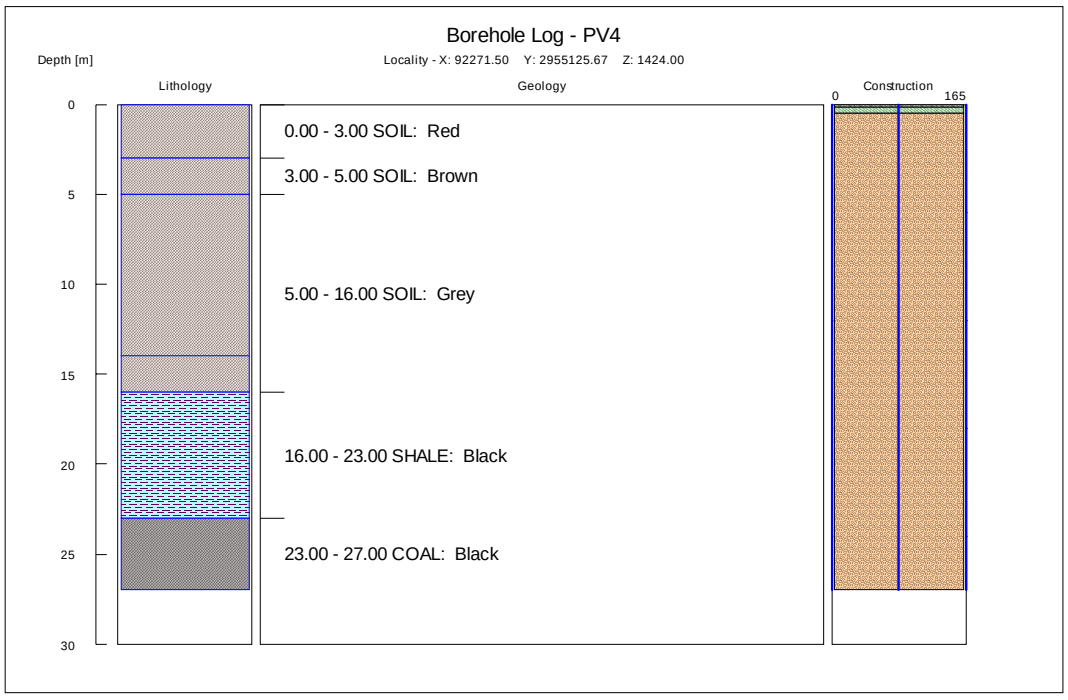

Figure I3. Borehole log illustrating geology and construction of PV4.

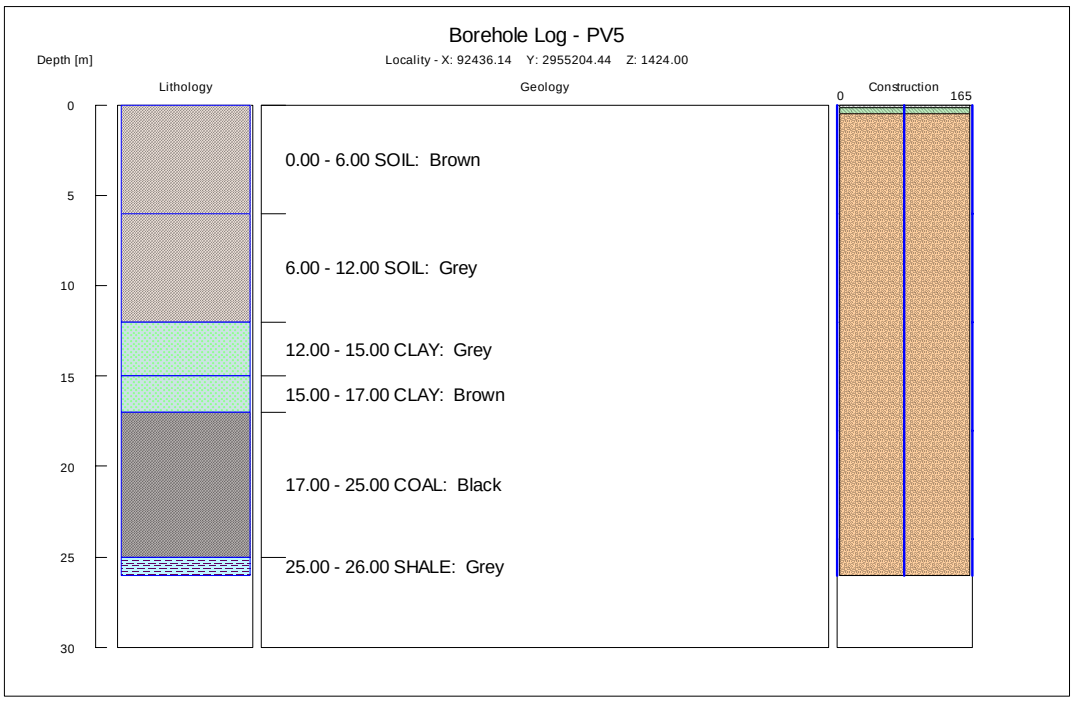

Figure I4. Borehole log illustrating geology and construction of PV5.

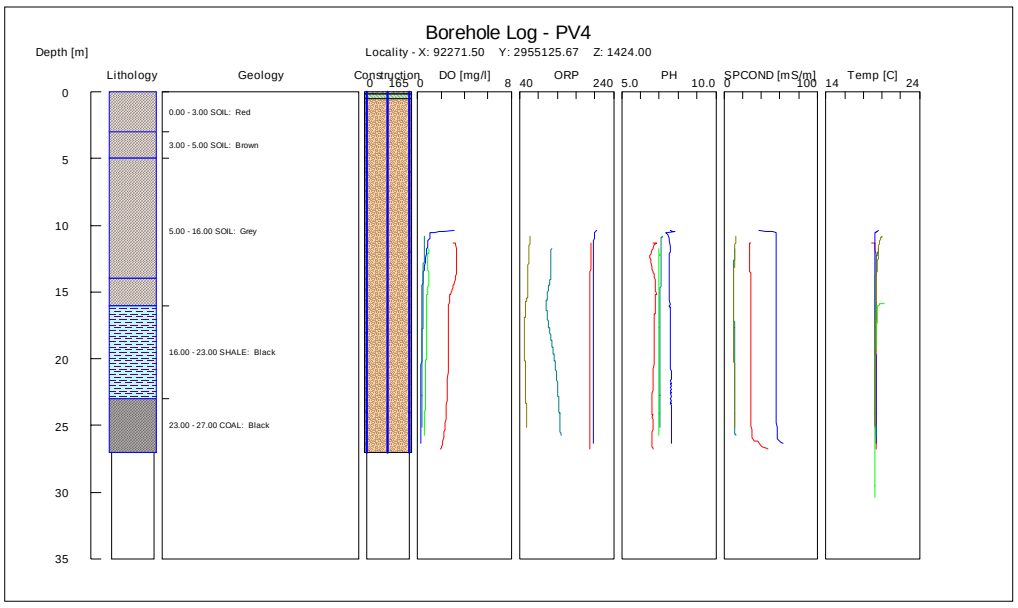

Figure I5. Multi-parameter profiling of PV4.

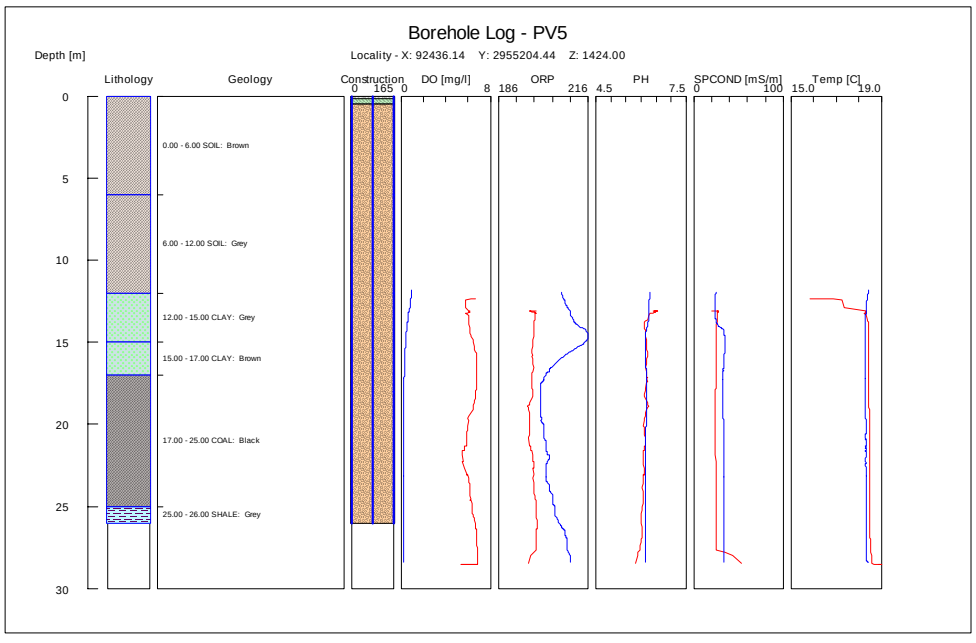

Figure I6. Multi-parameter profiling of PV5.

