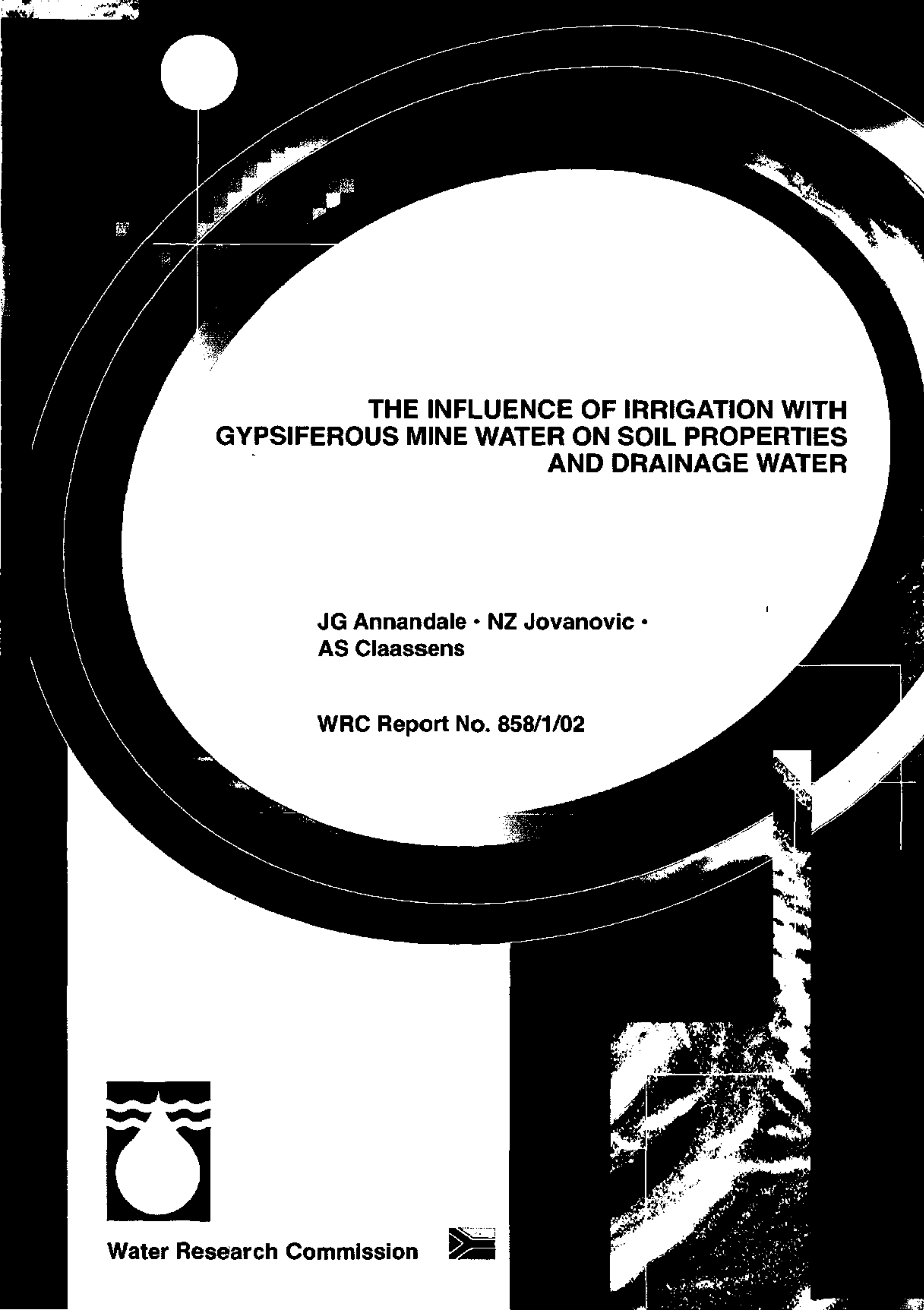

THE INFLUENCE OF IRRIGATION WITH GYPSIFEROUS MINE WATER ON SOIL PROPERTIES AND DRAINAGE WATER

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WRC Report No. 858/1/02

Water Research Commission

Printed by Silowa Printers

EXECUTIVE SUMMARY

Introduction

The mining industry is one of the most important in South Africa, both from the point of view of gross national product and job creation. In the mining of mineral resources, pollution problems are created with adverse effects on the already scarce water resources. The type of waste water emanating from mines depends largely on the geological properties of the coal, gold ore and other geological material with which waters come into contact. The concentrations of salts and other constituents frequently render this water unsuitable for direct discharge to the river systems except in periods of high rainfall when an adequate dilution capacity is present and controlled release is allowed. Gypsiferous mine water can either be regarded as one of mining's greatest problems, or as a potential asset. Large amounts of waste water could possibly be made available to the farming community and utilized for irrigation of high-potential soils in the coalfields of Mpumalanga Province, where water resources for irrigation are already under pressure. Concentrating the gypsiferous soil solution through evapotranspiration, thereby precipitating gypsum in the profile and removing this salt from the water system, could also limit environmental pollution. Therefore, the use of gypsiferous mine water for the irrigation of agricultural crops is a promising technology that could add value through agriculture production and utilize effluent mine drainage.

Objectives of the project

In this project, the general objective was to ascertain whether gypsiferous mine water can be used on a sustainable basis for irrigation of crops and/or amelioration of acidic soils. This was achieved by addressing the following secondary aims:

1) Assess the feasibility of managing irrigation with gypsiferous mine water at semi-operational scale in such a way that surface and groundwater contamination is reduced, while soil suitability and crop production are maintained.

2) Evaluate the effect of irrigation with gypsiferous water on the following:

    2.1) Yield and plant nutritional effects on a selection of agronomic crops that can be grown in the area.
    2.2) Gypsum precipitation and immobilization of other chemical constituents in the soil.
    2.3) Effects of gypsum precipitation and salt accumulation on soil characteristics.
    2.4) Depth of salinization of soil over time.
    2.5) Quality and quantity of drainage water.
    2.6) Impact of seasonal and annual rainfall on soil and drainage water characteristics.
    2.7) The ameliorating effect of gypsiferous water on acidic soils.

3) Develop predictive models for salt and water budgets for soil under irrigation with gypsum rich mine water.

4) Evaluate and refine these models practically over a (three year) period with summer and winter crops.

5) Model long-term salt and water budgets for different scenarios.

6) Provide inputs to any associated groundwater studies.

Following the acceptance of the project proposal, it was realized that investigations into the impact of irrigation on the groundwater regime were also necessary. The following objective was therefore added:

7) Investigate the extent of groundwater contamination through:

    7.1) A complete description of the groundwater regimes in areas to be irrigated, detailing the geohydrology as well as groundwater quality before, during and after irrigation.
    7.2) Interpretation of data through the establishment of an expert system and geohydrological modelling to facilitate the prediction of the medium- and long-term impacts on both local and regional scales.

Materials and methods

The objectives have been tackled using a multi-disciplinary approach, where various aspects of the impact of irrigation with gypsiferous mine water were investigated.

A field trial was set up at Kleinkopje Colliery from the summer season of 1997 until and including the winter of 2000, where several crops were irrigated with centre pivots using two mine waters (Jacuzzi and Tweefontein). Jacuzzi water is pumped from underground into a holding dam, whilst Tweefontein Pan holds water pumped from the active opencast pit. Pivots Major and Fourth were set up on virgin (unmined) land, whilst pivots Tweefontein and Jacuzzi were set up on rehabilitated land. A summary of water sources and pivots is presented below.

Water source	From 1997 to 1999	From 1999 to 2000	Pivot No.	Land
Jacuzzi Dam	Major	Major	# 1	Virgin
	Jacuzzi		# 2	Rehabilitated
Tweefontein Pan	Tweefontein	Tweefontein	# 3	Rehabilitated
		Fourth	# 4	Virgin

Three different irrigation management practices were adopted for each pivot: irrigation with a leaching fraction, irrigation up to field capacity and deficit irrigation (room for rain). Two farming companies were involved in commercial crop production on the pivot sites, namely, Amfarms from 1997 to 1999, and Smith Bros. from 1999 to 2000.

The following measurements were made during the course of the field trial:

i) Growth and yield of sugarbeans, maize and wheat were monitored to determine whether these crops can be commercially produced under irrigation with mine water, as well as to provide data sets for validation of the crop growth subroutine of the SWB model. Several alternative cropping systems were also tested.
ii) Plant samples were collected at different growth stages for laboratory analysis to identify and correct possible plant nutrient deficiencies through fertilization. Nutrient deficiencies could occur due to excess gypsum and other salts in irrigation water.

iii) Atmospheric measurements were made using an automatic weather station to provide data sets for validation of the SWB model.

iv) Soil materials were described in terms of their physical properties by determining bulk density, water retention, hydraulic conductivity and the solute transport characteristics of dispersion, adsorption and rate dependant transfers. This was done to describe the general behaviour of the water and salt fluxes in the profiles, to determine initial inputs for the SWB model and to evaluate specific phenomena in the porous media, such as changes to pore structure due to gypsum precipitation.

v) Soil water and salt balance data were collected using intensive monitoring stations for each pivot and irrigation treatment, to determine crop water use and soil salinity, as well as to provide data sets for validation of the water and salt redistribution subroutines of the SWB model.

The equipment used to measure the soil water balance included:

- Tipping bucket rain gauges for measurement of irrigation water applied and rainfall.
- Tensiometers and heat dissipation sensors for measurement of soil matric potential at different depths in the soil profile.
- Neutron water meter, CS-615 soil water reflectometers and time domain reflectometry (TDR) for measurement of volumetric soil water content at different depths in the soil profile.

The equipment used to measure the salt balance included:

- Ceramic cup soil water samplers used to extract soil water for laboratory analysis from different depths in the soil profile.
- TDR for measurement of bulk soil electrical conductivity.
- Electromagnetic induction was used to determine soil salinity over the entire field on a grid basis. This was done to get an idea of spatial variability of soil salinity.
- Laboratory analyses of irrigation water were also carried out to determine its quality. Irrigation water samples were collected with plastic bottles at the water source and from pivot nozzles.

vi) Soil chemical analyses were carried out at regular intervals (every season) to determine possible changes in soil chemical properties due to irrigation with mine water, as well as the amount of gypsum precipitated in the soil profile.

vii) Deep soil sampling was carried out in June 2000 for chemical analyses in the laboratory, in order to explore whether any salt breakthrough originating from irrigation could be identified deeper in the soil profile.

viii) Runoff volumes and quality were measured at crump weirs built at the lowest points below pivots Major and Tweefontein.

ix) Groundwater quality was monitored to determine possible breakthrough of salts originating from irrigation at pivot Major. For this purpose, nine boreholes were installed at specific localities where they were most likely to intersect polluted groundwater. Water quality and water levels were the key parameters measured. During the installation of the boreholes, the following additional features were also noted and measured: geology; water strikes and yields; the hydraulic conductivity of the strata through packer and/or pumping tests; the installation of piezometer tubes to exclude cross contamination from surface water to the groundwater.

Plant nutritional aspects were investigated in a glasshouse pot trial. The aims were to determine whether plants can grow and produce acceptable yields under irrigation with gypsiferous mine water, and to recommend optimal nutrient management. This work was done because nutritional problems could materialize under irrigation with water rich in Ca, Mg and SO_4 due to competition for nutrient uptake. Nutritional imbalances could cause both reduced economic return from crop production and reduced mine water consumption through crop transpiration.

A decision was taken to investigate the possible adverse effects of mine water on herbicide activity after maize crops were damaged on all three pivots in the beginning of the 1999/00 season, through the inadvertent application of excess herbicide. This resulted in significant yield losses. The objectives of this preliminary investigation were to determine the influence of mine water on the three important performance criteria for herbicides: weed control efficacy, herbicide selectivity, as well as herbicide persistence and mobility in soil (incorporating risks of environmental pollution). For this purpose, chemical analyses of selected herbicides in a gypsiferous tank mixture were done by gas chromatography analysis. In a parallel investigation, bioassays were conducted in a greenhouse in order to assess whether the biological activity of the selected herbicides is affected by the presence of gypsum in soil.

The purpose of the Kleinkopje field trial was to investigate commercial feasibility of crop production and environmental impact under irrigation with mine water in the short term (three years). However, the problem of saline water management also has long-term implications. Long-term changes in soil chemical and physical properties can be measured, but the execution of long-term experiments monitoring slow environmental processes can be prohibitively expensive and it is not always possible to wait for the outcome of such experiments. For this reason, it was necessary to adapt the SWB model for long-term (50 years) predictions of soil water and salt balance under irrigation with mine water. In order to be confident of the long-term predictions of SWB, the model had to be refined and validated using atmospheric, soil and crop data collected in the field trial.

It was not possible to investigate all cropping systems and management options that could be suitable for the utilization of gypsiferous mine water at the Kleinkopje irrigation sites. A scenario study was therefore carried out using the SWB model in order to recommend other suitable cropping systems and agricultural management practices for the area in the vicinity of Kleinkopje Colliery. A simple economic analysis was also required in order to recommend the most profitable and environmentally sustainable cropping and irrigation water management system.

In order to investigate the extent of groundwater contamination in the long term, SWB output was used by a finite element groundwater model. The purpose was to predict the groundwater flow and potential pollution migration for a case study at pivot Major.

General findings

In the field trial at Kleinkopje Colliery, crop yields were generally high and the farming companies were keen to participate in the project. The study has shown that crops can be successfully grown under irrigation with gypsiferous mine water on a commercial basis.

Yield losses were experienced on two pivots on rehabilitated land (Jacuzzi and Tweefontein) due to waterlogging during the summer seasons, even after levelling work had been carried out and waterways constructed. This was probably due to subsurface drainage from higher areas and accumulation of water in lower areas through lateral movement of water above the spoil layer.

No symptoms of foliar injury due to sprinkler irrigation with gypsiferous water were noted for any of the crops. Visual observation and laboratory analyses of plant samples indicated that no specific symptoms of nutrient deficiency or toxicity occurred due to excess gypsum in irrigation water.

Soil chemical analyses were carried out during the field trial to determine general trends in soil chemical properties. Soil pH(H_2O) generally showed a slight increasing tendency at all pivots over the study period. Soil salinity generally showed a tendency to increase over time, but fluctuated depending on seasonal rainfall as well as the irrigation and rainfall events prior to soil sampling.

The results of the spatial variability study indicated that there is a tendency for salinity levels to be higher in the central region of each pivot. This is believed to be due to the larger quantities of saline irrigation water applied in these zones during the course of the experiment. Major pivot showed an accumulation of salts in the lower south-eastern region, in clayey soils in the drainage line. This appears to reflect the direction of water movement down the slope, and the impedance to water and salt movement in the heavy soils.

Deep soil samples were collected in June 2000 for laboratory analyses. It was observed that at pivot Major and Tweefontein, most soluble salts were confined to the upper 1 m, probably due to the presence of a plinthic and spoil layer respectively, which were limiting free drainage. At pivot Fourth, in the absence of a layer preventing deep percolation, there was a more uniform distribution of salts in the soil profile, with a slight peak between 1.5 and 2 m down in the profile indicating leaching of salts below the root-zone, even though this field had not been irrigated for as long as pivot Major. An attempt to measure gypsum precipitated in the soil profile was also made on deep soil samples. It was, however, clear from the results obtained that a reliable method to measure gypsum precipitation still needs to be developed, as much higher values of measured precipitated gypsum were obtained than the amount of salts added through irrigation, based on measured irrigation water quality and amount.

Irrigation water quality analyses indicated that Jacuzzi and Tweefontein waters were similar. Seasonal fluctuations in irrigation water salinity can be expected depending on seasonal rainfall.

Runoff volumes and quality data collected at the weirs from November 1999 to April 2000, indicated that less than 2% of the salts added since the beginning of the trial were lost from the irrigated fields through runoff. More runoff was recorded at pivot Tweefontein compared to pivot Major, due to the restricted soil depth and steep slopes of the rehabilitated land. Due to impervious soil layers at pivots Major and Tweefontein, it is likely that runoff and salts in runoff could have mainly originated from lateral movement of soil water.

Salt migration through soil and aquifers is a slow process. After more than three years of irrigation, there was still no conclusive evidence that saline irrigation water had reached the aquifer below the irrigation site at pivot Major. This is in spite of the fact that groundwater levels are within 1 – 3 m from the surface. A slight rise in nitrate concentrations was observed at two boreholes. This was derived from fertilizer application. At five of the boreholes, a small increase in calcium, magnesium and sulphate levels was observed.

Data collected in the field trial were compared to model simulations in order to validate the SWB model. The model predicted crop growth, water and salt redistribution generally quite well. Field measurements and model predictions were used to compile soil water and salt balances for all seasons and treatments of the field trial. These accurate predictions of the water and salt balance with SWB in the short term gave confidence that the model can be applied for long-term predictions.

Fifty-year scenario simulations were then carried out with SWB. Multiple Criteria Decision-Making (MCDM) techniques were used to advise Kleinkopje Colliery's management on the best economically and environmentally sustainable cropping system for irrigation with gypsiferous mine water. From this scenario modelling study, it was clear that perennial pastures have the biggest year round green canopy, and will therefore use the most water and precipitate the most salts. They will also be the most profitable cropping systems, provided that the company managing the irrigation pivots is geared to animal production systems. These systems, however, tend to be more labour intensive and are therefore often not preferred. Cash crop systems lend themselves to mechanization and are therefore often preferred by bigger farming companies. Irrigation management practices also contributed to the sustainability of the system. Simulated yields were the highest for the leaching fraction strategy. However, with this strategy, more salts were leached (64% of the applied salts) compared to the "room for rain" strategy where only 53% of applied salts were leached.