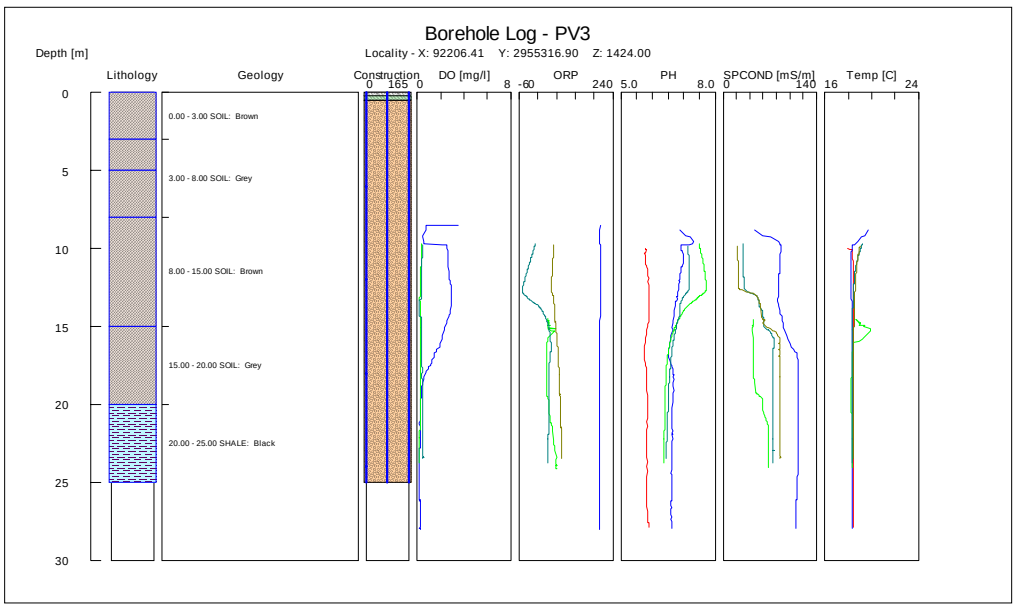

Figure I7. Multi-parameter profiling of PV3.

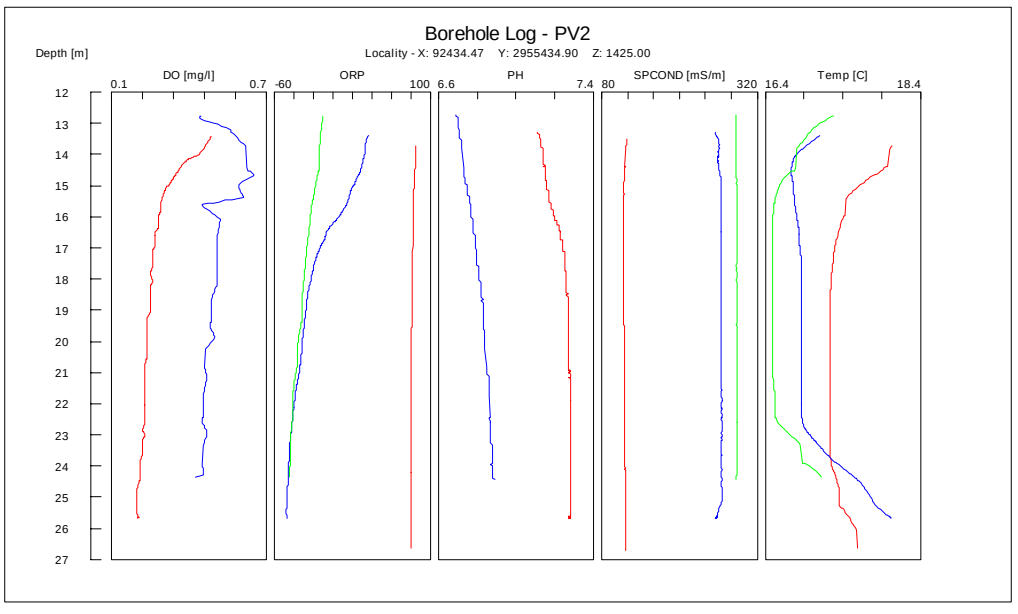

Figure I8. Multi-parameter profiling of PV2.

Borehole logs and Multi- parameter logs Syferfontein

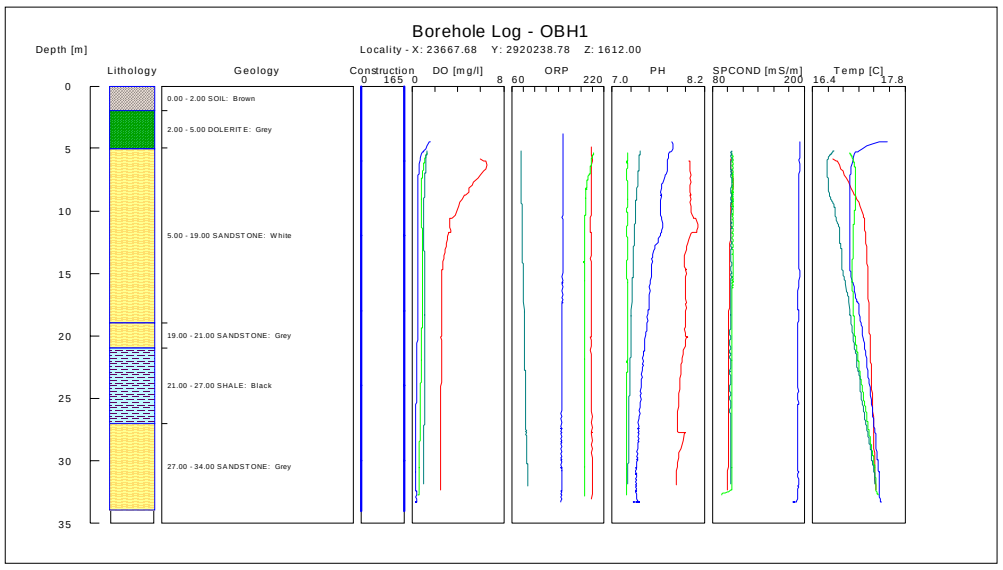

Figure I9. Borehole log illustrating geology, construction and profiling of different parameters at OBH1.

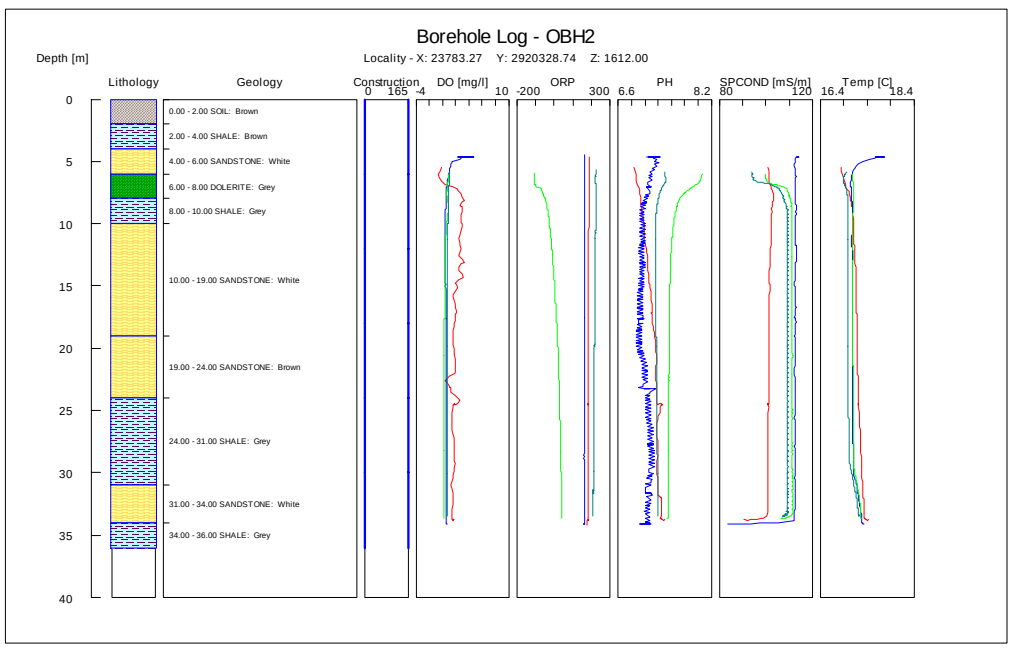

Figure I10. Borehole log illustrating geology, construction and profiling of different parameters at OBH2.

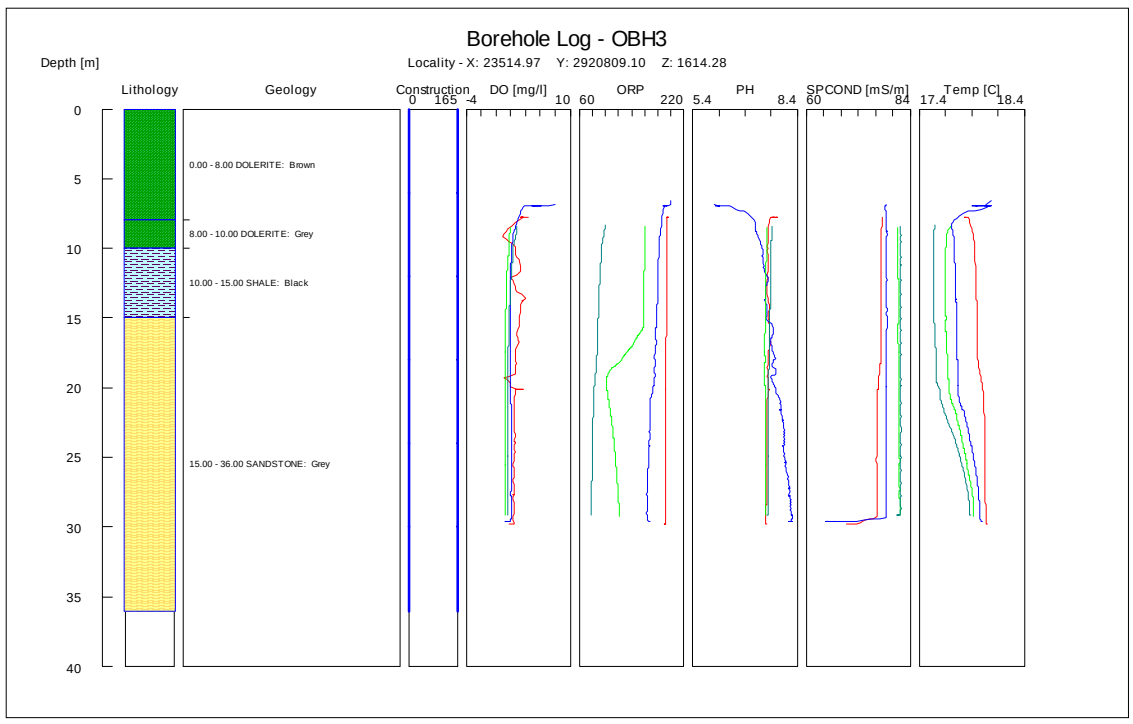

Figure I11. Borehole log illustrating geology, construction and profiling of different parameters at OBH3.

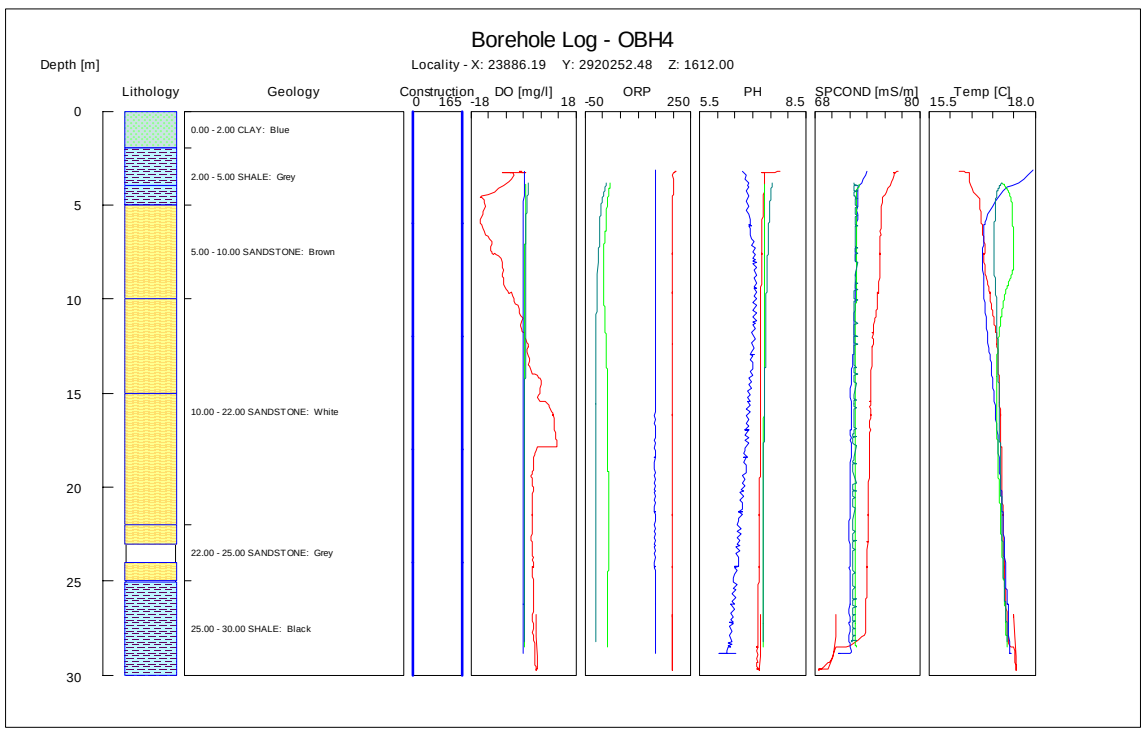

Figure I12. Borehole log illustrating geology, construction and profiling of different parameters at OBH4.

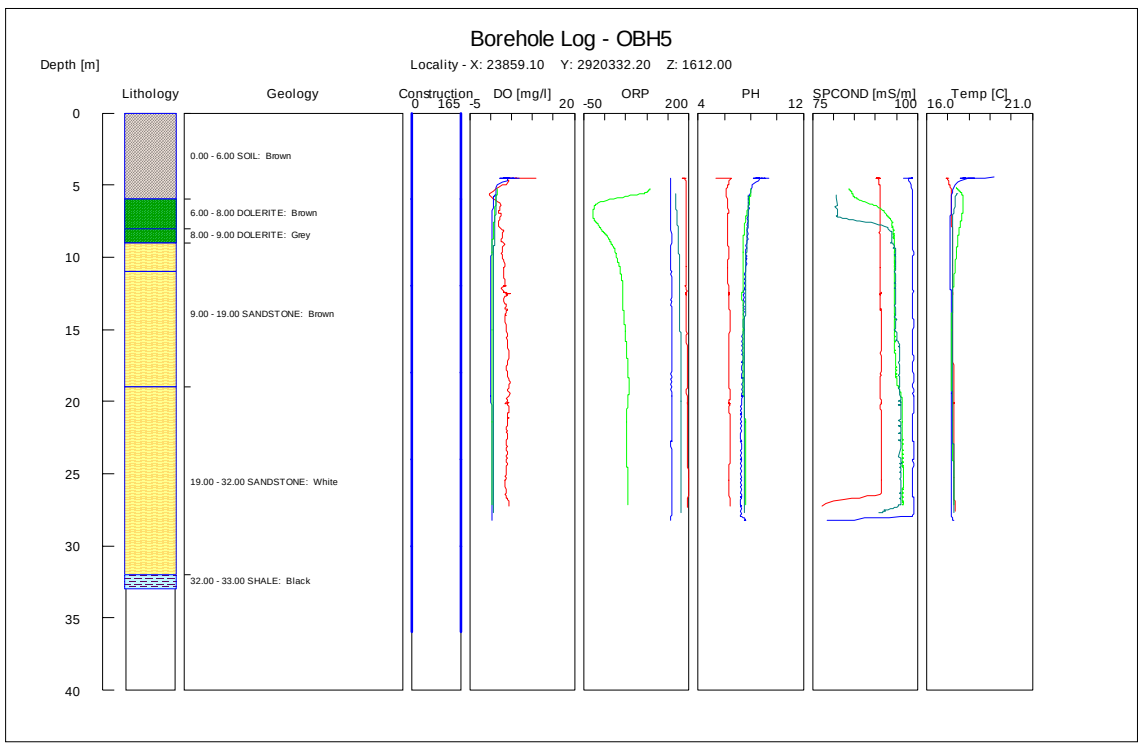

Figure I13. Borehole log illustrating geology, construction and profiling of different parameters at OB51.

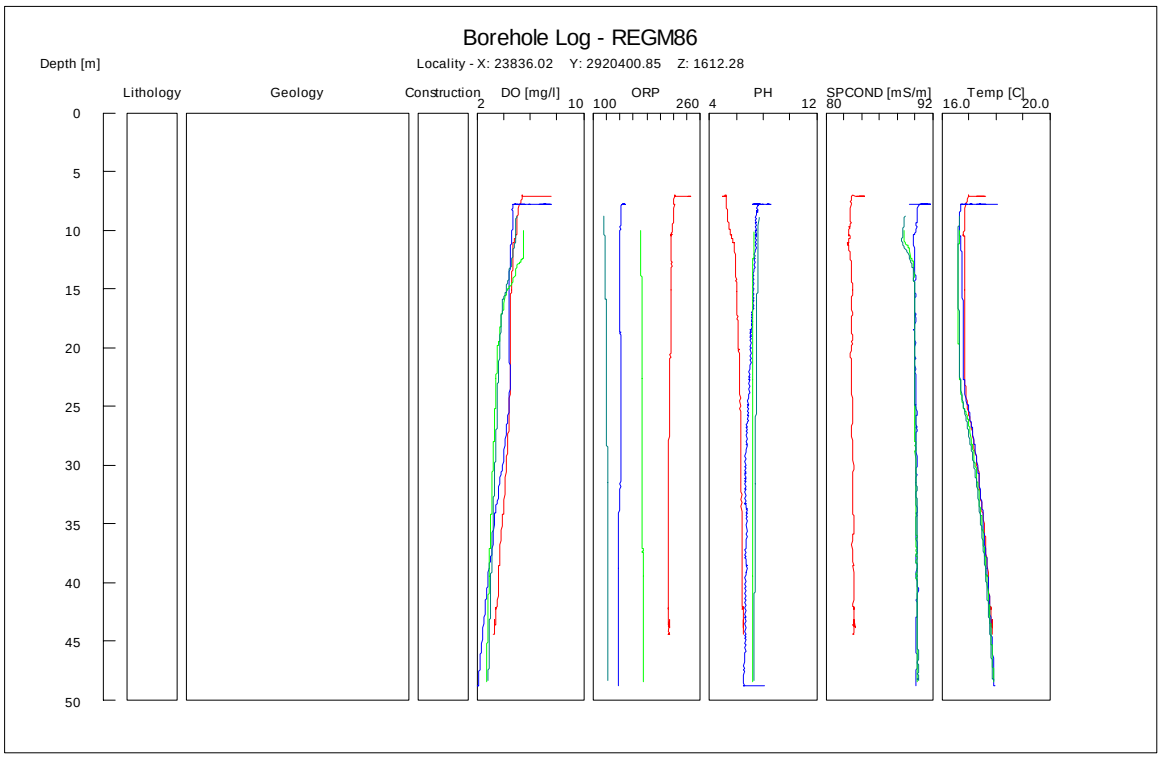

Figure I14. Borehole profiling of different parameters at REGM-86.