The output of the SWB model was used as input into a groundwater model in order to predict the long-term effects of irrigation with gypsiferous mine water on groundwater for a case study at pivot Major. Irrigation treatments were simulated with SWB for the period of the field trial (from December 1997 to November 2000) followed by 50 years of scenario simulation. Two simulations were done with the groundwater model. The first simulation was that of potential pollution dispersion from the irrigation area. The second simulation included the "dirty" Jacuzzi water controlled release dam. The results of modelling potential pollution migration through the aquifer suggested migration to the South-West, eventually to emanate in the stream at a concentration of about 30% of that in the aquifer below the irrigated site. This drop in salt levels was ascribed to dilution by rainwater infiltration and the dispersive characteristics of the aquifer.

Technical findings

In the field trial, several crops were irrigated with gypsiferous mine water. Although comparable yield data for crops irrigated with good quality water are not available, the yield of sugar beans under irrigation with mine water on virgin soil (3.23 Mg ha^{-1}) was comparable to yields registered in the area, and definitely higher than under dry land conditions (1.12 Mg ha^{-1}). Yields of sugar beans on rehabilitated land (between 1.23 and 1.37 Mg ha^{-1}) were, however, low compared to virgin land, likely due to late planting dates, hail damage, soil compaction, low soil pH and nutritional deficiencies. Excellent yields of wheat (between 5.04 and 8.08 Mg ha^{-1}) were obtained on both virgin and rehabilitated land. The yield of the short-season cultivar of maize was also good on virgin land (7.83 Mg ha^{-1}, 1998/99 season). An excess of herbicide mistakenly applied to all three pivots by the farming company, caused severe reductions in maize yields in summer 1999/2000. In October 2000, a hailstorm completely wiped out the wheat crops at pivots Fourth and Tweefontein. The estimated loss in crop at pivot Major was 40%. The potential yield at all three pivots was 8 Mg ha^{-1}.

Soil chemical analyses indicated that the soil saturated electrical conductivity and concentrations of soluble Ca^{2+}, Mg^{2+} and SO_4^{2-} generally increased over time at all four pivot sites. This was due to the relatively high concentrations of these ions in irrigation water. The values of soluble K^+ did not show any particular trend and they were lower by one order of magnitude than the other cations, as the irrigation water had a low concentration of K^+. Exchangeable Ca^{2+} and Mg^{2+} increased with time, whilst K^+ decreased at all four pivot sites. This indicated that Ca^{2+} and, to a certain extent Mg^{2+}, replaced K^+ on the soil adsorptive complex. Very low values of exchangeable Na^+ were measured during the course of the trial.

The results of the analyses of soil water extracted with ceramic cup soil water samplers, indicated that soil salinity is a very dynamic variable as it depends on many factors, mainly rainfall, irrigation amounts and evapotranspiration. The data generally indicated higher soil salinity in the topsoil layers compared to deeper layers. This proves that salt, in particular gypsum, accumulated and precipitated where the rooting system is most dense.

Several methods to measure gypsum precipitated in the soil were considered. The Adapted Dilution Method was eventually selected and applied. It appeared, however, from the results obtained, that this methodology is not suitable, as much higher values of measured precipitated gypsum were obtained compared to the amount of salts added through irrigation.

Plant nutritional aspects were investigated in a glasshouse pot trial. Salinity decreased the biomass production of wheat, mainly due to interactions of Mg and Mn with the uptake of Fe and K. Decreases in yield were also associated with significant increases in plant concentrations of SO_4 and Mg. The application of NO_3, NH_4, and K at rates different from the level considered beneficial for non-saline conditions (salinized control) improved wheat growth under sulphate saline conditions. Differential application of P had no effect on the yield of wheat. The extraordinary effect of a high NH_4 supply under sulphate salinity can be ascribed to the antagonistic effect that NH_4 exerted on Mg and Mn concentrations in plants and/or to NH_4 being a supplementary N source when large SO_4 concentrations suppressed NO_3 uptake by wheat. In practice this could mean that the inclusion of NH_4 fertilizers in a NO_3:NH_4 ratio of 2:1 could be advantageous when irrigating crops with water containing high levels of Ca and Mg sulphate. Further experimentation is needed to verify these results in soils under field conditions.

The possible adverse effects of mine water on herbicide activity were also investigated in a laboratory trial. The results indicated that there is rapid transformation of the herbicides in the mine water, with atrazine having a higher inactivation rate compared to 2,4-D. This suggested that the electrolytes found in the mine water interact with herbicide molecules to rapidly transform them. This could mean that mine water may not be a suitable carrier for herbicide spraying. In the bioassays, however, it was found that the biological activity of atrazine was significantly increased in the presence of gypsum, whilst the activity of metolachlor was significantly reduced by the same treatment.

The SWB model was refined during the course of this project and the following improvements were included:

i) The finite-difference water balance subroutine based on Richards' equation was included in the SWB model.
ii) The salt redistribution in the finite-difference water balance model can be simulated using the convection/dispersion equation. The convection/dispersion equation is currently being debugged and it was not used in this report.
iii) The cation exchange subroutine was introduced in the model. This subroutine can be enabled or disabled in order to test the effect of adsorption on soil salinity and leaching.

iv) Change in input data structure to allow variable irrigation water quality during the simulation.
v) Change in input data structure to allow input of initial salt contents per soil layer.
vi) Calculation of non-instantaneous drainage in the cascading water redistribution model.
vii) Simulation of groundwater table formation in the cascading water redistribution model.
viii) Calculation and output of parameters of the statistical analysis of measured and simulated data. This allows quick, efficient and quantitative evaluation of the model.
ix) Graphical output of salt balance parameters.
x) *Conversion of the* CLIMGEN *weather data generator to a user-friendly,* Windows 95 format. The database of CLIMGEN can be used as weather database of SWB.
xi) Import of weather data from spreadsheet files into the SWB or CLIMGEN model.
xii) Calculation of the soil water deficit from neutron water meter readings and graphical output. This facilitates real-time irrigation scheduling by neutron water meter measurements.
xiii) Compilation of a comprehensive help file that enables a better technical and operational understanding by the users.
xiv) Improvements in user-friendliness.

The finite-difference water movement and the subroutine for convection/dispersion of salts should enable a more accurate description of the dynamics of water and salt movement in the soil profile. For this purpose, however, additional input parameters were required, in particular those related to soil water retention properties, hydraulic characteristics and soil dispersivity. These parameters were determined using both *in situ* measurements and laboratory analyses on soil samples collected in the field trial at the intensive monitoring sites.

Model simulations were compared to measurements obtained in the field trial for all seasons and treatments. In this report, examples of model validation are presented. The following subroutines were validated:

i) Crop growth against growth analysis data.
ii) Soil water deficit against neutron water meter measurements.
iii) Soil water redistribution with the cascading and finite-difference models against measurements with heat dissipation sensors.
iv) Salt redistribution with the cascading model against measurements obtained with the ceramic cup soil water samplers.

Conclusions and recommendations

In the field trial carried out at Kleinkopje 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 term (three years) (Objective 1).

The impact of irrigation with gypsiferous water (Objective 2) was evaluated through field monitoring, laboratory experiments and modelling.

Excellent yields were obtained for wheat on both virgin and rehabilitated land, and also short-season maize grown on virgin land. The yields of sugarbeans were reasonable, and definitely higher compared to dry land cropping (Objective 2.1).

Exchangeable Ca^{2+} and Mg^{2+} increased with time, whilst K^{+} decreased at all four pivot sites. This indicated that Ca^{2+} and, to a certain extent Mg^{2+}, replaces K^{+} on the soil adsorptive complex. If loss of K^{+} through leaching causes nutrient deficiencies to the crop, corrective fertilization should be applied. Field monitoring of crop nutrient status is therefore essential (Objective 2.1).

Further experimentation is needed to verify the results of the salinity-nutrient interaction glasshouse trial under field conditions and determine the optimal rate, method and timing of especially NH_4 and PO_4 fertilizers when irrigating crops with calcium and magnesium sulphate enriched waste waters (Objective 2.1).

The results from the herbicide trial indicated that the Tweefontein and Jacuzzi water may exert an effect on the adsorption characteristics of the atrazine and 2,4-D molecules. This would mean that in the field, there is a possibility that soil retention would decrease and so leaching could increase, reducing the efficacy of the herbicides. Leaching would also lead to groundwater contamination. The increase in activity of atrazine found in bioassays probably does not hold any practical consequences in terms of herbicide efficacy, selectivity or persistence. In contrast, reduction of metolachlor activity in the presence of gypsum implies that weed control by the herbicide will be poor on soils irrigated with water containing high levels of calcium sulphate (Objective 2.1).

In the study on characterization of soil materials, a database of bulk density, water retention properties, hydraulic conductivity and the solute transport characteristics (dispersion, adsorption and rate dependant transfers) was generated. Based on these results, it was concluded that high bulk density due to soil compaction and the presence of the spoil layer with low hydraulic conductivity could be limiting factors for crop production under irrigation on rehabilitated land (Objective 2.1).

Proper preparation of rehabilitated land proved to be important. Settlement of rehabilitated land caused ponding and waterlogging that had to be overcome by contouring and installing surface drainage waterways. This problem is related to the physical nature of rehabilitated land, and not to the chemistry of the water used for irrigation. In the rehabilitation process, if rehabilitated land is to be used for crop production under irrigation, the spoil material should be packed on a slight slope to prevent waterlogging (Objective 2.1).

Several methods for measurement of gypsum precipitated in the soil were considered. The Adapted Dilution Method was eventually selected and applied. An attempt to measure gypsum precipitated in the soil profile was done on deep soil samples collected in June 2000. It was, however, clear from the results obtained that a reliable method to measure gypsum precipitation still needs to be developed (Objective 2.2).

The effects of gypsum precipitation and salt accumulation on soil characteristics (Objective 2.3) were investigated in a laboratory trial. There was no evidence that precipitated gypsum affected the water retention capacity adversely.

Soil chemical analyses indicated a general trend of increase of soil salinity during the trial. The values of soil saturated electrical conductivity were, however, still < 400 mS m^{-1} in the root-zone, even after particularly dry seasons, due to gypsum precipitation and leaching of soluble salts (Objective 2.4).

The results of chemical analyses on deep soil samples indicated that, at pivot Major and Tweefontein, most soluble salts were confined to the upper 1 m, probably due to the presence of the plinthic and spoil layers limiting free drainage. At pivot Fourth, there was a more uniform distribution of salts in the soil profile, with a slight peak between 1.5 and 2 m down in the profile indicating leaching of salts below the root-zone (Objective 2.4).

The results of the spatial variability study indicated that there is a tendency for salinity levels to be higher in the central region of each pivot. This is believed to be due to the larger quantities of saline irrigation water that have been applied in these zones during the course of the experiment. The salinity levels measured at the end of the trial are unlikely to have an adverse effect on the growth of most crops (Objective 2.4).

The quality and quantity of drainage water was calculated using the SWB model. Runoff amount and quality data collected at the weirs, indicated that less than 2% of the salts added since the beginning of the trial were lost from the irrigated fields through surface and subsurface runoff from November 1999 to April 2000. More runoff was recorded at pivot Tweefontein compared to pivot Major, due to the restricted soil depth and steep slopes of the rehabilitated land (Objective 2.5).

Variability in soil salinity over time and space was observed depending on rainfall, irrigation volumes applied and evapotranspiration rate, and over soil depth depending on root water extraction patterns (Objective 2.6).

Soil chemical analyses indicated a general trend of increase in soil pH(H_2O) during the trial at all pivots (Objective 2.7).

The SWB model was developed for predictions of salt and water budgets under irrigation with gypsum rich mine water (Objective 3).

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 validation of the chemical equilibrium subroutine in SWB, done by comparing model output to direct measurements of gypsum precipitated in the soil, failed as the method used to measure precipitated gypsum was inaccurate. A comparison between SWB and FAO-SWS, a modified user-friendly version of UNSATCHEM, was run in order to test the chemical equilibrium subroutine. There was excellent agreement between SWB and FAO-SWS. This gave confidence that SWB can be used to predict the water and salt balance in the long term (many decades or centuries) (Objective 4).

In the scenario modelling study, several management options were proposed for utilization of gypsiferous mine waste water through irrigation. The acceptability of the proposed management strategies will depend on the standards for environmental protection, as well as social and economic issues. It is essential that strategic decisions are made on cropping systems, as many options are available, all with different implications for job creation, ease of management, profitability, capital equipment requirements, water use, irrigated area and salt precipitation. It is also essential that the necessary management capacity and infrastructure is available, as only healthy, well-managed crops can use water and precipitate gypsum. Different cropping systems have different capital and running costs and this should be quantified. It is clear, therefore, that one is dealing with a very flexible system that can be managed in a certain way to achieve the desired result, be it maximum crop production, water use, job creation, economic return or maximum gypsum precipitation and minimum salt leaching (Objective 5).

The SWB model was linked to a groundwater model and provided inputs to associated groundwater studies (Objective 6).

The groundwater study (Objective 7) consisted of monitoring groundwater level and quality from boreholes installed on virgin (unmined) land at pivot Major, as well as modelling. .

Field monitoring (Objective 7.1) indicated that salt migration through soil and aquifers is a slow process. After more than three years of irrigation, there was still no conclusive evidence that saline irrigation water had reached the aquifer below the irrigation site at pivot Major (Objective 7.1).

The SWB model output was used as input into a groundwater model in order to predict the long-term effects of irrigation with gypsiferous mine water on groundwater for a case study at pivot Major. The conclusion was that pollution from two sources (irrigation site and Jacuzzi dam) will surface in the adjacent stream and furrow. Interception facilities can be installed at these points, from where polluted water can be returned to the dam. There is no risk of regional pollution in the aquifer (Objective 7.2).

Recommendations for further research

It is recommended to continue the field trial at Kleinkopje in order to collect more years of data on the impact of irrigation with gypsiferous mine water on soil and groundwater resources.

Extrapolation to other climatic conditions, soils and waters is also essential in order to get experience of other conditions. This could be achieved by testing the SWB model for different environmental conditions.

Attention should be paid to groundwater quality, as it will take significantly longer than three years for the pollution plume to migrate through the soil and into the aquifer. The link between SWB and the groundwater model gives the opportunity to predict the extent of groundwater contamination at specific mines. Groundwater contamination at regional scale will depend on the geometry and geological properties of specific sites. It is also suggested that the adsorption capacity of the vadose zone be investigated.

The fact that only gypsum can be held up in the soil to some extent, and all other more soluble salts must be leached for successful crop production, suggests that although this technology can make an enormous contribution to water management in the mining industry, it will not be able to completely solve all their problems. Some mines also generate significant volumes of saline waters that are not particularly gypsiferous. In order to deal with such waters and the concentrated leachate from gypsiferous mine water irrigation, other agricultural technologies should be considered. The most promising technology is serial biological concentration where increasingly concentrated leachate is applied to increasingly salt tolerant crops to reduce the volumes of water and to allow minimal salt export from the mines.

Soil physical analyses of rehabilitated profiles indicated that high bulk density due to soil compaction and the presence of the spoil layer with low hydraulic conductivity could be limiting factors for crop production under irrigation. It is recommended to investigate measures for reducing soil compaction on rehabilitated soil profiles in order to improve land capability, or make use of this opportunity to create a "duplex" soil from which drainage water can be retrieved for use in serial biological concentration.

There is opportunity for further improvement to SWB. The simulations with the finite-difference water balance model were carried out without simulating salt redistribution, as the convection/dispersion subroutine is currently being debugged. The finite-difference model has the potential to predict the soil water and salt balance more accurately than the cascading model, once the salt redistribution subroutine becomes operational.

ACKNOWLEDGEMENTS

The research in this report emanated from a project funded by the Water Research Commission entitled:

"The influence of Irrigation with Gypsiferous Mine Water on Soil Properties and Drainage Water in Mpumalanga".

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The contribution of the members of the Steering Committee is acknowledged gratefully.

The financing of the project by the Water Research Commission, the Technology and Human Resources for Industry Programme (THRIP, a partnership programme funded by the Department of Trade and Industry and managed by the National Research Foundation), and from the industry (Anglo Coal, Sasol, Duiker, Ingwe) is also acknowledged.

This project was only possible with the co-operation of many individuals and institutions. The authors therefore wish to record their sincere thanks to the following:

Mr A van der Westhuizen, who lobbied hard to ensure that generous THRIP funding was secured and used to significantly enhance the scope of the initially planned project.

Mr HC van Zyl, who served as project leader and kept all the mining houses committed to this project.

Prof CF Reinhardt and Mr L Kanyomeka (Dept. Plant Production and Soil Science, University of Pretoria), as well as Mr R Meinhardt (Agricultural Research Council – Plant Protection Research Institute, Pesticide Dynamics Division, Roodeplaat) for carrying out the investigation on the effect of gypsiferous mine water on herbicide activity.

PHE Strohmenger (Agricultural Research Council - Institute for Soil, Climate and Water, Pretoria) for completing two laboratory trials on plant nutrition, as well as for collecting and processing plant nutritional data of samples collected in the field.

Mr C de Jager (Dept. Plant Production and Soil Science, University of Pretoria) for collecting and processing plant nutritional data of samples taken in the field.

Ms L Grobler (Dept. Plant Production and Soil Science, University of Pretoria) for studying the effects of gypsum precipitation on soil properties.

Mr MP Nepfumbada (Dept. of Water Affairs and Forestry, Roodeplaat, formerly Dept. of Plant Production and Soil Science, University of Pretoria) for his study on characterization of soil material.

Prof MV Fey and Mr R Campbell (Dept. of Geology, University of Cape Town) for analysing deep soil samples.