Borehole logs and Multi- parameter logs Kleinkopjé

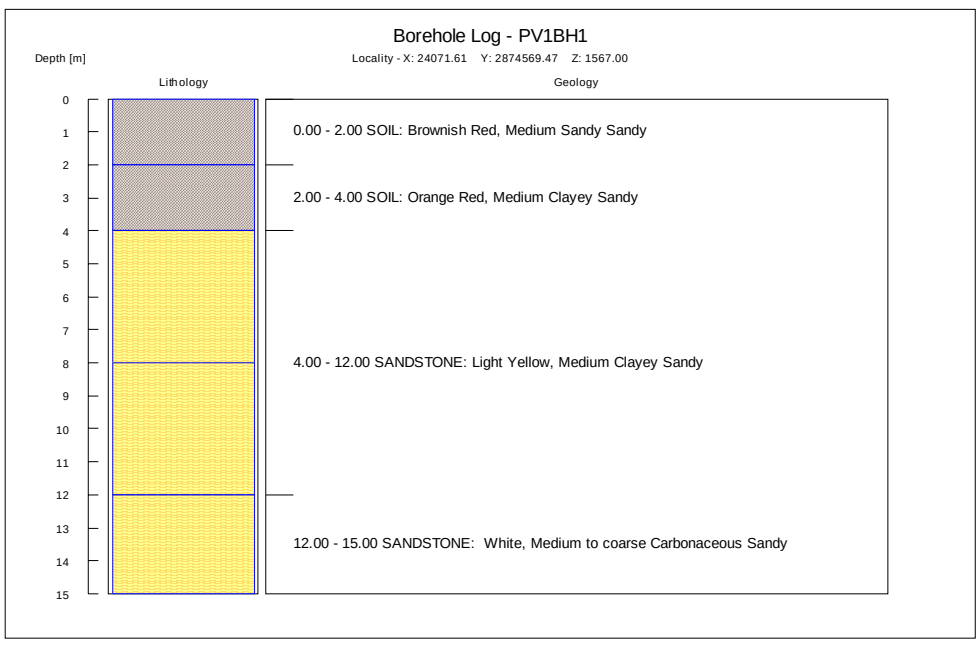

Figure I15. Geological log for PV1BH1.

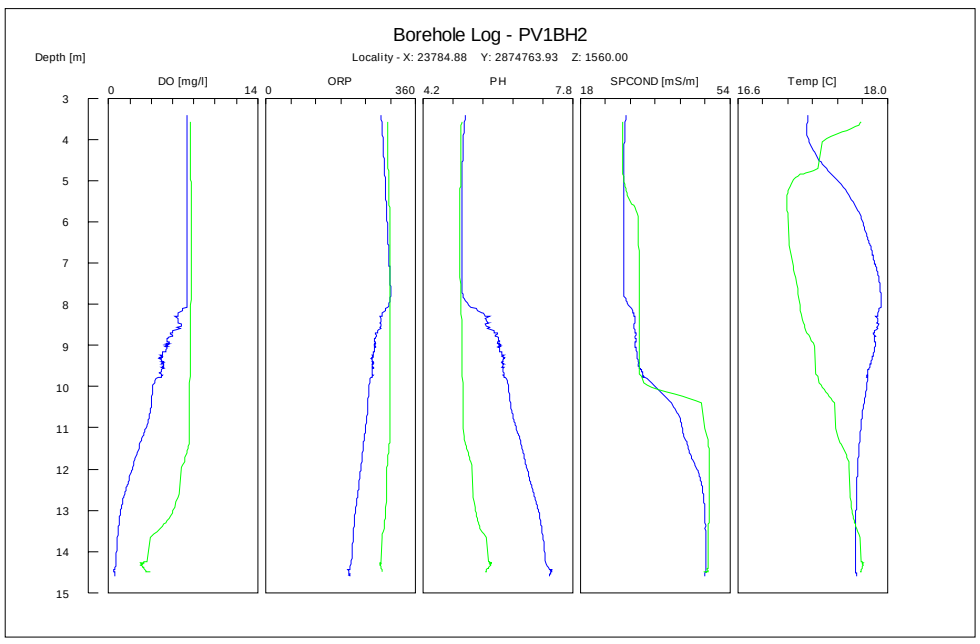

Figure I16. Multi-parameter profiling for PV1BH2.

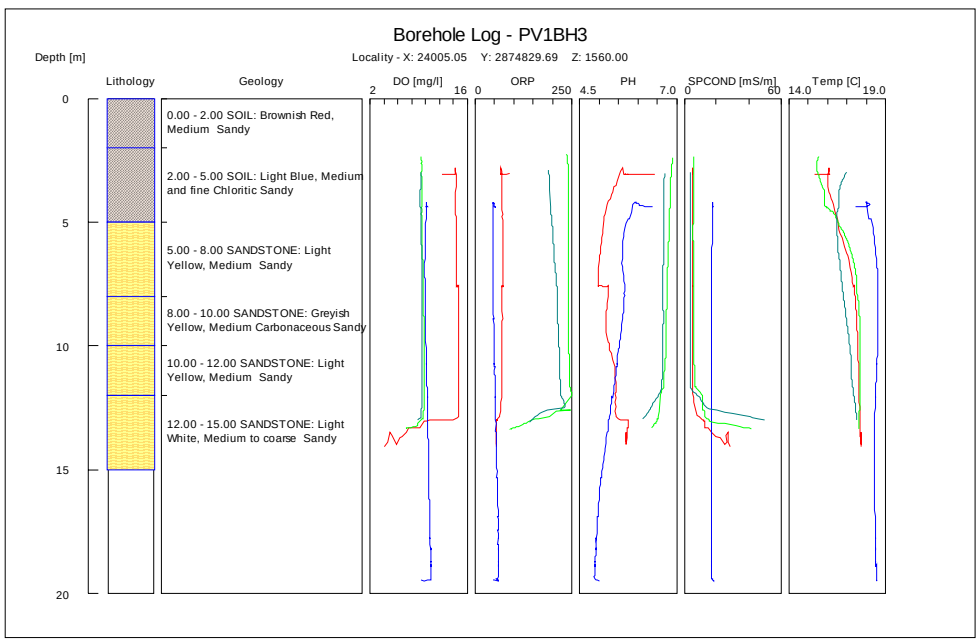

Figure I17. Geological log and multi-parameter profiling for PV1BH3.

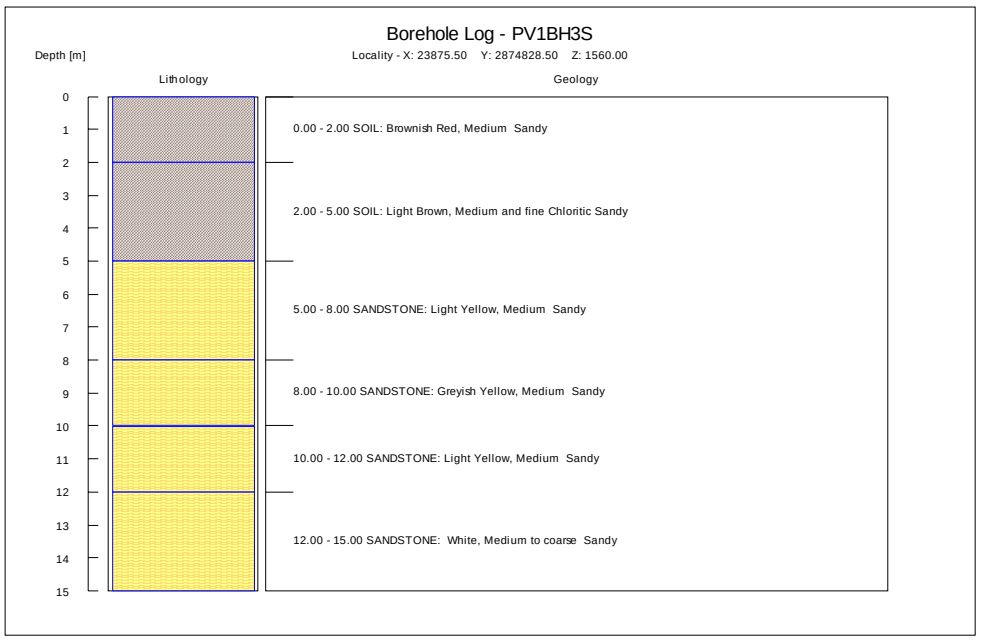

Figure I18. Geological log for PV1BH3S.