Mr G Ascough (School of Bioresources Engineering and Environmental Hydrology, University of Natal) for operating the GPS unit during the study on soil salinity spatial distribution, processing the data, and producing the salinity maps on ArcView.

Ms I van der Stoep (Dept. of Agricultural Engineering, University of Pretoria) for testing time domain reflectometry for measurement of volumetric soil water content and soil salinity.

Mr JJB Pretorius (Dept. Plant Production and Soil Science, University of Pretoria) and Mr OT Doyer (Dept. of Agricultural Economics, University of Pretoria) for their economic analysis of scenario simulations with the Soil Water Balance (SWB) model.

Mr G Narciso (Agricultural Research Council - Institute for Soil, Climate and Water, Pretoria) for analysing spatial variability of crop performance and yield with remote sensing.

Mr R Grobbelaar (Institute for Groundwater Studies, University of the Free State, Bloemfontein) for collecting and processing data from the boreholes.

Mr Werner Sullwald (AMFARMS) as well as Gert and Neels Smith (Smith Bros) who where responsible for the farming practices during the course of the field trial.

Mr RD Garner (Anglo Coal Environmental Services, Witbank) for managing meetings and supplying water consumption and irrigation water quality data.

Mr E Meier for his dedication to managing the field trial and supporting the farming company (as representative of Kleinkopje Colliery)

Kleinkopje Colliery (Witbank) for funding, installing the irrigation system and preparing the land at the experimental site.

Finally, a special word of thanks to Mr HM du Plessis (Water Research Commission) whose vision, guidance and encouragement throughout this project have been inspirational to the whole research team.

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a - Intercept of Campbell's log-log soil water retention function

ADG - Average daily gain

ADM - Adapted dilution method

AMD - Acid mine drainage

AVR - Average value ranking

A(I) - Term of the coefficient matrix

b - Slope of Campbell's log-log water retention function

BTC - Breakthrough curve

B(I) - Term of the coefficient matrix

C - Solute concentration in the soil solution (mol l^{-1})

CAM - Conflict analysis method

CDE - Convection-dispersion equation

C_{avg} - Time weighted average concentration of a particular solute (mol l^{-1})

CEC - Cation exchange capacity (cmol$_c$ kg^{-1})

CR - Total capital requirement per m^3 water used for the specific farming alternative

c_v - Vapour concentration in the soil atmosphere (kg m^{-3})

$c_v^{'}$ - Saturation vapour concentration (kg m^{-3})

CV - Control volume (m m^{-1})

C(0) - Concentration of the aerial node (of infiltrating water) (mol l^{-1})

C(I) - Term of the coefficient matrix

D - Combined diffusion and dispersion coefficient (m^2 s^{-1}); Drainage (mm); Willmott's (1982) index of agreement

DAP - Days after sowing

DE - Deficit irrigation strategy

DM_i - Dry matter increment (kg m^{-2})

D_o - Ionic or molecular diffusion coefficient in free water

D_v - Vapour diffusivity in soil ($m^2 s^{-1}$)

D_{vo} - Vapour diffusivity in air ($m^2 s^{-1}$)

D_X - Dispersion coefficient in the x-direction ($m^2 d^{-1}$)

DUL - Drainage upper limit ($m m^{-1}$)

D(l) - Term of the coefficient matrix containing the previous time step solute concentrations

E - Evaporation (m)

EA - Net present value for the specific farming alternative over 30 years

EC - Electrical conductivity ($mS m^{-1}$)

EC_e - Saturated soil electrical conductivity ($mS m^{-1}$)

EDX - Energy dispersive X-ray

EM - Electromagnetic induction

EM_h - Horizontal electromagnetic induction

EM_v - Vertical electromagnetic induction

EM_{mean} - Mean electromagnetic induction ($mS m^{-1}$)

E_p - Potential evaporation ($kg m^{-2} s^{-1}$)

ET - Evapotranspiration (m)

$\hat{e}_j(a,b)$ - Difference in impact score on criterion j for those criteria for which alternative a is better than alternative b

FAO - Food and Agricultural Organization of the United Nations

FC - Field capacity

g - Gravitational acceleration (9.8 $m s^{-2}$)

g_j - Relative importance of criterion j

h - Water level above the weir (m); Hydraulic head (m); Matric pressure head (mm)

h_a - Atmospheric humidity

h_d - Air entry pressure (mm)

HDM - Harvestable dry matter (kg m^{-2})

HDS - Heat dissipation sensors

h_e - Campbell air entry parameter (mm)

h_i - Inflection point where Campbell's water retention equation changes from exponential to quadratic

h_r - Fractional relative humidity

h_s - Humidity of the surface

i - Time step in the finite-difference model

I - Irrigation (m)

IC - Ion chromatography

J_l - Liquid flux (kg m^{-2} s^{-1})

J_l^0 - Liquid flux at the surface (kg m^{-2} s^{-1})

jsd - Diffusive and dispersive solute fluxes

jsm_i - Mass solute flux

J_v - Vapour flux (kg m^{-2} s^{-1})

k - Hydraulic conductivity (m d^{-1}); Ranking for economic criterion

K - Hydraulic conductivity (kg s m^{-3})

K_s - Saturated hydraulic conductivity (mm h^{-1} or kg s m^{-3})

k_v^i - Transfer coefficient

l - Lower half of a soil layer

LAI - Leaf area index

LF - Leaching fraction

m - Pore connectivity parameter

MAE - Mean absolute error

MBE - Mass balance error

MCDM - Multiple criteria decision-making

M_w - Molecular mass of water (kg mol^{-1})

n - Effective porosity; Number of criteria; Coefficient of the hydraulic conductivity function; Empirical constant in the solute dispersion/diffusion equation

N - Number of observations

NWM - Neutron water meter

PCM - Precipitation of salts over 30 years (Mg ha^{-1})

PET - Potential evapotranspiration (mm)

P(a,b) - *Aggregate preference indices between alternatives a and b*

Q - Abstraction/recharge (m^3 d^{-1}); Water flow over the weir (m^3 s^{-1})

r^2 - Coefficient of determination

r_{uk} - Root water uptake coefficient (kg s m^{-4})

R - Retardation coefficient; Rainfall (mm)

RD - Root depth (m)

RMSE - Root mean square error

R_u - Root water uptake (kg m^{-2} s^{-1})

S - Storage coefficient; Source/sink of water (kg m^{-3} s^{-1})

SCS - Soil Conservation Service of the U.S. Department of Agriculture

Se - Effective saturation

SEM - Scanning electron microscope

SPE - Saturated paste extract

SWB - Soil Water Balance model

t - Time (s)

T - Transmissivity (m^2 d^{-1}); Temperature (K); Transpiration (mm)

TDM - Top dry matter (kg m^{-2})

TDR - Time domain reflectometry

TDS - Total dissolved salts (mg l^{-1})

$_u$ - Upper half of a soil layer

USDA - U. S. Department of Agriculture

v - Seepage velocity (m d^{-1})

V - Average convective pore liquid velocity

WP - Wilting point (m m^{-1})

WU - Water utilization over a period of 30 years (m^3)

X - Set of feasible alternatives; Distance (m)

Y - Criterion space

z - Vertical distance (m); Layer depth (m)

α - Air entry parameter (mm^{-1})

$\varnothing_g$ - Gas filled porosity

δ, ε - Space weighting factors

γ - Coefficient due to time dependant transfer of solute species

ΔS - Control volume change in storage (kg m^{-2} s^{-1})

Δz - Layer thickness (m)

ε - Dispersivity of the medium (m^2 s^{-1})

ϕ - Matric flux potential (kg m^{-1} s^{-1})

λ - Pore size distribution parameter

μ - Coefficient due to time dependant transfer of solute species

η - Time weighted factor for average concentration of a particular solute

ν - Pore water velocity (m s^{-1})

θ - Volumetric water content (m^3 m^{-3})

θ_r - Residual volumetric water content (m^3 m^{-3})

θ_s - Saturated volumetric water content (m^3 m^{-3})

ρ_b - Dry bulk soil density (Mg m^{-3})

ρ_{gypsum} - Density of gypsum (kg m^{-3})

ρ_s - Particle density (Mg m^{-3})

ρ_{soil} - Density of soil (kg m^{-3})

ρ_w - Density of water (kg m^{-3})

σ - Space weighting factor for gravity flow which can vary between 0 and 1

τ - Tortuosity

P - Matric potential (J kg^{-1})

P_e - Air entry potential (J kg^{-1})

P_i - Threshold water potential (J kg^{-1})

ψ_x - Water potential in the xylem (J kg^{-1})

CHAPTER 1

1. INTRODUCTION

1.1. Statement of the problem

The mining industry is one of the most important in South Africa, both from the point of view of gross national product and job creation. In the mining of mineral resources, pollution problems are created with adverse effects on the already scarce water resources. Disposal of mine waste water is a world-wide problem occurring wherever operating coal and gold mines, as well as closed underground workings are found (Pulles et al., 1995). The type of water emanating from mines depends largely on the geological properties of the coal, gold ore and other geological material with which waters come into contact. The concentrations of salts and other constituents frequently render this water unsuitable for direct discharge to the river systems except in periods of high rainfall when an adequate dilution capacity is present and controlled release is allowed.

Current measures to prevent pollution of the environment include: i) prevention of ingress of water into the workings by grading the surface area around the mine, or building channels to collect and divert storm water; ii) establishment of vegetation on tailing dumps and dam surfaces to prevent erosion, reduce the quantity and improve the quality of rainfall runoff from dump sites; iii) storage of mine water in evaporation areas; iv) recycling of water from tailing dams through gold-recovery plants; and v) utilization of mine water for cooling and by selected industries which can tolerate low quality water (Pulles et al., 1996). In several mines, the effluent is highly acid ($pH \approx 2$). This acidity is usually associated with sulphuric acid generated by the exposure of sulphide minerals to oxidizing conditions and water (Thompson, 1980). In many rock types natural neutralisation occurs as a result of reaction between the sulphuric acid and base minerals. Where inadequate natural neutralisation potential is present, acid mine drainage (AMD) is usually neutralised using calcium carbonate, oxide or hydroxide (Van Staden, 1979). Most of the resulting $CaSO_4$ is precipitated in sedimentation basins, but the liquid effluent is saline and gypsiferous with an electrical conductivity (EC) typically in the range from 130 to 290 mS m^{-1}, due mainly to the presence of Ca^{2+} and SO_4^{2-} in solution (Jovanovic et al., 1998). In all cases the end product is a pH-neutral water with a high calcium sulphate (gypsum) content. This effluent is then used for dust alleviation on gravel roads and for irrigation of lawns. Other physico-chemical and biological methods of water purification, like reverse osmosis, ultra- and nanofiltration, ion exchange with cation and anion resins, and biological reduction of SO_4^{2-}, are often prohibitively expensive.

Gypsiferous mine water can be regarded as one of mining's greatest problems, or as a potential asset. Large amounts of waste water could possibly be made available to the farming community and utilized for irrigation of high-potential soils in the coalfields of Mpumalanga Province, where water resources for irrigation are already under extreme pressure. In this summer rainfall region, dry-land winter cropping is not feasible and mine water is often the only source of water for irrigation. Moreover, concentrating the gypsiferous soil solution through evapotranspiration, thereby precipitating gypsum in the profile, could limit environmental pollution. Contamination of downstream water supplies for other users could also be reduced, and additional income could be achieved through farming. The high capital expenses and operational costs of effluent treatment could also be offset to some extent by farming income. Al toxicity, often occurring in these soils, could be reduced through irrigation with gypsiferous mine water (Barnard et al., 1998). An enormous surplus water problem for the coal mining industry could also be significantly reduced.

The size of the opportunity depends on the availability of water in proximity to suitable soils (Tanner et al., 1999). At present, there are no accurate measures of the total volumes of water contained in old underground workings, nor of the rate at which additional affected water is accumulating. Some estimates of the quantities of salt that are discharged into the national streams have been made. In 1992 it was estimated that some 130 000 t of salt were discharged from coal mines, and 200 000 t from gold mines. At an average total dissolved salts concentration of 2 g l^{-1}, this would indicate an annual discharge of some 65 million m^3 of water from the coal mines, and 100 million m^3 from the gold mines. These volumes are expected to increase with time.

Reasonable estimates of volumes of mine water stored and generated are available for a number of active mines, and the accuracy of these estimates is improving rapidly. For instance, Kleinkopje Colliery (near Witbank, Mpumalanga) currently has some 12 million m^3 of water stored underground, and it is estimated that the generated volume is in the order of 14 Ml d^{-1}. This is sufficient to sustain an irrigated system of some 500 to 700 ha (depending on cropping system). There are a number of operating and closed coal mines in the Mpumalanga Highveld region. If 30 of these are generating water of suitable quality for irrigation at a rate similar to that of Kleinkopje Colliery, then the potential exists to irrigate some 15 000 to 20 000 ha. The goldfields areas, similarly, have significant areas that could be used for irrigation. As more water is generated in the goldfields of South Africa, this potential could be at least doubled.

1.2. Background

The use of gypsiferous mine water for irrigation of agricultural crops is a promising technology that could add value through agricultural production and utilize effluent mine drainage. The potential for use of this water for 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 salts leached that would contaminate groundwater. Simulation results indicated that irrigating with a gypsum rich water will result in lower soil and percolate salinity compared to a chloride rich water of otherwise similar ionic composition. This can be attributed to precipitation of gypsum in the soil. The increased sodium hazard caused by gypsum precipitation is not expected to seriously affect soil physical properties and crop yield using a typical mine water quality for irrigation (Du Plessis, 1983).

In a previous Water Research Commission project, Barnard et al. (1998) carried out field and laboratory screening trials, where a wide range of crop and pasture species were irrigated with lime-treated AMD. They proved that irrigation with this water should not present a soil salinity or crop production problem within a relatively short time period (three years), provided careful fertilization practices are carried out. The problem of saline water management, however, has also long-term implications (Bresler et al., 1982). Long-term changes in soil chemical properties can be measured, but the execution of long-term experiments monitoring slow environmental processes can be prohibitively expensive and it is not always possible to wait for the outcome of such experiments. The long-term effect (fifty years) of irrigation with gypsiferous water on soil and water resources was assessed by Annandale et al. (1999a) for a case study at the Kleinkopje mine. They used the Soil Water Balance (SWB) model (Annandale et al., 1999b) in combination with the CLIMGEN weather data generator (Campbell, 1990) to simulate the long-term soil water and salt balance, and concluded that irrigation with gypsiferous mine water should not cause irreparable damage to soil and groundwater resources. Considerable amounts of salts could be, for all practical purposes, permanently removed from the water system by precipitating gypsum in the soil profile, with very slow dissolution and leaching after the cessation of irrigation. They also recommended high-frequency irrigation and careful fertilization practices to provide crops with the right amounts of available soil water and nutrients throughout the growing season.

1.3. Objectives of the project

In this project, the general objective was to ascertain whether gypsiferous mine water can be used on a sustainable basis for the irrigation of crops and/or amelioration of acidic soils. This was achieved by addressing the following secondary aims:

1) Assess the feasibility to manage irrigation with gypsiferous mine water at semi-operational scale in such a way that surface and groundwater contamination is reduced, while soil suitability and crop production are maintained.

2) Evaluate the effect of irrigation with gypsiferous water on the following:

    2.1) Yield and plant nutritional effects on a selection of agronomic crops that can be grown in the area.
    2.2) Gypsum precipitation and immobilization of other chemical constituents in the soil.
    2.3) Effects of gypsum precipitation and salt accumulation on soil characteristics.
    2.4) Depth of salinization of soil over time.
    2.5) Quality and quantity of drainage water.
    2.6) Impact of seasonal and annual rainfall on soil and drainage water characteristics.
    2.7) The ameliorating effect of gypsiferous water on acidic soils.

3) Develop predictive models for salt and water budgets for soil under irrigation with gypsum rich mine water.

4) Evaluate and refine these models practically over a (three year) period with summer and winter crops.

5) Model long-term salt and water budgets for different scenarios.

6) Provide inputs to any associated groundwater studies.

Following the acceptance of the project proposal, it was realized that investigations into the impact of irrigation on the groundwater regime were also necessary. The Institute for Groundwater Studies (Bloemfontein) was approached by Anglo Coal and the Water Research Commission for the necessary groundwater research. The following objective was therefore added:

7) Investigate the extent of groundwater contamination through:

7.1) A complete description of the groundwater regimes in areas to be irrigated, detailing the geohydrology as well as groundwater quality before, during and after irrigation.

7.2) Interpretation of data through the establishment of an expert system and geohydrological modelling to facilitate the prediction of the medium- and long-term impacts on both local and regional scales.

1.4. Approach

The objectives have been tackled using a multi-disciplinary approach, where various aspects of the impact of irrigation with gypsiferous mine water were investigated.

The sustainability of the use of gypsiferous mine water for irrigation of crops and/or amelioration of acidic soils (General Objective) was investigated in a three-year field trial set up at Kleinkopje Colliery. Two farming companies were involved in crop management and commercial production, namely Amfarms from 1997 to 1999, and Smith Bros. from 1999 to 2000. Modelling was used to ascertain the long-term sustainability.

The feasibility of managing irrigation with gypsiferous mine water on a commercial scale in such a way that surface and groundwater contamination is minimized, while soil suitability and crop production are maintained (Objective 1), was addressed through field monitoring and laboratory experiments (Chapter 2).

The impact of irrigation with gypsiferous water (Objective 2) was also evaluated through field monitoring and laboratory experiments (Chapter 2) as well as modelling (Chapters 3 and 4).