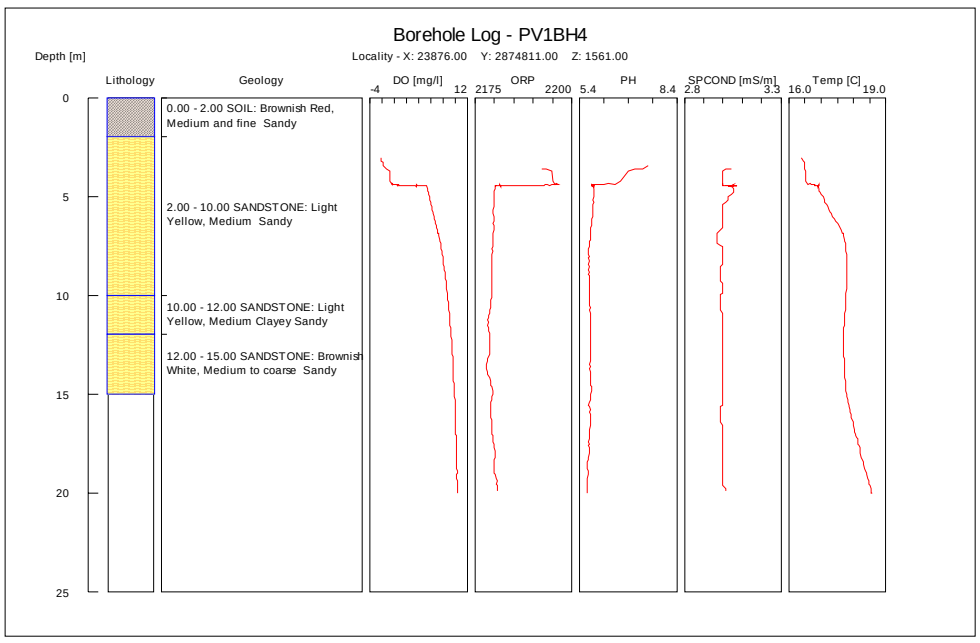

Figure I19. Geological log and multi-parameter profiling for PV1BH4.

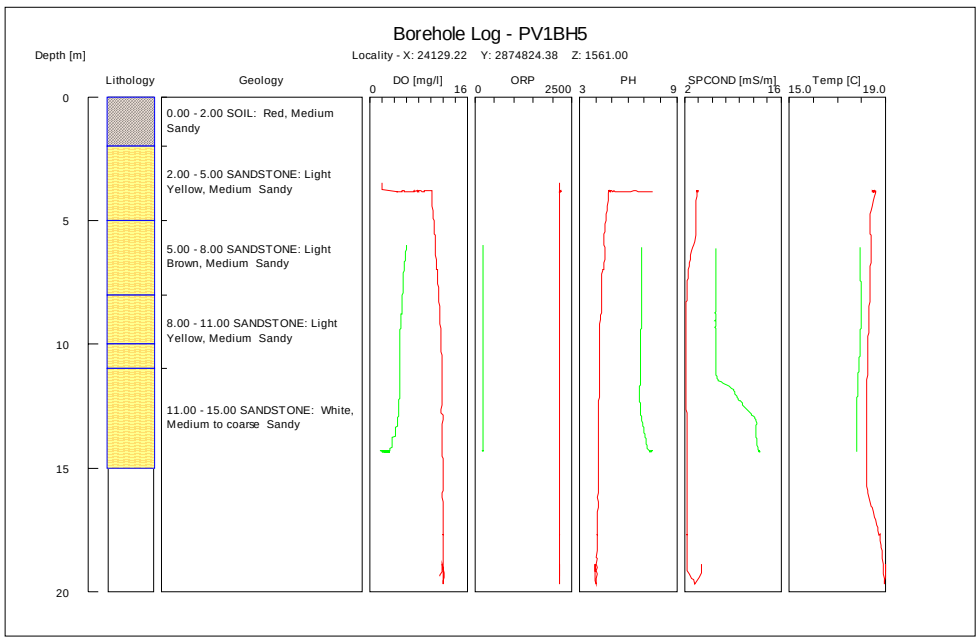

Figure I20. Geological log and multi-parameter profiling for PV1BH5.

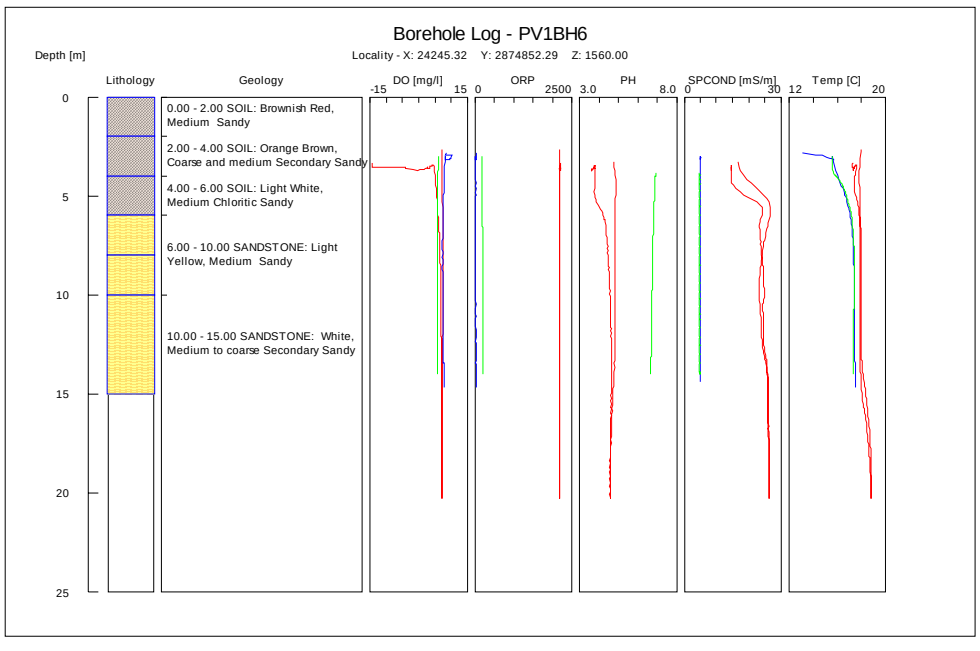

Figure I21. Geological log and multi-parameter profiling for PV1BH6.

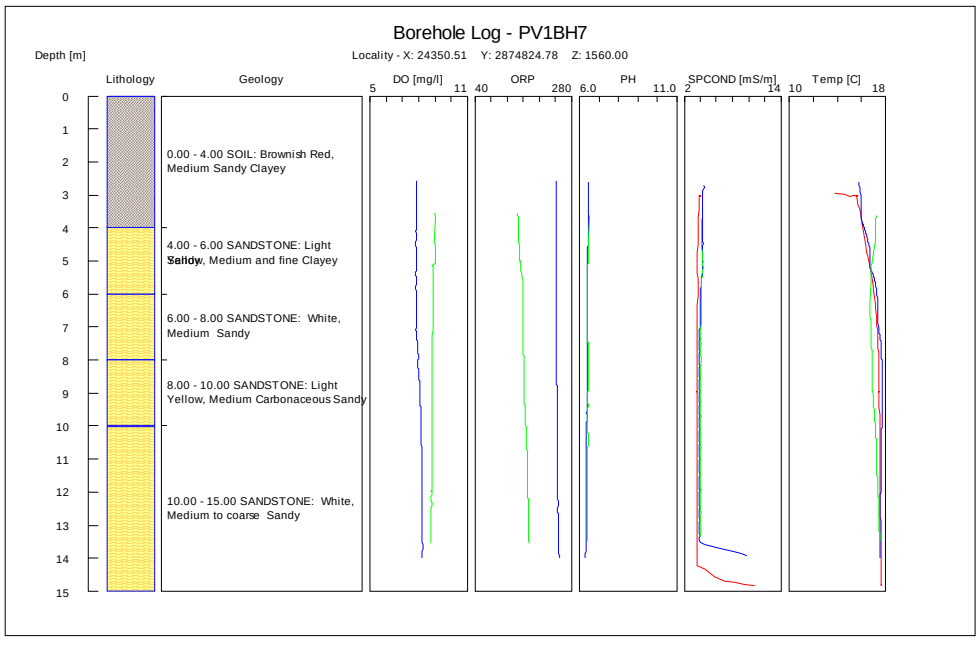

Figure I22. Geological log and multi-parameter profiling for PV1BH7.

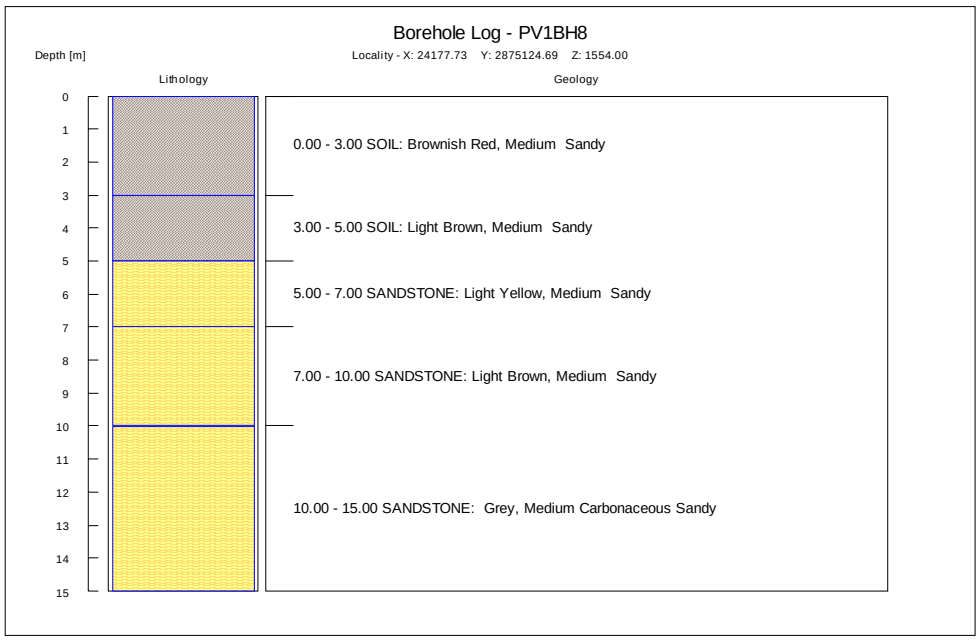

Figure I23. Geological log for PV1BH8.