In particular, field trial and laboratory experiments were used for Objective 2.1. Data from the field trial were used to evaluate crop yields (Section 2.3.2.1) and investigate plant nutritional aspects (Section 2.3.2.2). Additional glasshouse and laboratory experiments were carried out on crop response to irrigation with gypsiferous mine water. A reason for concern was that nutritional problems could materialize under irrigation with water rich in Ca, SO_4^{2-} and Mg, due to competition for nutrient uptake. This was observed, in some cases, in a field trial at Landau Colliery where several species were screened for tolerance to irrigation with lime-treated AMD (Barnard et al., 1998; Jovanovic et al., 1998). Nutritional imbalances could cause both reduced economic return for crop production and reduced mine water consumption through impaired crop transpiration. Plant nutritional aspects were therefore investigated in a glasshouse pot trial (Section 2.4.1). The aims were to determine whether plants can grow and produce acceptable yields under irrigation with gypsiferous mine water, and to recommend optimal nutrient management. An investigation was also carried out to determine possible adverse effects of mine water on herbicide activity (Section 2.4.2). This study was done by the Department of Plant Production and Soil Science, University of Pretoria and the Pesticide Dynamics Division, Plant Protection Research Institute of the Agricultural Research Council (Roodeplaat).

Gypsum precipitation and immobilization of other chemical constituents in the soil (Objective 2.2) was investigated and reported on in Section 3.2.4 and Appendix E.

The effects of gypsum precipitation and salt accumulation on soil characteristics (Objective 2.3) were evaluated. This was done in laboratory experiments by investigating the effect of gypsum precipitation on pore size distribution and soil hydraulic properties (Section 2.3.1.6).

Depth of salinization of soil over time (Objective 2.4) was investigated in the field trial at Kleinkopje Colliery for different irrigation management practices. Firstly, the soil material was characterized (Section 2.3.1). Soil chemical properties in the root-zone were then monitored every season during the course of the trial (Section 2.3.3.1). The impact of irrigation with gypsiferous mine water on the soil below the root-zone was also investigated (Section 2.3.3.1). Deep soil samples were collected in June 1999 and were analysed at the Universities of Cape Town and Pretoria. Measurements of soil salinity over the entire irrigated fields on a grid basis were carried out in order to get an idea of spatial variability (Section 2.3.3.2). This was done by the Department of Soil Science (University of Natal, Pietermaritzburg) at the beginning of each cropping season using electromagnetic induction.

The quality and quantity of drainage water (Objective 2.5) was calculated using the SWB model. The model was validated using data from the field trial and used to simulate soil water redistribution (Section 3.2.2) and salt redistribution (Section 3.2.3). In winter 1999, runoff crump weirs were built at the lowest points of two irrigated fields and used to measure surface and subsurface runoff at a field level (Section 2.3.4.2). Electrical conductivity was also recorded at the weirs to estimate the mass of salts lost through runoff (Section 2.3.4.2).

The impact of seasonal and annual rainfall on soil and drainage water characteristics (Objective 2.6) was investigated using field data and modelling. Chemical analyses of soil samples collected in the field were used to determine the impact of seasonal and annual rainfall on the soil (Section 2.3.3.1). The salt content in the soil solution was also measured by extracting soil water with ceramic cup soil water samplers for laboratory analyses (Section 2.3.3.1). Modelling soil water redistribution (Section 3.2.2) and salt redistribution (Section 3.2.3) as well as data collected at the weirs (Section 2.3.4.2) were used to determine seasonal variations of drainage quantity and quality.

Soil pH was analysed in the laboratory at the end of every season on samples collected in the field (Section 2.3.3.1) to evaluate the ameliorating effect of gypsiferous water on acidic soils (Objective 2.7).

The SWB model was developed for predictions of salt and water budgets under irrigation with gypsum rich mine water (Objective 3). The detailed model description is presented in Section 3.1.

The SWB model was refined and validated in detail using data from the field trial for summer and winter crops (Objective 4). The model was improved to include finite-difference water movement, whilst the subroutine for convection/dispersion of salts is under development (Section 3.1 and Appendix M). This should enable a more accurate description of the dynamics of water and salt movement in the soil profile. For this purpose, however, additional input parameters are required, in particular those related to soil water retention properties, hydraulic characteristics and soil dispersivity. These parameters were determined using both *in situ* measurements and laboratory analyses on soil samples collected in the field trial (Section 2.3.1). This work was carried out by the School of Bioresources Engineering and Environmental Hydrology (University of Natal, Pietermaritzburg). The University of Natal set up instrumentation for the measurement of these parameters at the Soil Physics Laboratory of the University of Pretoria. Data collected in the field trial were compared to model simulations in order to validate the SWB model (Section 3.2). The soil water and salt balances in the root-zone of crops were measured and calculated for two water qualities, as well as three water and salt application treatments on virgin and rehabilitated soil. The measurements were done at representative point locations in the irrigated fields by setting up intensive monitoring stations.

Accurate predictions of the water and salt balance with SWB in the short-term, should give confidence when applying the model for longer term predictions (Objective 5). In the field trial at Kleinkopje Colliery, it was not possible to investigate all options of cropping systems and management that could be suitable for the utilization of gypsiferous mine water through irrigation. An additional study was therefore carried out in order to recommend suitable cropping systems and agricultural management for the area in the vicinity of Kleinkopje Colliery. The SWB model was used to simulate different long-term scenarios of cropping systems and irrigation with saline water (Chapter 4). A simple economic analysis was also performed.

The SWB model was used to provide inputs to a groundwater model (Objective 6). The link between the irrigation and groundwater model is presented in Chapter 5.

The extent of groundwater contamination (Objective 7) was investigated using both field monitoring at Kleinkopje Colliery and modelling. This work was carried out by the Institute for Groundwater Studies (University of the Free State, Bloemfontein).

A complete description of the groundwater regimes in the irrigated area, detailing the geohydrology as well as groundwater quality before, during and after irrigation (Objective 7.1) was carried out. Field monitoring consisted of measuring groundwater levels and extracting groundwater samples from boreholes installed on virgin (unmined) land for laboratory analyses (Section 2.3.4.3). The monitoring on rehabilitated land was not done because the level of contamination of the spoil material is so high that little impact was expected from drainage water originating from irrigation.

Output of the SWB model was used as input into the groundwater model in order to predict the medium- and long-term impacts on both local and regional scales (Objective 7.2). A case study was run for Kleinkopje Colliery (Chapter 5). Groundwater contamination at regional scale will depend on the geometry and geological properties of specific sites.

CHAPTER 2

2. FIELD MONITORING AND LABORATORY EXPERIMENTS

2.1. Introduction

In order to meet the objectives of the project, a field trial was established at Kleinkopje Colliery, close to Witbank (Mpumalanga Province). In addition, a number of laboratory experiments were carried out in order to get a better understanding of the processes under investigation. In this chapter, materials and methods as well as results of field monitoring and laboratory experiments are presented.

Due to the large number of measurements carried out during the course of the field trial, materials and methods of field monitoring are grouped in Section 2.2. The results of the field trial follow in Section 2.3.

Section 2.3.1. presents results related to the characterization of soil material used in the field trial. Soil material was characterized using both field and laboratory measurements. As these measurements are interlinked, it was decided to present them under the same Section. Crop yields measured to determine crop response to irrigation with gypsiferous mine water, and chemical analyses of plant material carried out to identify possible nutritional problems due to excess gypsum in irrigation water are presented in Section 2.3.2. Results of soil chemical analyses are also presented in order to determine whether changes in soil chemical properties occurred during three years of irrigation with mine water (Section 2.3.3). Section 2.3.4. includes irrigation water quality, as well as runoff and groundwater data. Runoff data included measurements of the volumes and quality of water that ran off the irrigated fields. Groundwater monitoring was an essential part of this project. Water quality and water levels were the main indicators, once the monitoring system was in place. These were measured through monitoring boreholes that were placed at specific localities where they were most likely to intersect pollution. During the installation of the boreholes, the following additional features were also noted and measured:

- Geology.
- Water strikes and yields.
- The hydraulic conductivity of the strata through packer and/or pumping tests.
- The installation of piezometer tubes to exclude cross contamination from surface water to the groundwater.

Glasshouse and laboratory experiments are presented in Section 2.4. Both material and methods as well as results of laboratory trials are included in the same Sections. Section 2.4.1. presents a laboratory pot trial carried out to identify possible nutritional problems due to irrigation with gypsiferous water, whilst Section 2.4.2 describes herbicide trials carried out to quantify the effects of gypsiferous mine water on herbicide activity.

2.2. Materials and methods - Field monitoring

The field trial was established at Kleinkopje Colliery (26°00' S, 29°21' E; altitude 1570 m), close to Witbank (Mpumalanga Province). A regional map is shown in Figure 2.1. The climate is summer rainfall with an average annual precipitation of about 650 mm. The trial lasted from the 1997/98 summer season until the 2000 winter season.

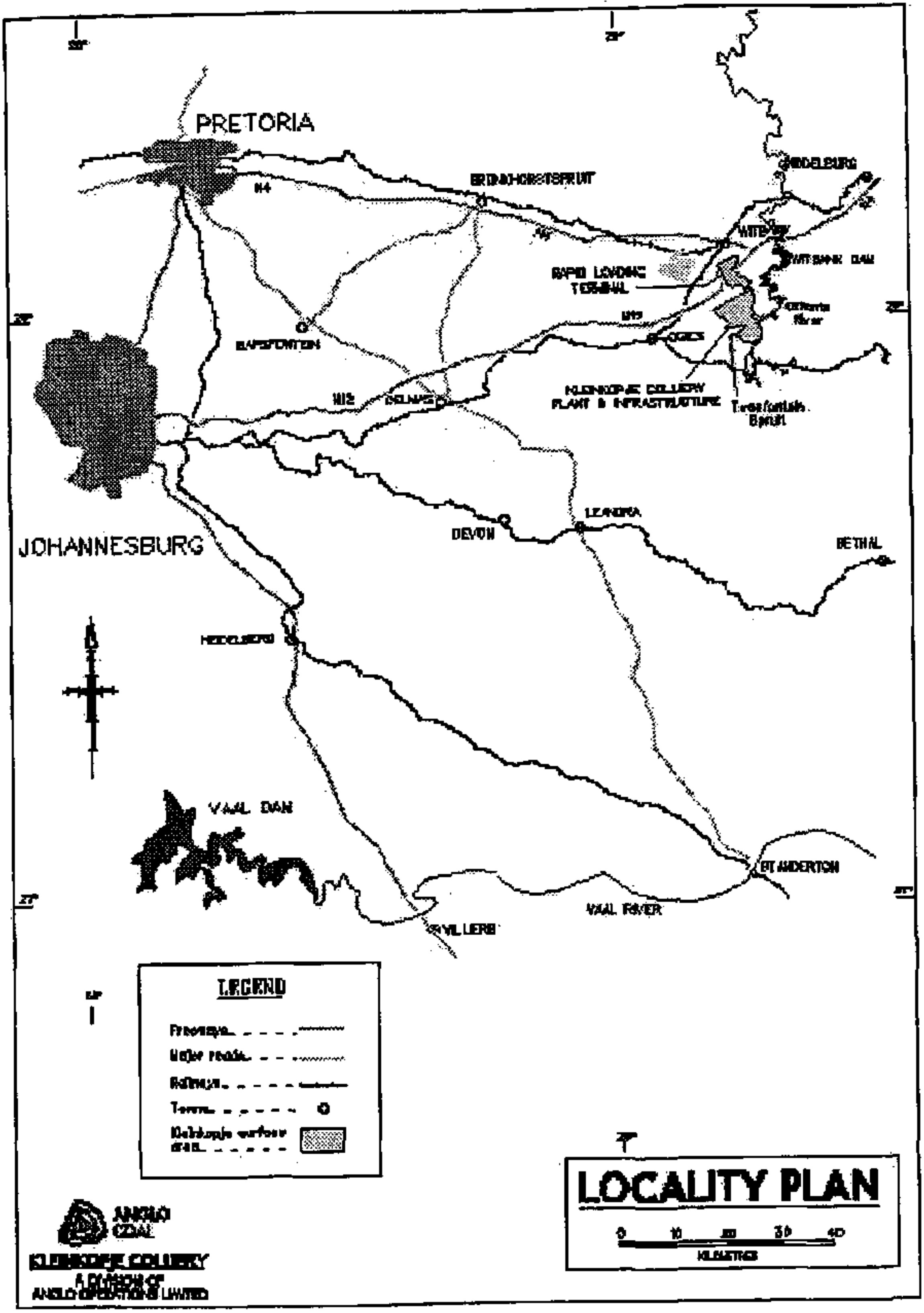


Figure 2.1. Locality plan of Kleinkopje Colliery.

2.2.1. Irrigation waters

Irrigations were carried out using two water qualities, namely Jacuzzi and Tweefontein. Jacuzzi water is pumped out of old underground workings and needs to be utilized by Kleinkopje Colliery in order to enable mining operations to continue. Most of this water is pumped to a large storage dam and is released under controlled conditions under licence from the Dept. of Water Affairs and Forestry, Pretoria. Tweefontein water is pumped from an active opencast pit and stored in the Tweefontein Pan.

2.2.2. Irrigation pivots

Four centre pivots were used for irrigation with gypsiferous mine water during the course of the trial:

- **Pivot Major:** Irrigated 30 ha of virgin (unmined) soil, predominantly Bainsvlei and Clovelly (Soil Classification Working Group, 1991); Used Jacuzzi water for irrigation.

- **Pivot Tweefontein:** Irrigated 20 ha of rehabilitated soil; Used water from the Tweefontein dam for irrigation.

- **Pivot Jacuzzi:** Irrigated 20 ha of rehabilitated soil from 1997 to 1999; Used Jacuzzi water for irrigation.

- **Pivot Fourth:** In autumn 1999, pivot Jacuzzi was moved to a virgin (unmined) site, due to problematic drainage at the rehabilitated site, and from then on, it was referred to as pivot Fourth. This was done to collect data for validation of the one-dimensional SWB model at a well-drained site. One tower and an extension were added to the pivot, so that pivot Fourth irrigated 30 ha of Hutton soil (Soil Classification Working Group, 1991) and used Tweefontein water for irrigation.

The mine map with the locations of the pivots, dams, plants, infrastructure and mining areas is shown in Figure 2.2.

Sugarbeans (*Phaseolus vulgaris*), maize (*Zea Mays*) and wheat (*Triticum aestivum*) were grown during the course of the trial. Maize, babala (*Pennisetum glaucum*), stooling rye (*Secale cereale*), ryegrass (*Lolium multiflorum*) and a lucerne (*Medicago sativa*) - fescue (*Festuca arundinacea*) mixed perennial pasture were also grown under pivot Major on 0.5 ha large strips in order to test crop response and water use of alternative cropping systems.

Crops, cultivars, planting dates and agronomic techniques are summarized in Tables A1 to A4 (Appendix A) for each pivot. The lucerne-fescue pasture was fertigated according to the requirements of the main crop at pivot Major (Table A1, Appendix A).

From winter 1998, contours and waterways were shaped before the beginning of each cropping season in order to facilitate drainage of excess water from the cultivated fields at pivots Major and Tweefontein.

Figure 2.2. Mine map with the location of the pivots, dams, plants, infrastructure and mining areas.

2.2.3. Irrigation water treatments

The nozzle packages of the pivots were chosen to provide three application rates of irrigation water (treatments):

i) Irrigations up to field capacity (FC strategy);
ii) Irrigations with a leaching fraction applied (LF strategy); and
iii) Irrigations below field capacity (deficit or "room for rain" strategy).

A sketch of the pivot area showing the typical layout of treatments is presented in Figure 2.3. The area of the field capacity treatment (towers 3 and 4) was used for irrigation scheduling with a neutron water meter (NWM) up to field capacity (FC strategy). The nozzles of towers 1 and 2 were chosen to provide a leaching fraction treatment with irrigation applications approximately 20% higher than in the field capacity treatment. The nozzles of towers 5 and 6 were chosen to provide a deficit treatment with irrigation applications approximately 80% of the field capacity treatment.

From the winter 1999 season, pivot Tweefontein had only a uniform application, the FC treatment, in order to prevent waterlogging in certain areas of the rehabilitated field. In the same season, tower 6 of pivot Major was converted to a field capacity treatment to avoid crop losses due to water stress, as this tower covered quite a large area. Tower 6 of pivot Fourth, as well as the added seventh tower and the extension were also set up to irrigate to field capacity.