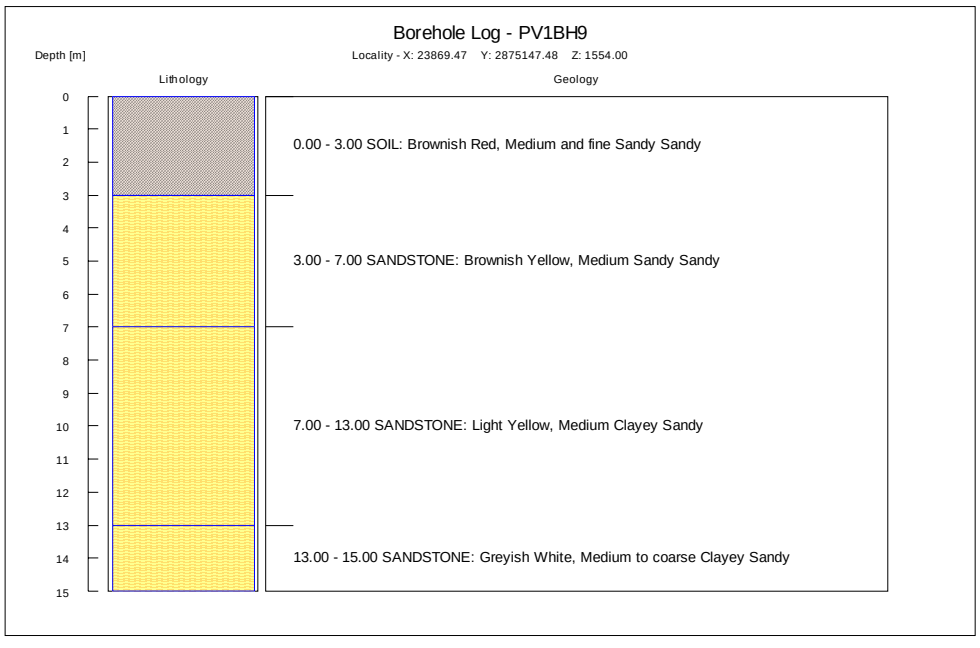

Figure I24. Geological log for PV1BH9.

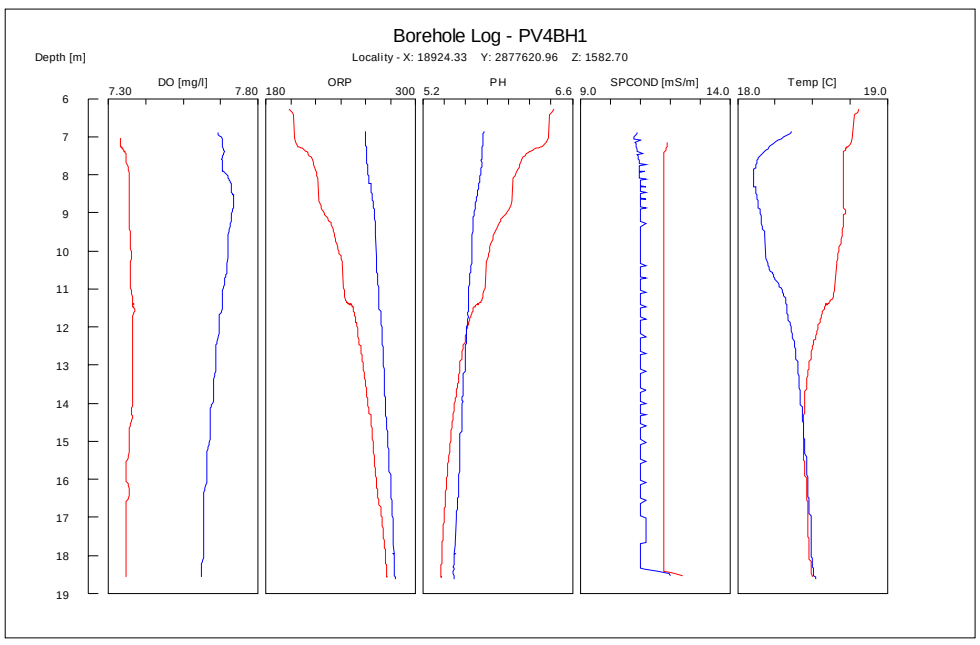

Figure I25. Multi-parameter profiling for PV4BH1.

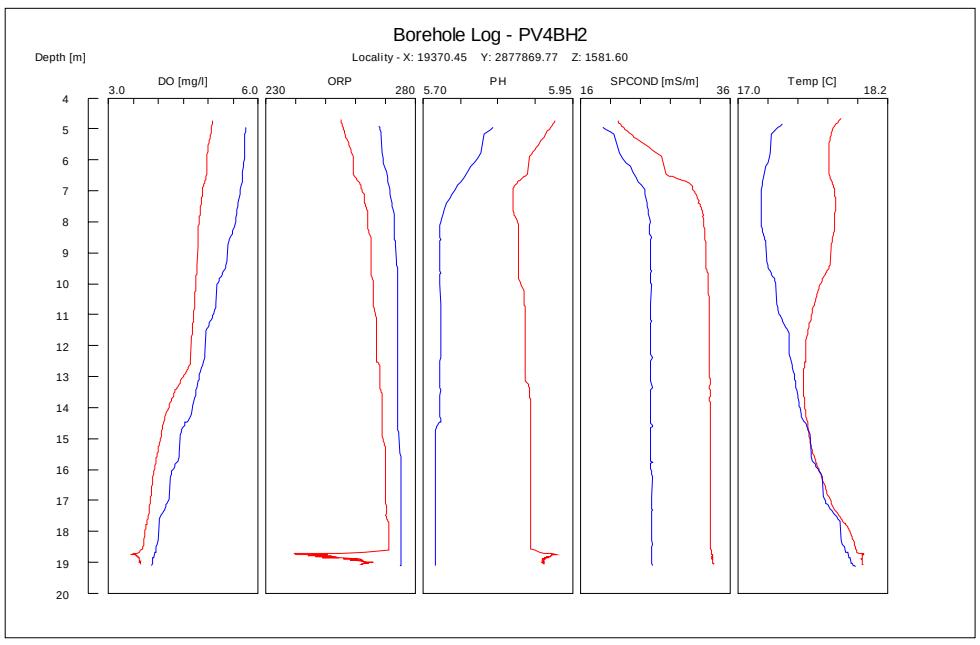

Figure I26. Multi-parameter profiling for PV4BH2.

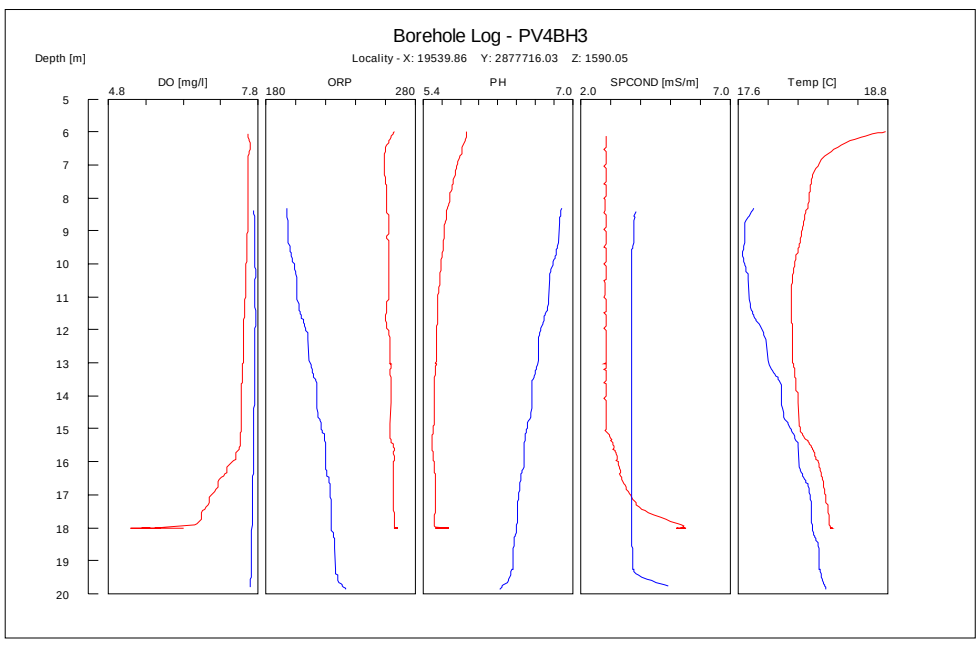

Figure I27. Multi-parameter profiling for PV4BH3.