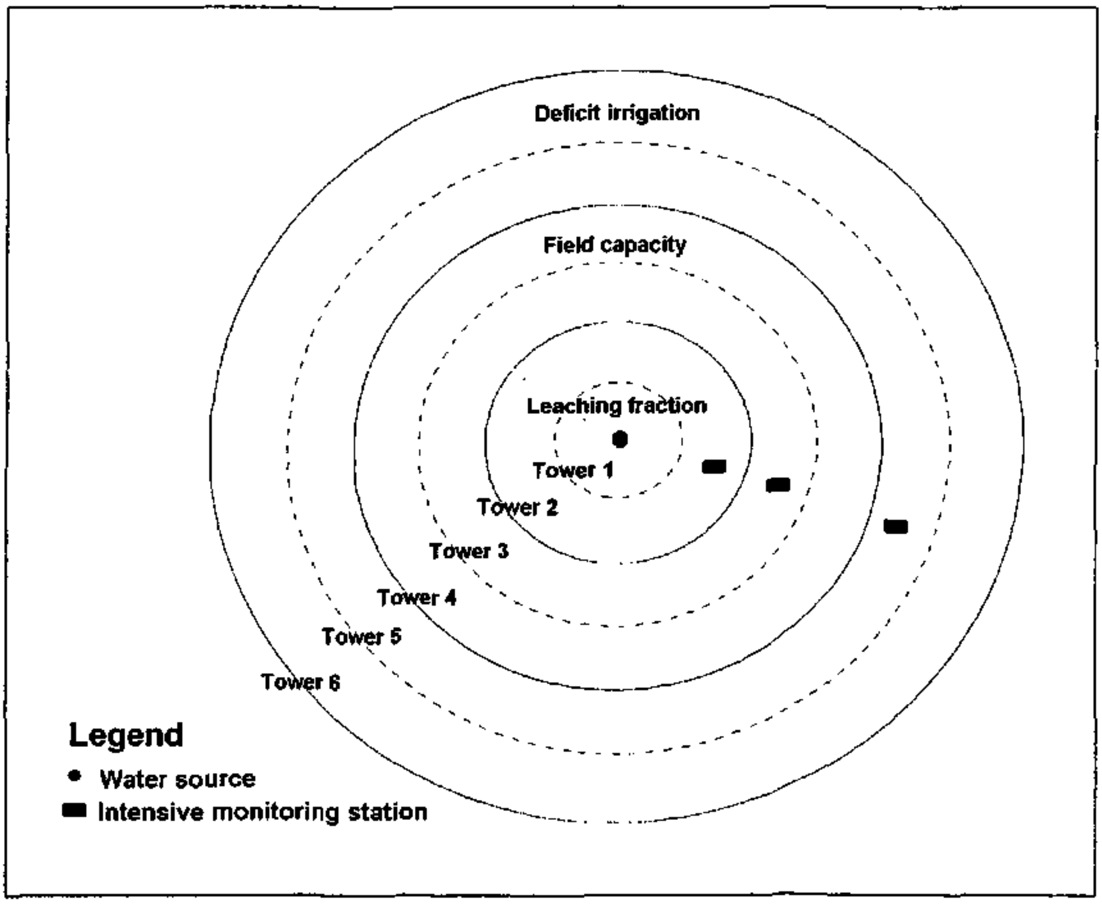


Figure 2.3. Typical layout of irrigation pivot.

2.2.4. Atmospheric measurements

An automatic weather station was set up on 27/10/1997, at a location adjacent to pivot Jacuzzi, approximately 100 m from the cropped area. In June 1999, before the beginning of the winter season when pivot Jacuzzi was moved to become pivot Fourth, the weather station was also moved to a location adjacent to pivot Tweefontein, approximately 100 m from the cropped area. Both sites where the weather station was set up, were surrounded by grass and on a slight slope. The sites were assumed to be representative for the area where the three pivots were located.

The following 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;
- Wind speed with an R.M. Young cup anemometer; 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 CR10 data logger. Temperatures were averaged hourly, as well as averaged, maximized and minimized daily. Daily average, maximum and minimum relative humidity were 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.

Rainfall, if occurring, was recorded every minute in order to determine intensity, and totalised hourly and daily. Rainfall recorded with the weather station could have been very different from the rainfall occurring at the locations of the pivots. For this reason, intensive soil monitoring stations at the pivots were provided with tipping bucket rain gauges (see following Section 2.2.5. on intensive soil monitoring stations).

All sensors were regularly calibrated. Data recorded with the weather station were used as input in the SWB model.

2.2.5. Soil measurements

Intensive monitoring stations were established under the pivots for measurement of the water and salt balance in the soil profile. The purpose was to collect data for validation of the one-dimensional SWB model. Representative locations were chosen for each treatment in areas as flat as possible to minimize lateral movement of soil water.

The intensive monitoring stations included the following instrumentation:

i) Tipping bucket rain gauges for measurement of amount and intensity of rainfall and irrigation. Rainfall and irrigation, if occurring, were recorded every minute and totalised hourly and daily.
ii) Heat dissipation sensors (HDS) for measuring soil matric potential. Data were recorded every 15 min or hourly, and sampled at the end of the day with Campbell Scientific CR10X data loggers.
iii) CS-615 soil water reflectometers for measuring volumetric soil water content. Data were recorded every 15 min, averaged hourly, and sampled at the end of the day with Campbell Scientific CR10X data loggers.
iv) Neutron probe access tubes for monitoring volumetric soil water content with a NWM, every 0.2 m down to 1.4 m. Readings were taken weekly.

v) Time domain reflectometry (TDR) probes for monitoring volumetric soil water content and bulk soil electrical conductivity with a Campbell Scientific TDR100 system. Readings were taken every hour.

vi) Ceramic cup soil water samplers to extract soil water samples for laboratory analyses.

vii) Automated tensiometer nests, comprising a logger and three or four tensiometers, to determine the direction and magnitude of the hydraulic gradients and ultimately to verify detailed modelling of the liquid fluxes (Appendix B).

The treatments, instrumentation used, depths of installation and the description of the soil profile where the instrumentation was installed are summarized in Tables A5 to A8 (Appendix A) for each pivot and season.

During the first cropping season (summer 1997/98), the dry land area outside pivot Major was monitored as a control, both for the main crop (sugarbeans) and for the alternative cropping systems (babala and maize) (Table A5, Appendix A).

Two neutron probe access tubes per crop and treatment were installed in the alternative cropping systems plot of pivot Major during the 1997/98 summer season (babala and maize) and during the 1998 winter season (ryegrass and stooling rye). Soil water content readings with the NWM were taken weekly. Irrigations and rainfall were recorded with manual rain gauges for each treatment (LF, FC, deficit and dry land).

Two neutron probe access tubes per treatment were also installed in the wheat crops (1998, 1999 and 2000 winter season) and maize crop (1999/2000 summer season) at pivot Major. Soil water content readings with the NWM were taken weekly. Irrigation and rainfall amounts and intensities were measured in the intensive monitoring stations of the lucerne-fescue perennial pasture for wheat and maize.

From winter 1999, the nozzle package of pivot Tweefontein was replaced to apply uniform amounts of water along its radius (FC strategy, Table A6, Appendix A). This limited the waterlogging and crop losses, which were experienced in some areas of the LF treatment in the previous summer cropping seasons.

Pivot Jacuzzi operated only from summer 1997/98 until summer 1998/99 (Table A7, Appendix A). Before the beginning of the 1999 winter season, pivot Jacuzzi was removed from its original location to a virgin land site next to the Tweefontein dam (Kleinkopje Colliery). The soil is Hutton (Soil Classification Working Group, 1991) with good drainage properties. The main reason for the removal of the pivot was to collect field data at a well-drained site where lateral drainage is negligible. The original location of pivot Jacuzzi was on rehabilitated land, where lateral drainage was an important component of the soil water and salt balance. Lateral drainage could only be modelled with a two- or three-dimensional model. One of the main objectives of this project was to validate the SWB model in its present one-dimensional form.

From the winter 1999 season, and following the visit of Prof DR Nielsen (University of Davis, California) and the workshop on "Sampling field soils and their vegetation" held at the University of Pretoria on the 24-25/07/1999, it was decided to move the remaining equipment from pivot Major to pivot Fourth in order to get replications and account for spatial variability in measuring the soil water and salt balance. Six intensive soil monitoring stations were established at pivot Fourth, along a diameter transect. Two stations were set up in each treatment (Table A8, Appendix A).

2.2.6. Irrigation water chemical analyses

Irrigation water samples were collected in winter 1998 for chemical analyses at the Soil Science Laboratory (University of Pretoria). The samples were collected from the pivot nozzles. The irrigation water was analysed for concentrations of Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, SO_4^{2-} and Cl^{-}. Electrical conductivity and pH were also measured. Irrigation water samples were also collected and analysed by Kleinkopje Colliery at regular intervals. The results of irrigation water chemical analyses are presented in Section 2.3.4.1.

2.2.7. Characterization of soil material

The soil profiles at the intensive monitoring stations were described and classified. Dry bulk densities were determined with a variety of methods (Appendix C), whilst texture was determined by sieving and with the hydrometer method.

The physical, hydraulic and solute transport characteristics of the soils and disturbed materials were determined for each of the pivots. Characterization of the soils served three purposes:

i) The soil characteristics were used to describe the general behaviour of the water in the profiles prior to modelling;
ii) The measured characteristics were used as initial model inputs to simulate the physics and chemistry of liquid and solute movement in and below the root-zone; and
iii) Characteristics measured at different times were used to evaluate specific phenomena in the porous media, such as changes to pore structure due to gypsum precipitation. Specific laboratory experiments were also conducted to accelerate gypsum precipitation so that the pore structure changes could be evaluated without resorting to long-term *in situ* measurements.

The method of soil hydraulic characterization involved both *in situ* and laboratory measurements. A consistent procedure was adopted, wherever possible, for characterizing the soil profiles investigated.

Firstly, at each level in the profile, a duplicate set of measurements was made. The measurements included an *in situ* tension infiltrometer test, followed by a double ring infiltrometer test on exactly the same location. Secondly, an undisturbed core was taken from the precise site of the tension infiltrometer and double ring tests for laboratory determination of water retention characteristics and bulk density. The specific methods employed in developing the characteristics of the porous media are summarized in Appendix C. Detailed descriptions of conventional methods are not included here, except where the methods used in this study differ from convention.

A series of 300 mm deep by 110 mm diameter columns were packed with soil from pivot Major in order to accelerate the gypsum precipitation process with loadings of approximately 8, 30, 75 and 90 ton gypsum ha^{-1}. A saturated solution was fed into the column intermittently. A vacuum pump was used to draw air through the pore spaces in the column between the cycles of gypsum solution inflow in order to enhance the precipitation of gypsum and to ensure that the gypsum precipitated throughout the column as it would in a root-zone in the field. A series of qualitative observations and a few quantitative estimates of the effect of the gypsum on the soil pore system were performed.

2.2.8. Soil analyses

Soil samples were collected before the beginning of the trial in the soil profiles from each pivot and treatment area. The following parameters were determined for 0.2 m soil layers down to 1 m:

- Bulk density;
- Volumetric soil water content at -10 and -1500 J kg^{-1} soil matric potential;
- Concentrations of soluble Ca^{2+}, Mg^{2+}, K^+, Na^+, NH_4^+, SO_4^{2-}, Cl^-, NO_3^-, HCO_3^- and CO_3^{2-};
- Concentrations of exchangeable Ca^{2+}, Mg^{2+}, K^+ and Na^+; and
- Bray I P.

In addition, soil pH(H_2O) and electrical conductivity of the saturated soil extract (EC_e) were determined.

Soil samples were also collected at the beginning of each season in the soil profiles from each pivot and treatment area. The following parameters were determined for 0.2 m soil layers down to 1 m:

- Concentrations of Ca^{2+}, Mg^{2+}, K^+, Na^+, NH_4^+, SO_4^{2-}, Cl^-, NO_3^-, HCO_3^- and CO_3^{2-};
- Concentrations of exchangeable Ca^{2+}, Mg^{2+}, K^+ and Na^+;
- Soil pH(H_2O);
- Electrical conductivity of the saturated soil extract; and
- Bray I P.

These data were essential for the initial input settings of the SWB model, and for fertilization recommendations.

Water analyses were carried out on samples of soil water collected with the ceramic cup soil water samplers. These samples were analysed for concentrations of Ca^{2+}, Mg^{2+}, K^+, Na^+, SO_4^{2-} and Cl^-. Electrical conductivity and pH were also measured. The purpose was to compare these measurements to model predictions. Due to difficulties encountered in extracting soil water with the ceramic cup soil water samplers, particularly under dry conditions, soil samples were taken on 19/10/1998 in the deficit irrigation treatments of the wheat crop at all three pivot sites for laboratory analyses.

Deep soil sampling was carried out before the beginning of the winter 2000 season (June 2000). This was done in order to explore whether any salt breakthrough originating from irrigation could be identified in the vadose zone between the root-zone and the groundwater. Deep soil samples were collected from pivots Major, Fourth and Tweefontein. A geological drill rig fitted with a 100 mm diameter push-tube soil corer was used to obtain complete cores of soil from surface to a depth of 4.5 m in each of the irrigation treatment areas, and in an area just outside each of the three pivots, the latter samples being intended to represent soil not exposed to irrigation with gypsiferous mine water. Each soil core was divided in 200 to 300 mm long sub-samples and bagged. The samples were air dried and analysed by the Department of Geology (University of Cape Town) and by the Soil Science Laboratory (University of Pretoria). Replicate sub-samples were analysed at both laboratories for double-checking purposes.

2.2.9. Measurement of precipitated gypsum

Precipitated gypsum was measured on deep soil samples collected in June 2000 for each pivot and treatment block, as well as outside the pivot areas. Measurements of precipitated gypsum were carried out on replicate sub-samples both at the Soil Science Laboratory (University of Pretoria) and at the Department of Geology (University of Cape Town). In this Section, the methods used for measurement of precipitated gypsum are presented.

Soil Science Laboratory (University of Pretoria)

Because of the low solubility of gypsum in water, the biggest problem with most of the gypsum determination methods is to determine the right soil to solution ratio in which all the gypsum in the soil will dissolve. This has lead to mostly lengthy and laborious methods. The other drawback of gypsum analysis methods is that these methods have been developed mostly for taxonomical purposes, and not to obtain quantitative data. A brief overview of the methods found in the literature to determine soil gypsum content is given in Appendix D. After evaluation of all methods, it was decided to adapt the methods of Bower and Huss (1948) and the U.S. Soil Conservation Service (1972). This method is referred to as the Adapted Dilution Method (ADM). In this method, the low solubility of gypsum was an advantage rather than a drawback and it was used to distinguish between gypsum and other sulphates, especially magnesium sulphates.

Department of Geology (University of Cape Town)

The research conducted at the Department of Geology (University of Cape Town) was intended to supplement our knowledge of the potential of the soils of the Mpumalanga Highveld to serve as repositories for the salts dissolved in saline mine water. In particular, this study had two aims: firstly, to assess whether the method used by Campbell (2001) to detect gypsum in soils - i.e. the analysis of the ionic composition of saturated paste extracts and the calculation of the gypsum saturation index (SI) - is reliable, and, secondly, to study the capacity of the soils currently under irrigation with mine water at Kleinkopje to adsorb sulphate ions. The methodology and results for gypsum precipitation obtained at the Department of Geology (University of Cape Town) are given in Appendix E. The first part of this Appendix deals with the gypsum detection method and the second part with sulphate adsorption.

2.2.10. Evaluation of changes in soil salinity distribution on the irrigated areas

Establishment of changes in the spatial distribution of soil salinity with time was based on surveys conducted using the electromagnetic induction (EM) technique. The EM-38 sensor of Geonics Ltd (Ontario) makes rapid measurements of soil EC and has been shown to provide a cost-effective method to map soil salinity distribution (Rhoades, 1992; McKenzie et al., 1989; Johnston et al., 1994). Measurements can be made with the sensor positioned either in the horizontal (EM_h) or vertical (EM_v) position. In the former position the response is primarily from the upper soil profile (64% of the response arises from the upper 60 cm), while in the vertical position the instrument is more responsive to the deeper layers (only 36% attributed to the upper 60 cm). Interpretation of the measurements is greatly enhanced by calibration during each survey of the EM values with the EC_e of soil samples taken down the profile (Johnston et al., 1997). From a limited number of observation points a regression relationship can be established that allows the prediction of EC_e from the numerous EM measurements that are made over the whole survey area.

Each year since 1997 a survey has been conducted at the different centre pivots. The EM-38 sensor has been used to obtain field measurements of EM_v and EM_h These have been corrected to a standard temperature of 25°C, as recommended by McKenzie et al. (1989), based on soil temperature at a depth of 45 cm. From these values the mean of the EM_v and EM_h (i.e. EM_{mean}) was determined. The salinity surveys have increased in their sophistication over the period of this project, partly due to new equipment that has become available. This relates mainly to the use of a G.P.S. receiver. The measurement positions were, during

1997-1999, located at points on a grid. This 40 X 80 m (or 40 X 40 m) grid had to be pegged out manually, which was a laborious and time-consuming exercise. The SURFER graphics package (Golden Software Inc.) was used in 1998 and 1999 to plot salinity contours. In December 2000 the G.P.S. (Trimble model TSC1) was used to provide accurate (< 1.0 m) positions of measurement points at spacings of between 25 and 50 m on three centre pivots (Major, Tweefontein and Fourth). This allowed for a faster and more appropriate procedure. In that geographic co-ordinates were being recorded, the ArcView G.I.S. package could be used to process the data and produce salinity contours using the "Kriging" statistical option. During each survey, soil samples were taken at 30 cm intervals down the profile from dominant soil types on each pivot for saturation extract analysis. A regression relationship was then established between EC_e (0-60 cm) and EM_{mean}.

2.2.11. Runoff amounts and quality

During winter 1999, runoff crump weirs were built at the bottom of the waterways at pivot Major and Tweefontein. The depth of water overflowing the weirs was measured with a pressure transducer connected to a CR-510 data logger. This was then used to determine the amount of water overflowing the weir. Electrical conductivity of runoff water was also measured with a salinity sensor connected to the CR-510 data logger. Data were recorded every 2 min only during runoff events (weir overflowing). The data collected at the weirs were used to quantify the amount of water and salts running off the irrigated areas at pivots Major and Tweefontein.

2.2.12. Installation of monitoring boreholes

2.2.12.1. Siting of the boreholes

A budget was provided by the mine for nine monitoring boreholes at pivot Major. These were spaced as indicated in Figure 2.4.

The surface slope through the irrigation area is to the South-West at an average gradient of 1:30.

Borehole 1 was intended to monitor virgin conditions, but it collapsed soon after installation. Boreholes 2 – 7 are spaced on a West to East line, approximately coinciding with the 1 560 m contour across the irrigation area. Boreholes 8 and 9 are located at the lowest surface positions.

The holes were all drilled to a depth of 15 m. This shallow depth was necessitated by the presence of underground mining of the No. 5 Seam Horizon (Figure 2.4), which could be as shallow as 20 m below the surface in some places.