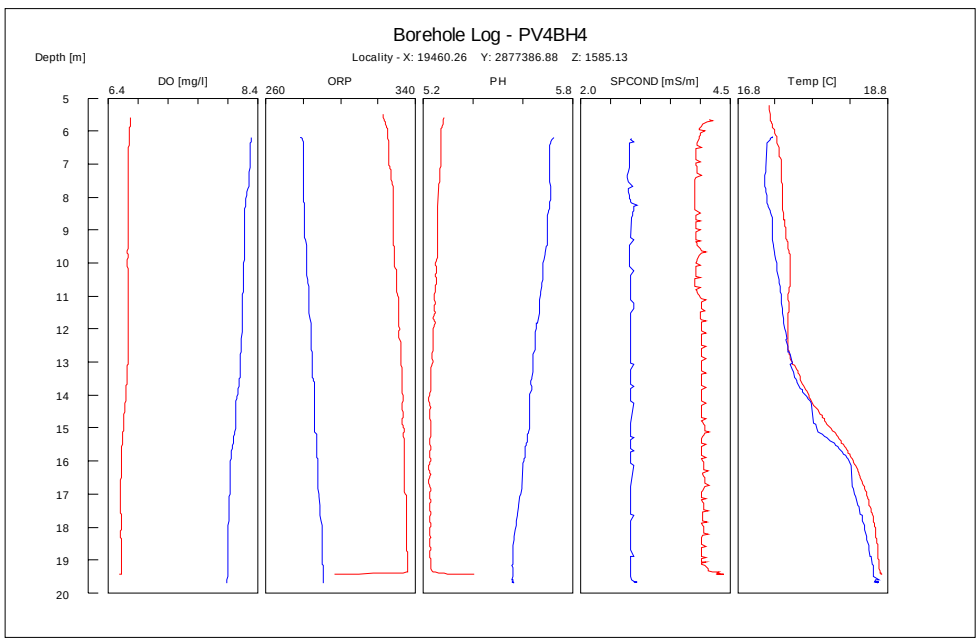

Figure I28. Multi-parameter profiling for PV4BH4.

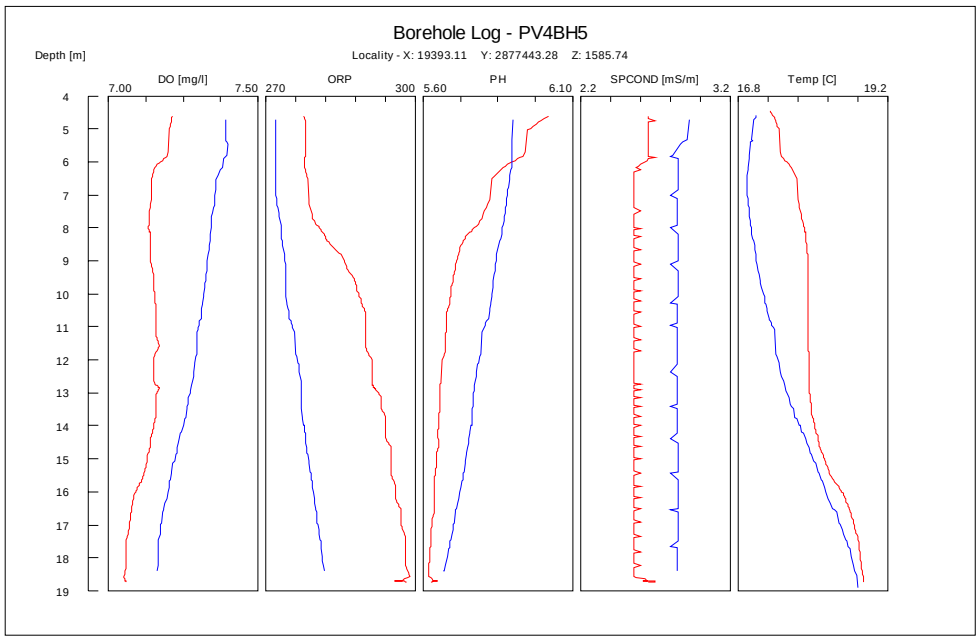

Figure I29. Multi-parameter profiling for PV4BH5.

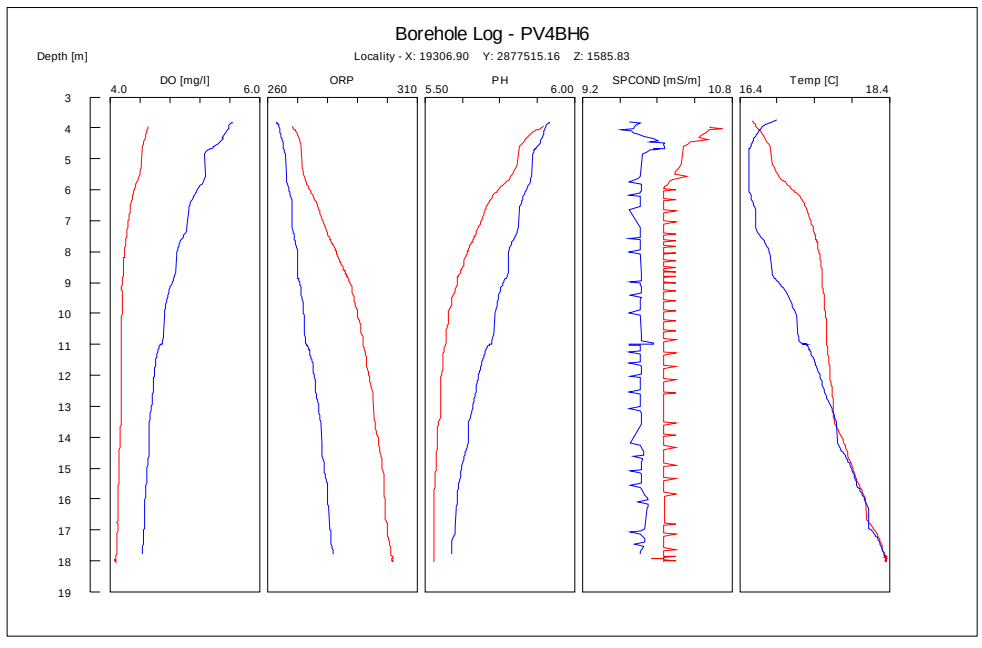

Figure I30. Multi-parameter profiling for PV4BH6.

Appendix J

New Vaal waterlogging

NEW VAAL COLLIERY

Coaltech Irrigation Project

Waterlogging at Pivot Site

Executive summary

On 19 April 2004, Mr. A. Johnson (General Manager, New Vaal Colliery) asked M. Aken (ACES) to arrange a meeting between Taaibos Landgoed (farmers managing the irrigation pivot), the Coaltech research team and other specialists to discuss the problem of waterlogging and poor crop production on the Coaltech Irrigation Project pivot site. At the meeting it was agreed to drill a number of auger holes in and around the pivot site to determine the water levels and the direction of groundwater flow. From the results of the drilling program it was clear that the holding dam was leaking water into the surrounding soil profile and causing the severe waterlogging at the pivot site. Several options are recommended to alleviate the waterlogging problem. In the short term a shallow interception gallery should be excavated between the holding dam and pivot site to drain water away from the area. Longer-term solutions would be to construct a new holding dam or to refurbish (line) the existing holding dam to stop the leaking. Cost and the expected life of the Coaltech project will dictate the most appropriate way forward.

Introduction

ACES were requested by Mr. A Johnson, New Vaal Colliery General Manager to assess the problem of waterlogging and poor crop production on the Coaltech Irrigation Project pivot site. The waterlogged situation became a problem in the 2003/4 planting season and caused the complete saturation of the site and prevented the farmer from harvesting his crop. This note describes the current situation and gives possible solutions to the problem.

Observations

A field visit with the farmers managing the New Vaal pivot (Taaibos Landgoed), the Coaltech research team (University of Pretoria) and other drainage/soils experts was arranged for 23 April 2004 to discuss the waterlogging problem and possible solutions. During the meeting it was noted that the land was totally water logged and that crop cover (pumpkins) was poor. It was stated at the meeting that the irrigation pivot had been sited before a soil survey had been completed, and as a result the pivot was not positioned on the best soils available in the area (in fact the pivot had been sited in part over an old sand borrow pit). The Coaltech research team had anticipated that the site may have a waterlogging problem early in the life of the project and consulted with a drainage expert who designed a subsurface drainage system that could be installed at an additional R120 000. Because of the cost, this was not considered to be a feasible option at the inception of the project.

Mine management requested that the cause for the waterlogging be found as soon as possible in order to find an appropriate solution to the problem. It was suggested that auger holes be drilled in and around the pivot site and the water levels determined. This would allow one to determine the direction of ground

water flow and the source of the water. The positions of the auger holes in relation to the pivot and Dam 595 (the holding dam) are shown in Figure 1.

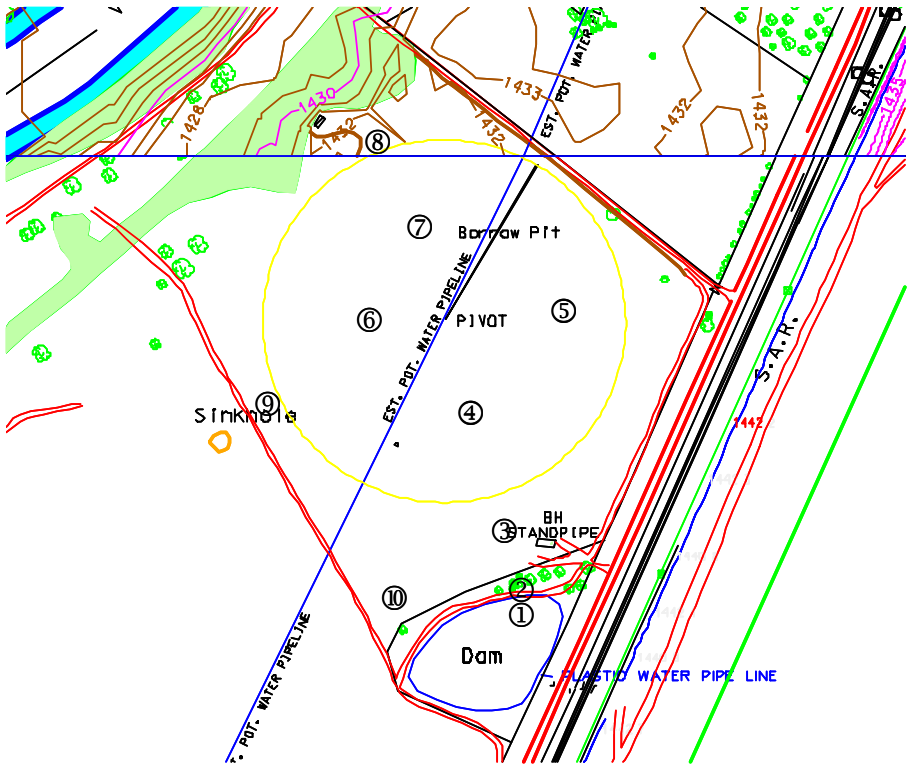

Figure J1. Position of auger holes in relation to the pivot.

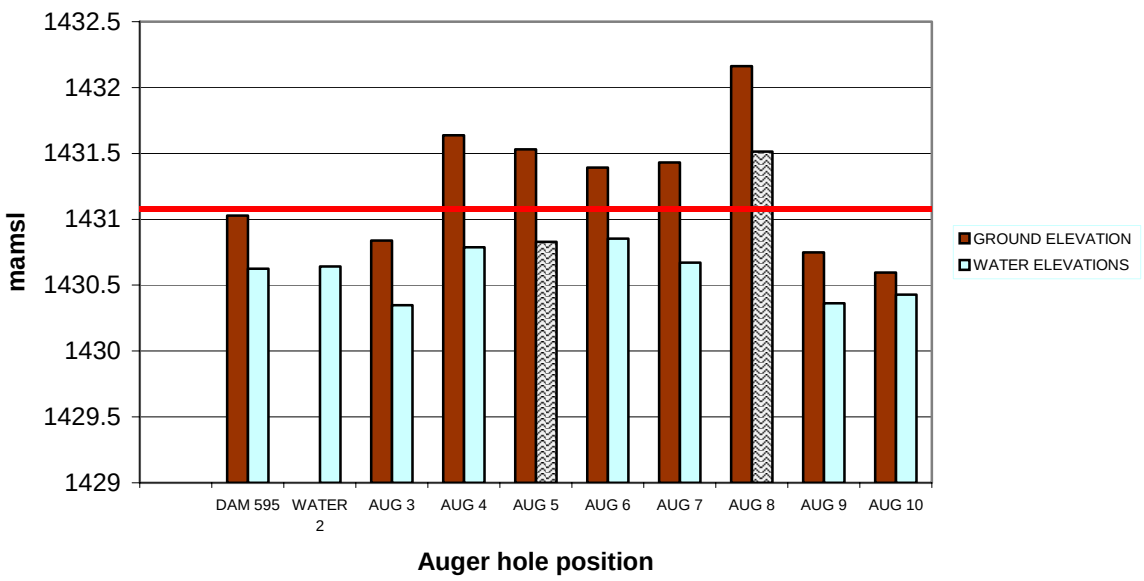

Figure J2. Water table elevations at New Vaal Pivot Site.

Ms Johanna Botha (Environmental Co-ordinator) and survey staff from the New Vaal Survey Department performed the water level survey.

The water levels measured during the drilling exercise are shown in Figure 2. It is clear that where water was encountered, the water table is very shallow. This illustrates the shallow nature of the soil profile as this site has previously been used for sand winning purposes.

Prior to obtaining water table results the following were considered probable causes for the waterlogging:

* Over-irrigation
* Heavy rainfall
* Leaking holding dam
* Combination of the above.

Figure 3 shows that significant volumes of pit water were pumped to the holding dams during the period January to April 2004. The Figure also shows the volume of water irrigated, and the rainfall that fell during this period. The possibility of over-irrigation can be ruled out as very little irrigation took place in the reporting period. Rainfall for the mentioned period was exceptionally high (402 mm)

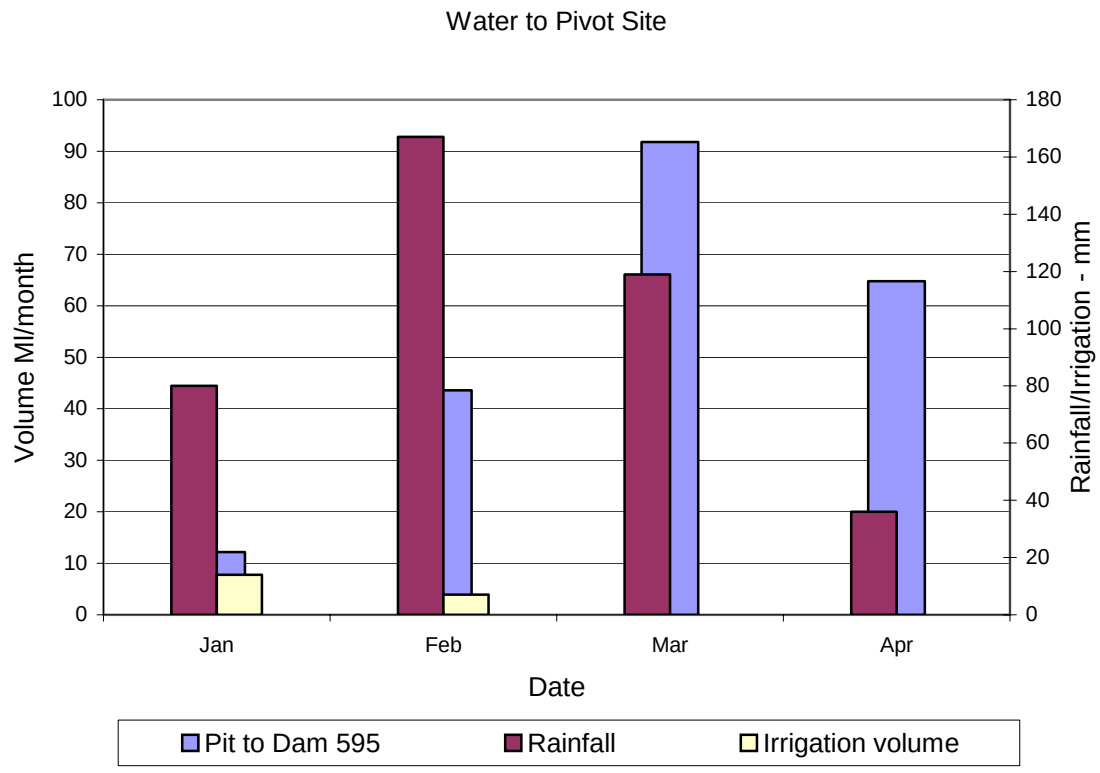

Figure J3. Water to the Pivot site.

Although the dam water level (Figure 2) was below the water table at the pivot site on the day the measurements were made, this is misleading, as the water level in the dam drops quickly after pumping stops (It was noted how much the water level in the dam was below the spillway despite recent volumes pumped to the dam and no water used for irrigation.)

There is no doubt that with the high volumes pumped during January to April (212.4 Ml) that the dam was at overflow point for most of this period. This resulted in a higher head of water driving seepage to the pivot site.

Conclusions

The following conclusions can be made from the above evidence:

- Very little irrigation took place during January to April due to good rainfall
- Dam 595 is very “leaky” and was likely to be the major contributor to waterlogging at the pivot site.

If Dam 595 continues to be used as a holding dam for the irrigation site, certain interventions are needed because of the waterlogging problem; an alternative needs to be found.

Recommendations

The following recommendations are made:

- For a short-term solution an interception trench can be dug between the Holding Dam and pivot site. The trench should be constructed to drain the intercepted water downstream of Dam 595 (the trench will require regular maintenance)
- If the interception trench does not work (and if the Coaltech project life is extended), mine water for the irrigation pivot will need to be supplied differently to the current practice. The following options may be considered:
    - Drain Dam 595 and line it with an impermeable lining – then reinstate the dam as an irrigation buffer dam
    - Breach Dam 595 so water can run freely in this drainage line - this will reduce the water head in the dam that is driving water toward the pivot area. If this is done then the following options remain to supply the pivot with water:
        - Build a watertight buffer dam to supply the pivot with water (e.g. an Erichson dam). The dam will have to be sized in accordance with the maximum volume of water needed by the pivot at any given time (probably 500 m3).
        - Install a submersible pump and draw water directly from underground through the borehole next to the pivot.

The interception trench should be constructed immediately to determine if this intervention solves the problem. It is likely to be the most cost effective solution if it works.

If the interception trench is not successful then the other options will need to be costed and evaluated in the light of the expected life of the Coaltech Irrigation Project (currently running to end 2005, but additional funding may be received to extend the life beyond this date).