2.2.12.2. Drilling

Drilling of the boreholes was done through air percussion drilling. The hole diameters are 165 mm. Samples for geological logging were taken at 1 m intervals. The blowout yields from the boreholes were noted while drilling.

Considerable instability of the strata was encountered while drilling. Yields from the boreholes were very low, but sufficient to cause additional instability in the holes once water was intersected. This instability necessitated a change in test procedures. It was intended to perform packer, pumping and slug tests on the boreholes to determine the hydraulic characteristics of the strata. The collapse of the boreholes was so severe that piezometers had to be installed immediately after each borehole was drilled.

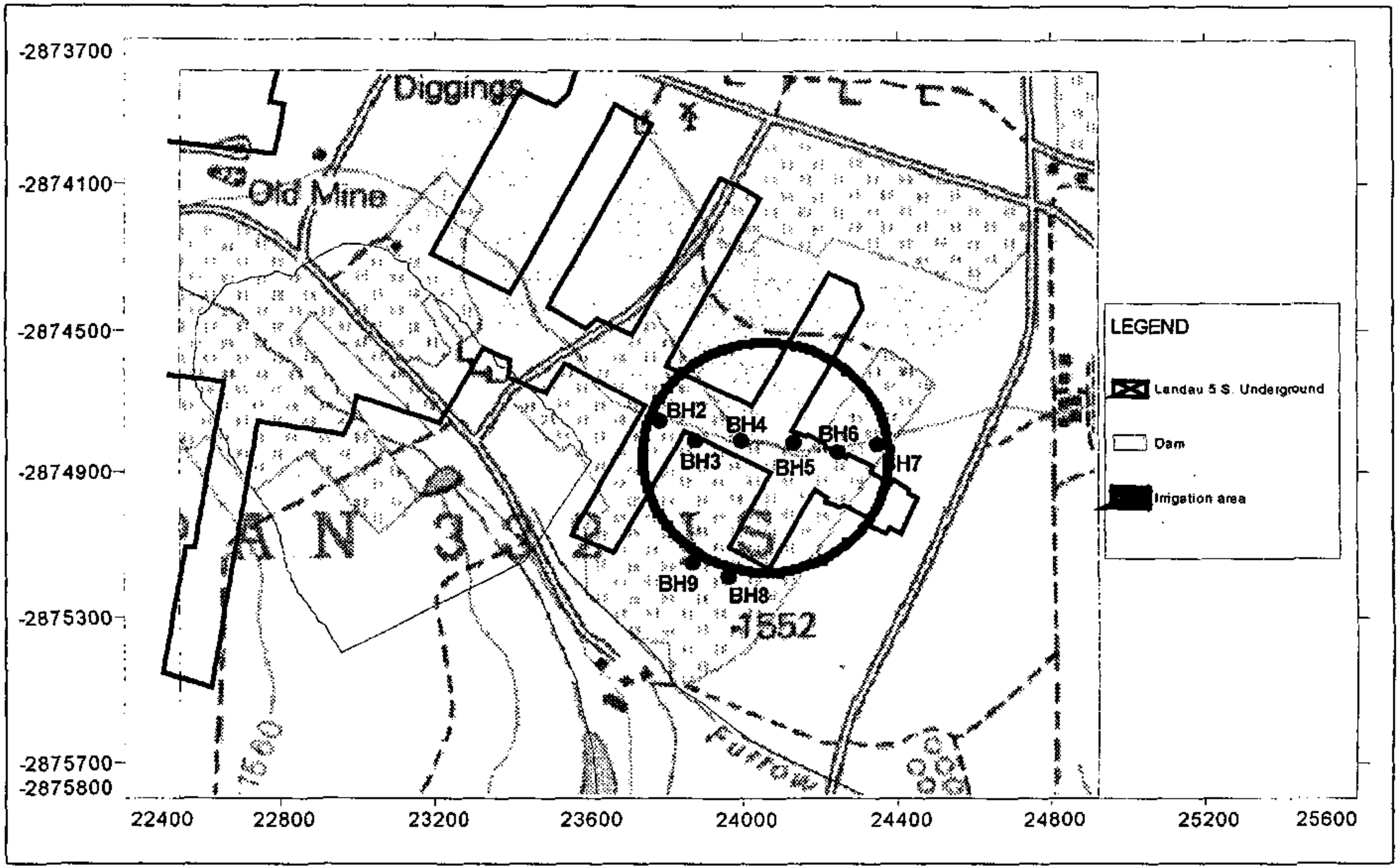


Figure 2.4. Locality plan of the irrigation pivot Major showing the positions of boreholes.

2.2.12.3. Geology and geohydrology

The geology of the area is relatively homogeneous. It consists of 2 – 5 m soil, followed by sandstone. The sandstone is highly weathered to depths of 10 – 12 m. Below this depth, the sandstone is fresh with a white appearance. A typical geological profile is shown in Figure 2.5. Complete geological logs for each of the boreholes are presented in Appendix F.

Water, in small quantities, was intersected in all boreholes in the weathered sandstone.

2.2.12.4. Piezometer installation

A piezometer consists of a slotted PVC tube, 62.5 mm in diameter, which is installed in a borehole for the purpose of measuring and sampling at specific elevations.

The purpose of piezometer installation in each of the monitoring boreholes was two-fold. In the first instance, the piezometer tubes serve to keep the holes from collapsing. Secondly, they effectively seal the holes in the vertical dimension, thus preventing surface water from flowing into the holes. A typical piezometer design is demonstrated in Figure 2.6. Details of piezometer installations in all the boreholes are provided in Appendix F.

2.2.12.5. Hydraulic characteristics of the aquifer

Due to the collapsing nature of the strata, hydraulic tests could not be performed before piezometer installation. As a result, pumping tests had to be performed with a small diameter pump, which was lowered into the piezometer tubes. The pumping test curves are included in Appendix G. Table 2.1 summarizes the results from the pumping tests.

The calculated transmissivities are low and incapable of sustaining prolonged groundwater abstraction. Nevertheless, hydraulic conductivity is high enough for water on the surface to penetrate into the sediments below. Water will move vertically to a depth of 10 - 12 m, whereafter it will move laterally on top of the fresh sandstone. The hydraulic gradient is towards South-West, i.e. in the direction of the stream.

Noticeable is the higher transmissivity of the strata at BH5 and the associated deeper static groundwater level. This suggests a lateral hydraulic connection, which allows drainage of groundwater from this area.

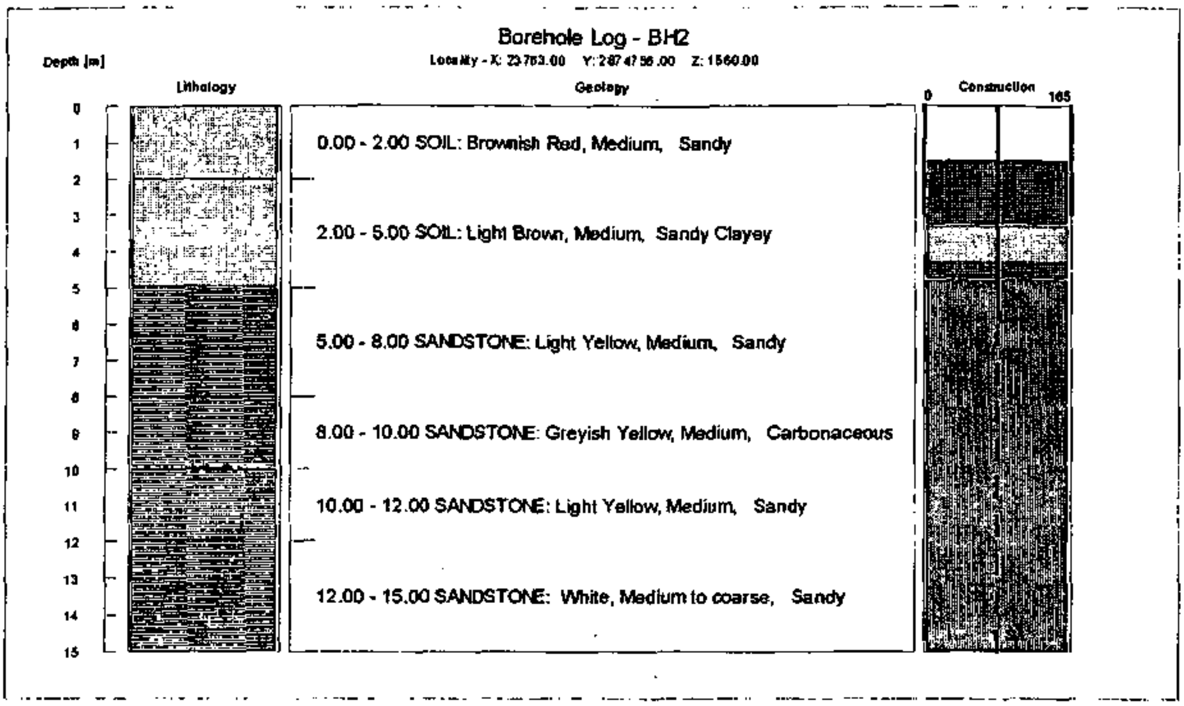


Figure 2.5. Typical geological log in the irrigation pivot Major area.

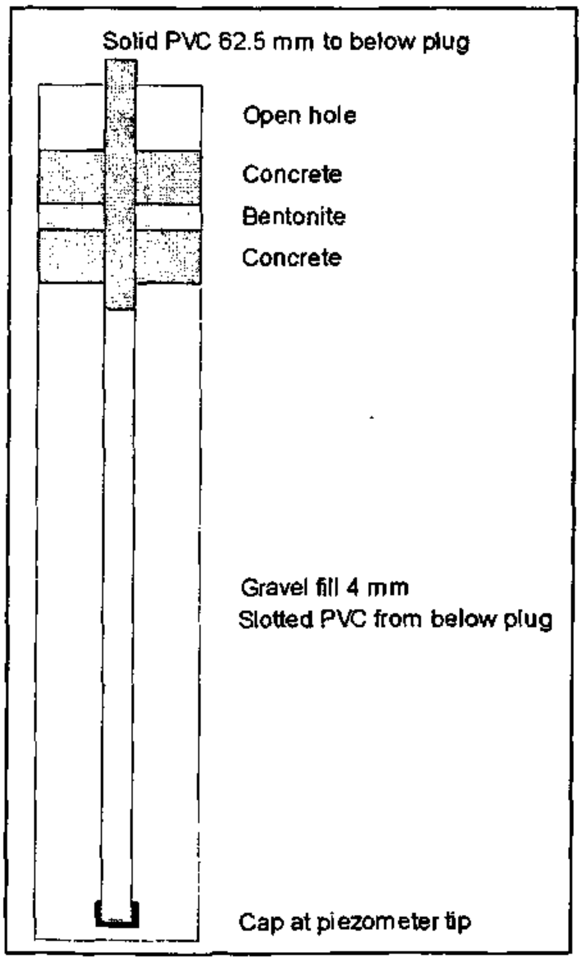


Figure 2.6. Typical installation of a piezometer in borehole at the irrigation pivot Major.

Table 2.1. Results from pumping tests on monitoring boreholes at pivot Major.

Borehole Number	Pumping rate ($m^3\ d^{-1}$)	Transmissivity ($m^2\ d^{-1}$)
BH1	Hole collapsed, not tested	
BH2	7.8	0.25
BH3	8.6	0.43
BH4	6.0	0.27
BH5	7.8	0.83
BH6	7.8	0.68
BH7	7.8	0.28
BH8	8.6	0.44
BH9	7.8	0.53

2.2.13. Crop measurements

The following measurements were carried out for each crop and treatment:

- Leaf area index (LAI) with *a Li-Cor LI-3100 belt driven leaf area meter every two* weeks;
- Growth analyses (dry matter production per plant organ, dried in oven at 60°C for two days) every two weeks;
- Fractional interception of radiation with a Decagon sunfleck ceptometer, every week; and
- Crop yield at the end of the season.

The objective was to determine specific crop growth parameters and use them as model input to test the crop growth simulations of the SWB model.

During the course of the trial, plant samples were taken at all pivot sites and analysed in the laboratory in order to identify and correct possible nutritional deficiencies through fertilization. This was done for wheat and lucerne (winter 1998 season), sugarbeans and maize (summer 1998/99 season) and for wheat in the winter 2000 season.

2.3. Results of field monitoring

2.3.1. Characterization of soil material

The unmined and mined soils in the centre pivots have been characterized in terms of their texture, physical, hydraulic and solute transport behaviour. Characterization of the soils served three purposes:

i) The soil characteristics were useful in describing the general behaviour of the water and salt fluxes in the profiles prior to modelling;
ii) The measured characteristics were used as initial model inputs to simulate the physics and chemistry of liquid and solute movement in and below the root-zone; and
iii) Characteristics measured at different times were used to evaluate specific phenomena in the porous media, such as changes to pore structure due to gypsum precipitation.

In addition, specific laboratory experiments have been conducted to accelerate gypsum precipitation so that the pore structure changes can be evaluated without resorting to long-term *in situ* measurements.

The soil characteristics are presented in terms of the physical characteristic of texture and bulk density, the hydraulic characteristics of water retention and hydraulic conductivity and the solute transport characteristics of dispersion, adsorption and rate dependant transfers. A comprehensive summary of all the measurements performed, the resultant characteristics as well as the mathematical parameters describing these characteristics are presented in Tables A55 to A59 (Appendix A).

2.3.1.1. Soil classification and texture

The soil at pivot Major on virgin land is loamy sand (clay 12%, silt 5% and sand 83%), predominantly Bainsvlei and Clovelly (Soil Classification Working Group, 1991). The soil at pivot Fourth on virgin land is sandy loam (clay 14%, silt 3% and sand 83%) Hutton (Soil Classification Working Group, 1991). The soil at pivots Jacuzzi and Tweefontein on rehabilitated land is sandy loam (clay 17%, silt 10% and sand 73%).

The detailed description of soil profiles at the intensive monitoring sites is given in Tables A5 to A8 (Appendix A).

2.3.1.2. Soil bulk density and porosity

The bulk densities of the soil profiles tested varied significantly (Table A56, Appendix A). The highest bulk densities were found in the consolidated spoil materials of the rehabilitated profiles. The bulk densities in these spoil materials range from 1760 kg m^{-3}, (porosity 0.336), to 2048 kg m^{-3}, (porosity 0.227). This range of densities is typical of both the Tweefontein and Jacuzzi rehabilitated centre pivot spoil layers.

The bulk densities of the layers below the rooting zone in the natural profiles are typically lower than the densities found in the spoil layers of the rehabilitated profiles. The densities below 2.5 m at pivot Fourth are approximately 1600 kg m^{-3}, (porosity 0.396), while those in the plinthite layer of pivot Major, at 1.8 m, have been recorded somewhat higher, at 1813 kg m^{-3} (porosity 0.316).

The topsoil layers in the natural profiles have bulk densities suitable for crop growth. The bulk densities generally range between 1600 kg m^{-3} (porosity 0.396) and 1760 kg m^{-3} (porosity 0.336), although low spots have been recorded at 1420 kg m^{-3} (porosity 0.464) and high spots at 1813 kg m^{-3} (porosity 0.316). The topsoil layers in the rehabilitated profiles generally have higher bulk densities compared to natural profiles, due to soil compaction by machinery.

2.3.1.3. Water retention characteristics

The results of 23 water retention characteristic determinations are summarized in Table A56 (Appendix A). Three common mathematical functions have been fitted to all the retention characteristic data (Tables A57 to A59, Appendix A). Retention characteristic functions have been fitted to the van Genuchten and Brooks-Corey functions using the RETC optimisation model (van Genuchten et al., 1991) while Campbell functions have been fitted using spreadsheet analysis. The Campbell parameters b and h_e were fitted to the data by inspection and the full parameter sets are listed in Table A59 (Appendix A). A rating has been listed against each parameter set in Tables A57 to A59 (Appendix A) to reflect both the goodness-of-fit as well as the quality of the data. This rating can be used as an indication of the reliability of the parameters in modelling the water movement in the profiles.

Typical ranges of water retention characteristics for four locations at pivot Major are shown in Figure 2.7 for the surface layer, and in Figure 2.8 for materials sampled at 0.5 m below surface. The Campbell mathematical function was fitted to the data for the upper and lower range of retention characteristics, which define the envelope of the distribution of data. The retention characteristic curve fitted to the data with the larger water content for a given capillary pressure head (Major 1 in Figures 2.7 and 2.8) is called the upper bound. The retention characteristic curve fitted to the data with the lower water content (Major 3 in Figure 2.7 and Major 4 in Figure 2.8) is called the lower bound. These fitted characteristics, therefore, define the limits of the range of water retention parameters that would be used in a sensitivity study of modelled soil water dynamics.

Both these sets of retention characteristics show a significant loss of liquid at low matric pressure heads (below 2 m), reflecting a loose structure and the presence of a significant volume of large pore sizes and, thus, a low Drained Upper Limit (DUL). However, this volume of large pore sizes is greater for the surface samples than for those at 0.5 m. The residual water content at a matric pressure head of 20 m (2 bar), ranges between 0.05 and 0.12 for the samples at 0.5 m, while on the surface this residual water content is narrowly distributed between 0.03 and 0.05. The spatial variation in water retention characteristic appeared to be greater at 0.5 m than at the surface, where the materials have probably been more disturbed through the tilling processes.

The water retention characteristic for the plinthite material at pivot Major is shown in Figure 2.9. The porosity of this material (0.31) is lower than the porosities found in the surface and near surface soils (0.35 – 0.45). The residual water content at 20 m matric pressure head (0.18) is also greater than any recorded for the upper layers.

The water retention characteristics for a typical topsoil and spoil sample are shown for the rehabilitated profile at pivot Tweefontein in Figure 2.10. The porosity is low (0.32) and the residual water content at 2 m matric pressure head is high (0.18), indicative of the compacted structure of the material.

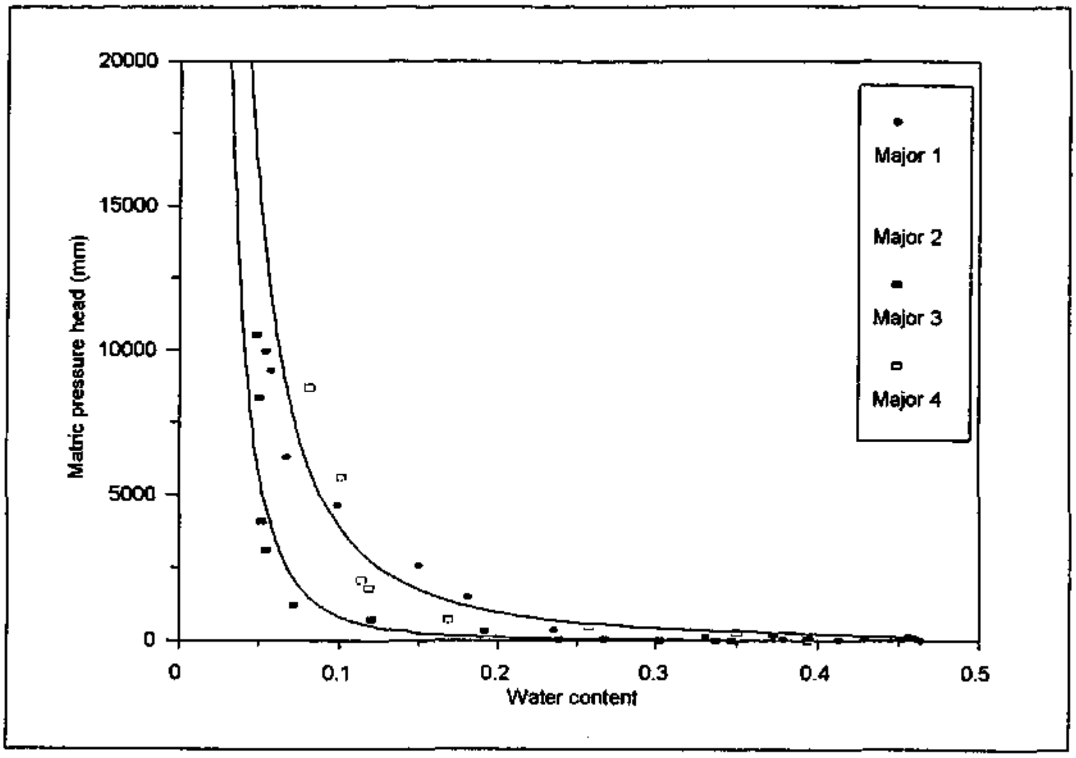


Figure 2.7. Water retention characteristics for pivot Major on the surface. The Campbell functions (solid lines) are fitted to the sets of data for Major 1 (upper bound) and for Major 3 (lower bound).

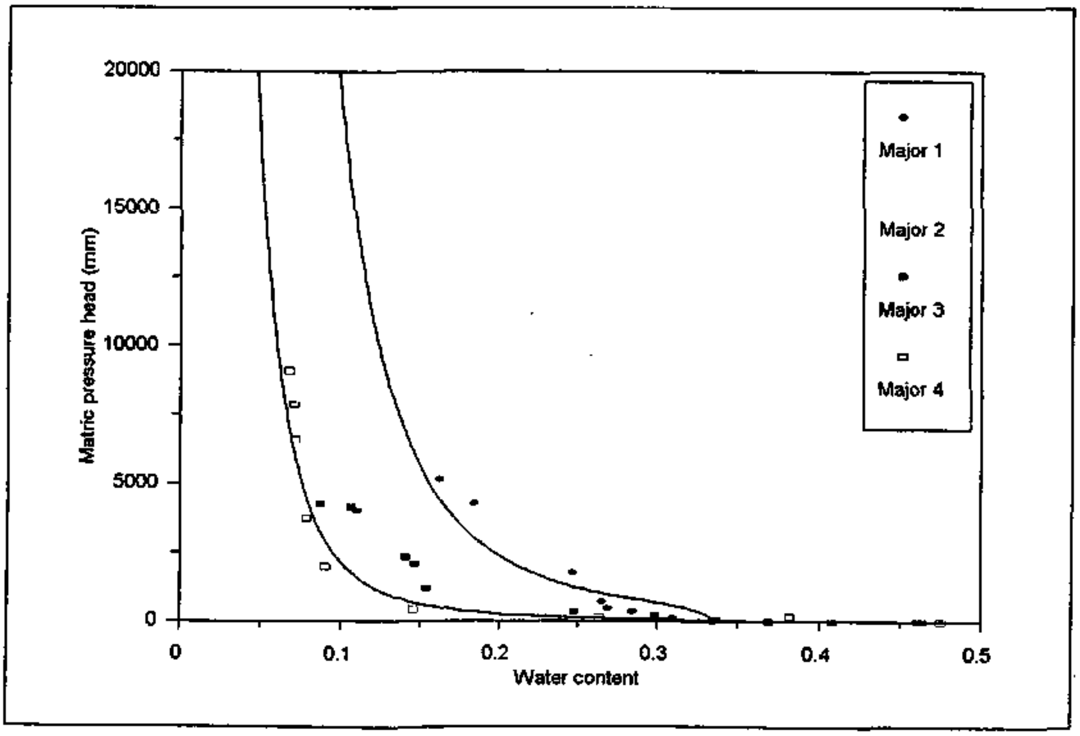


Figure 2.8. Water retention characteristics for pivot Major at 0.5 m below the surface. The Campbell functions (solid lines) are fitted to the sets of data for Major 1 (upper bound) and for Major 4 (lower bound).

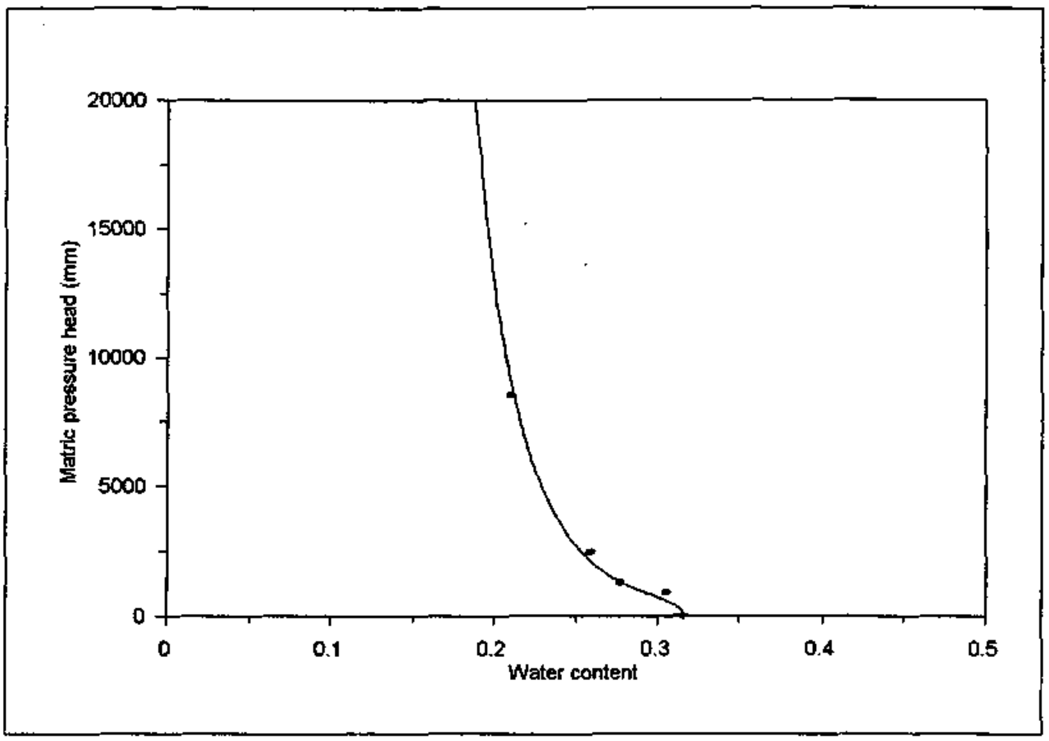


Figure 2.9. Water retention characteristic for pivot Major on the plinthite layer, 1.0 m below the surface. The Campbell function (solid line) is fitted to the data set.

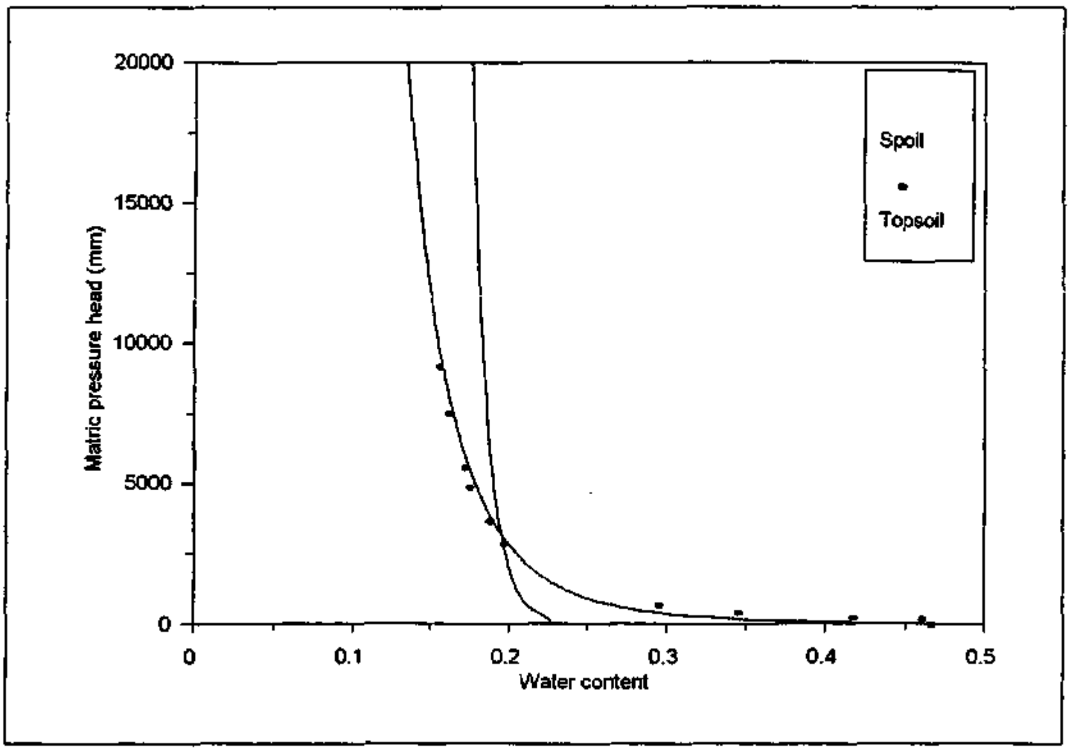


Figure 2.10. Water retention characteristics for topsoil and spoil material at pivot Tweefontein. The Campbell functions (solid lines) are fitted to the data sets.

2.3.1.4. Hydraulic conductivity characteristics

The results of the saturated and unsaturated hydraulic conductivity measurements are summarized in Table A56 (Appendix A) for all the pivots. The hydraulic conductivities of all profiles, whether natural or disturbed, decreased with depth. Saturated hydraulic conductivities at the surface ranged typically from 5 mm h^{-1} and 500 mm h^{-1} with pivot Major exhibiting the highest conductivities. A single measurement in the spoil layer at Jacuzzi yielded a conductivity of 0.9 mm h^{-1}, however the measurements of unsaturated hydraulic conductivity at 60 mm and 150 mm matric pressure head in the spoil were similar to those in the topsoil profile.

Typical hydraulic characteristic curves were plotted for pivot Major, Jacuzzi and Tweefontein in Figures 2.11 to 2.13. The mathematical functions derived by simultaneously optimizing the van Genuchten characteristic functions to the water retention and hydraulic conductivity data are also shown in Figures 2.11 to 2.13. The curves show the typical variation of hydraulic conductivity characteristic with depth. Parameters of the van Genuchten, Brooks-Corey and Campbell functions that have been simultaneously fitted to the retention and hydraulic conductivity data are summarized in Tables A57 to A59 (Appendix A).

In the rehabilitated profiles, the conductivity characteristic is high at low matric pressure heads (high saturation), typically between 10 and 100 mm h^{-1} (Figure 2.11 and 2.12). However, the characteristic curve drops off rapidly with conductivities decreasing two orders of magnitude over a range of 1 m of matric pressure head. In the deeper spoil profiles the conductivities near saturation are low (between 1 and 10 mm h^{-1}), but do not drop off as rapidly with increasing matric pressure head as those near the surface. Here the conductivities reduce by less than an order of magnitude over a change in matric pressure head of 1 m. This behaviour reflects the loose structure of the near surface materials in contrast to the compacted structure of the deeper soil layers and spoil materials.

In the natural profile at pivot Major, the conductivity characteristic shapes are similar for the surface and plinthite materials, but the plinthite conductivities are some two orders of magnitude smaller than those of the soil, both nearer the surface and at 0.85 m below the surface (Figure 2.13). The soil/plinthite contact is therefore likely to conduct water easily, without ponding or inducing lateral movement of water at this interface.

In order to define the spatial variability of hydraulic characteristics, a set of 35 tension infiltrometer measurements were performed in a radial pattern at pivot Major. The average of the hydraulic conductivity measurements decreased with increased applied tension, while the range of the maximum and minimum of the hydraulic conductivity measurements increased with increased applied tension. The decrease of the average hydraulic conductivity was small, varying from 12.6 mm h^{-1} at an applied tension of 60 mm to 7.5 mm h^{-1} at 150 mm.

The spatial distribution of the hydraulic conductivity measurements is represented in Figure 2.14 for the 60 mm tension and in Figure 2.15 for the 150 mm tension. While the range of hydraulic conductivity values was high for the 150 mm measurements, the variability spatially was low, with most of the pivot area exhibiting conductivities between 6 and 8 mm h^{-1}. The spatial variability of the measurements at 60 mm tension was larger than that for the 150 mm tension measurements, however some 50% of the field had conductivities between 8 and 14 mm h^{-1} at 60 mm tension.

Based on these results, it is clear that high bulk density due to soil compaction and the presence of the spoil layer with low hydraulic conductivity are limiting factors for crop production under irrigation on rehabilitated land.

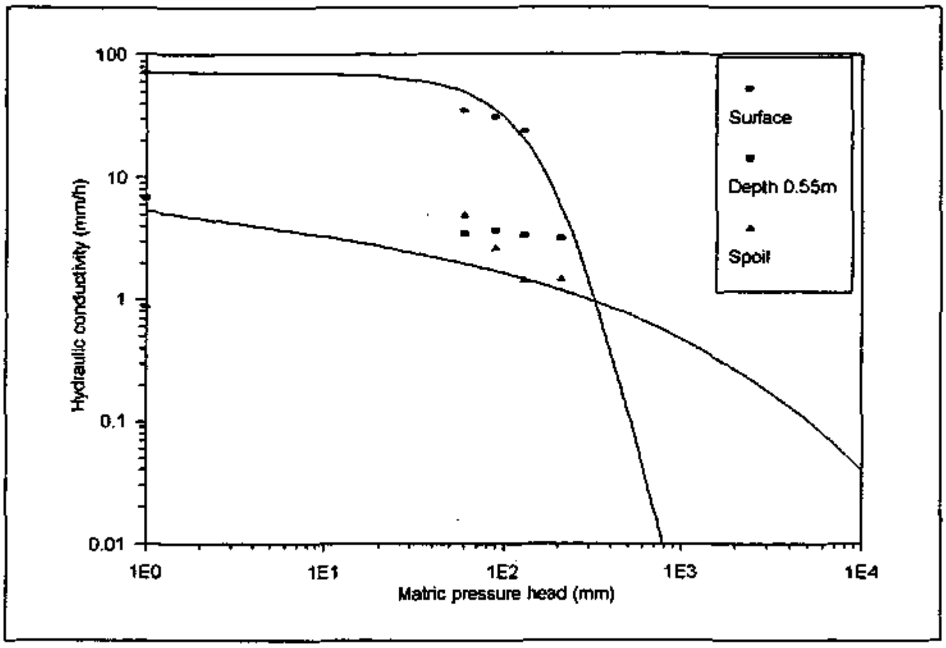


Figure 2.11. Hydraulic conductivity characteristic for topsoils and spoil material at pivot Jacuzzi. The mathematical functions for surface and spoil layer (solid lines) were derived by simultaneously optimizing the van Genuchten characteristic functions to the water retention and hydraulic conductivity data.

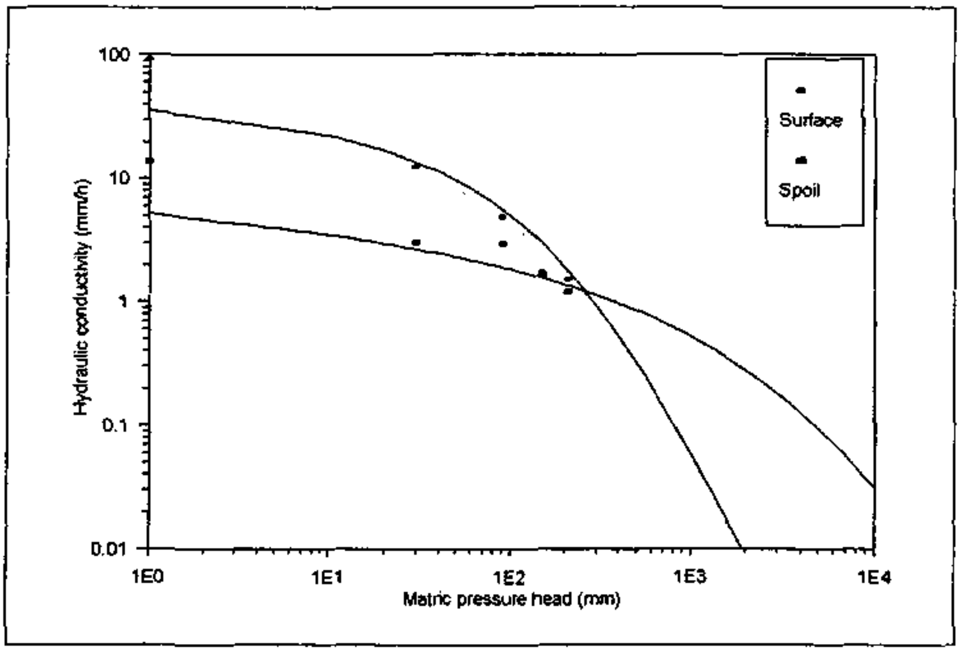


Figure 2.12. Hydraulic conductivity characteristic for topsoil and spoil material at pivot Tweefontein. The mathematical functions for surface and spoil layer (solid lines) were derived by simultaneously optimizing the van Genuchten characteristic functions to the water retention and hydraulic conductivity data.

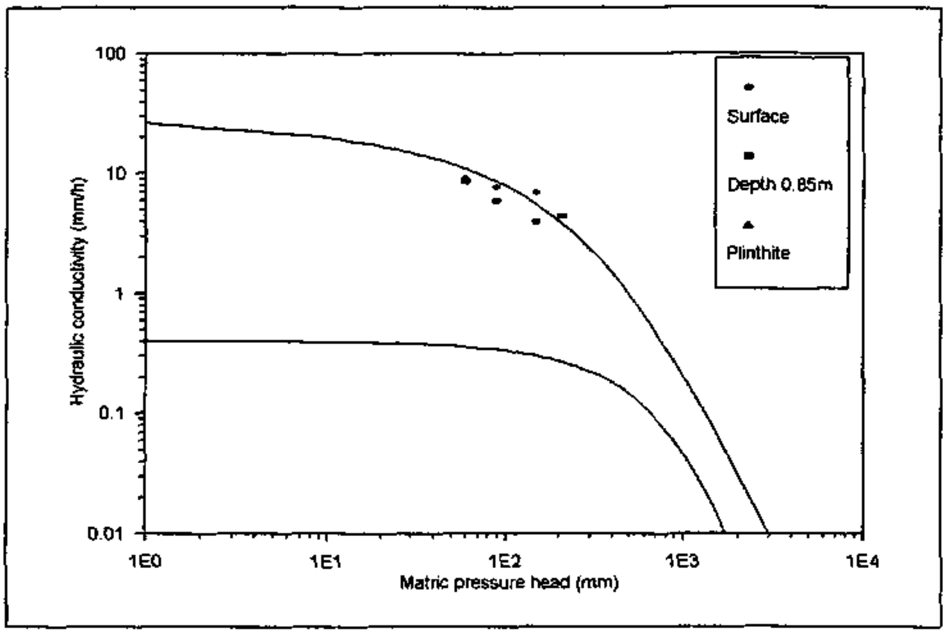


Figure 2.13. Hydraulic conductivity characteristic for topsoils and plinthite material at pivot Major. The mathematical functions for surface and plinthite layer (solid lines) were derived by simultaneously optimizing the van Genuchten characteristic functions to the water retention and hydraulic conductivity data.

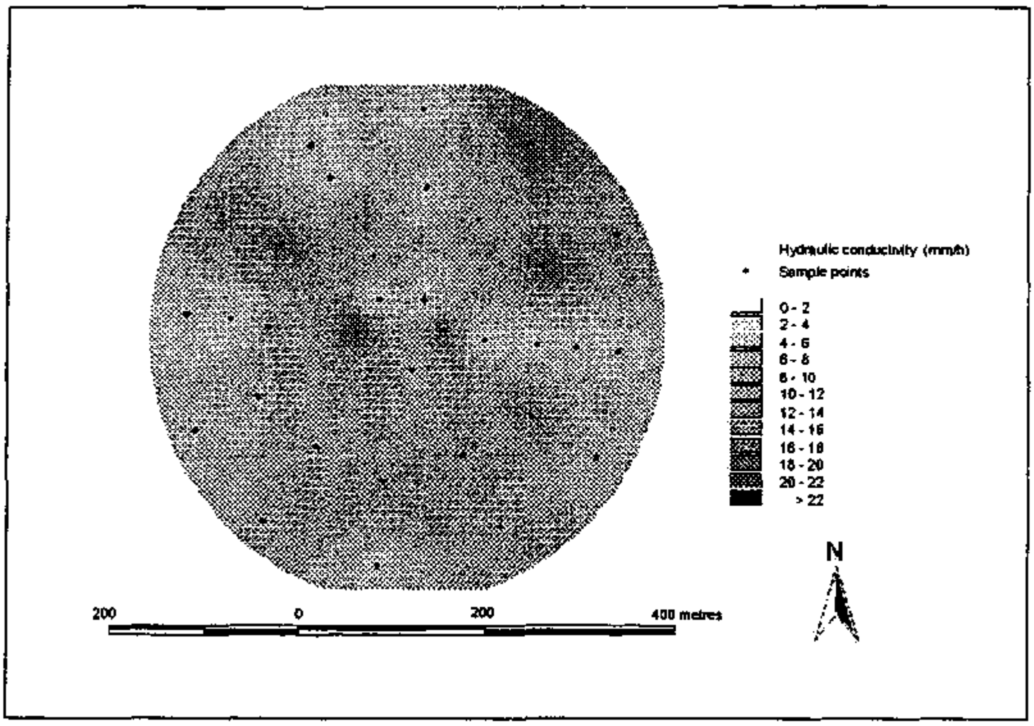


Figure 2.14. Spatial distribution of hydraulic conductivities at 60 mm tension at pivot Major.

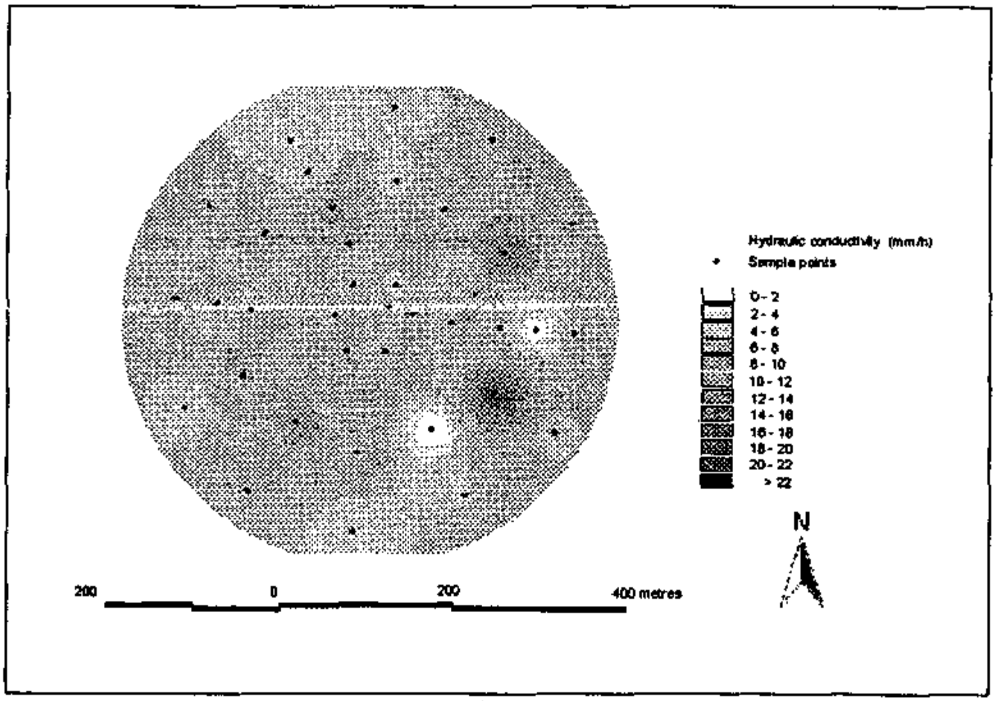


Figure 2.15. Spatial distribution of hydraulic conductivities at 210 mm tension at pivot Major.

2.3.1.5. Solute transport characteristics

The breakthrough characteristics for two column leach tests on materials from each of the pivots, Fourth, Tweefontein and Major, were studied. The first of the column leach tests was performed by injecting distilled water into a column packed at a specific liquid content using a solution of $CaSO_4$ and KCl. The displacement of the antecedent solution with the distilled water was observed by plotting the relative concentration of Ca and Cl against the volume of distilled water injected, expressed as a fraction of the pore volume of the material in the column. The Cl data were then optimized against parameters describing the solution to the solute transport equation, taking into account convection and dispersion. Since the Cl was introduced as a conservative tracer, the dispersion coefficient was derived from the fit of the theoretical curve to the data. Thereafter the Ca breakthrough characteristic data was fitted to a theoretical solution taking into account convection, dispersion, adsorption and rate dependent transfers. In this optimization the dispersion coefficient from the Cl fit was used and parameters defining adsorption and rate dependent transfers were derived.

The second of the leach tests was performed after 24 h of continuous injection of distilled water. This test comprised the injection of the $CaSO_4$ and KCl solution to displace the distilled water resident in the column. Fitting of characteristic curves was performed as in the previous test.

The solute transport equation is:

$$R\frac{\partial c}{\partial t}=D\frac{\partial^2 c}{\partial x^2}-v\frac{\partial c}{\partial x}-\mu c+\gamma(x)$$

where

C - Concentration of the species of interest
D - Dispersion coefficient
v - Average convective pore liquid velocity
R - Retardation factor due to adsorption and

μ and γ are combined first order and zero order rate coefficients due to time dependant transfers of the species.

The breakthrough characteristics for pivot Fourth are shown for the distilled water injection in Figure 2.16 and for the $CaSO_4$ and KCl solution injection in Figure 2.17. The Cl breakthrough curve in both instances is typical for a conservative species without time dependant transfer. The Ca breakthrough curve, plotting ahead of the Cl curve, is indicative of a species being retarded by linear adsorption. However, the Ca curve is also symmetrical, indicating that no rate dependant transfer of the Ca ion has occurred. This rate dependant transfer could arise from either a time dependant chemical reaction involving the Ca ion, or by rate dependant diffusion from a stagnant pore water phase into the mobile pore water phase. The parameter set describing these breakthrough characteristics is presented in Table 2.2.

Breakthrough characteristics for the Tweefontein and Major samples are presented in Appendix H. The Cl breakthrough characteristic for the Tweefontein materials exhibited some time dependant behaviour, with a rapid drop in concentration in the mobile solution, followed by a prolonged "tail" as the Cl ion diffused from the stagnant phase into the mobile phase. The Ca ion was retarded in both the distilled water and salt solution injection tests.

The pivot Major sample had a significant retardation of Ca ion in both tests. Theoretical curves could not be fitted to these data. Significant quantities of Ca ion, precipitated in the field, appeared to have remained in the sample during laboratory packing and were dissolving into solution throughout both tests. This, despite 24 h of flushing with distilled water between the two tests. Parameters for the Tweefontein sample and the Cl breakthrough of the Major sample are presented in Table 2.2.

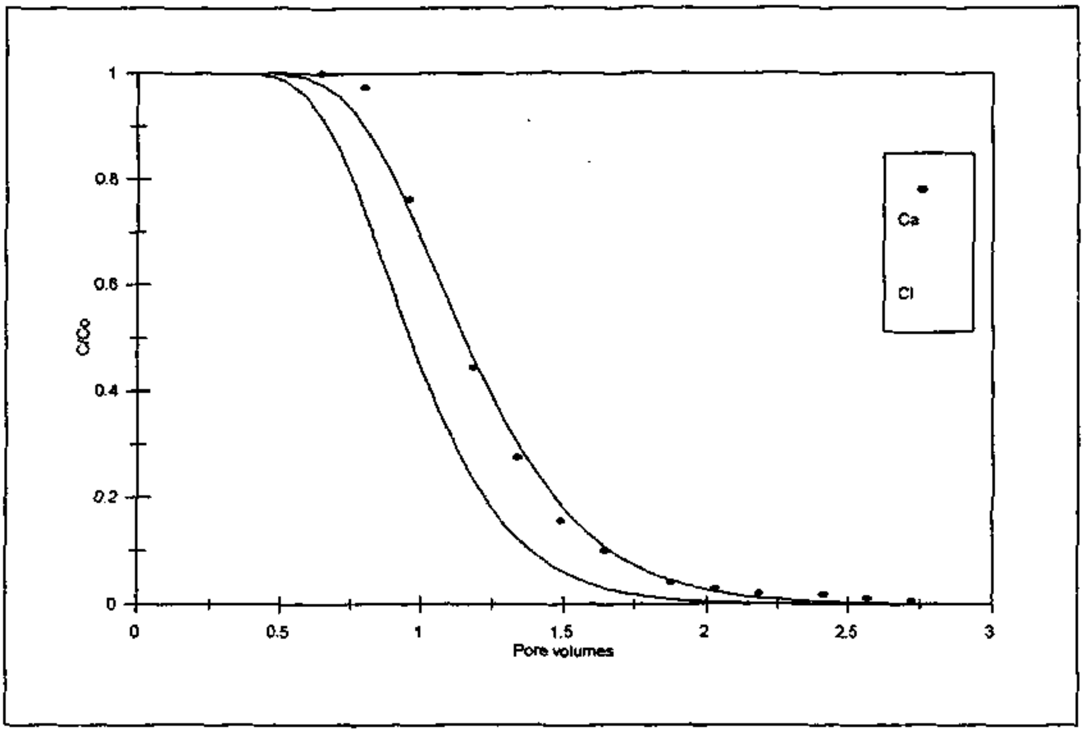


Figure 2.16. Breakthrough characteristic for distilled water injection of sample from pivot Fourth.

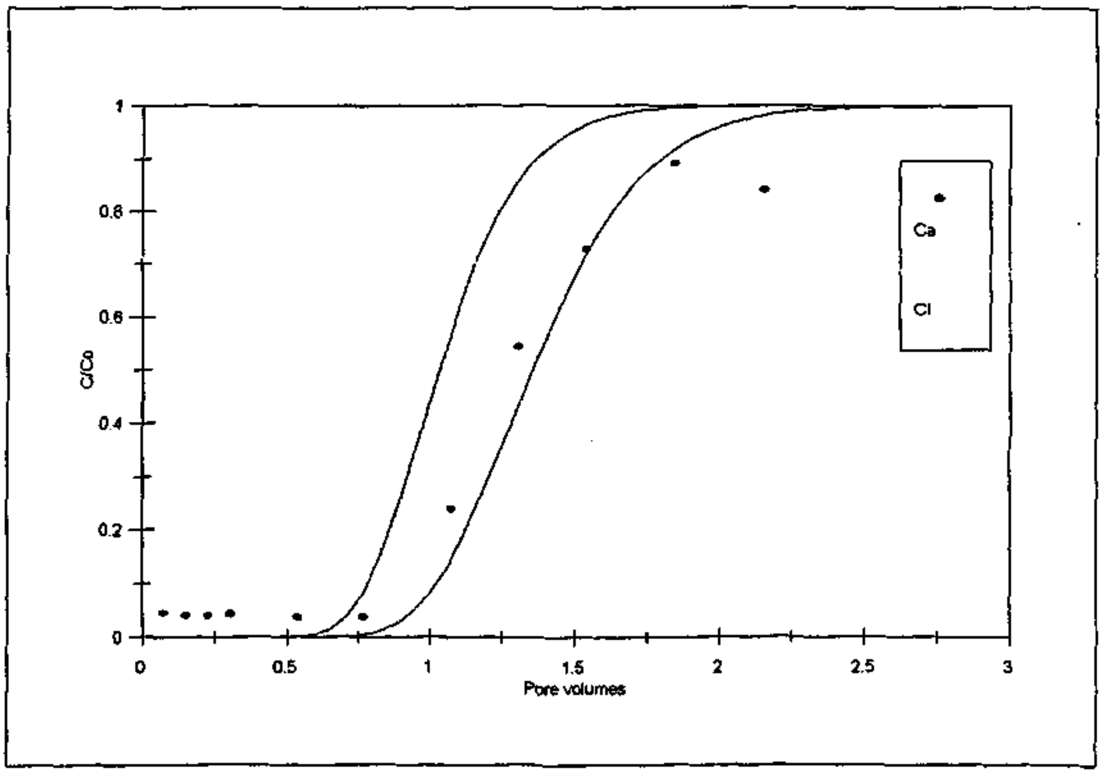


Figure 2.17. Breakthrough characteristic for $CaSO_4$ and KCl solution injection of sample from pivot Fourth.

Table 2.2. Summary of solute transport parameters.

Sample	Invading fluid	Ion	D ($mm^2 d^{-1}$)	v ($mm d^{-1}$)	R	μ (d^{-1})	γ ($mg l^{-1} d^{-1}$)
Pivot Fourth	Distilled water	Cl	4770	364	1.00	0.00	0.00
		Ca	4770	364	1.20	0.00	0.00
	$CaSO_4$ / KCl	Cl	3020	364	1.00	0.00	0.00
		Ca	3020	364	1.33	0.00	0.00
Pivot Tweefontein	Distilled water	Cl	4770	399	1.08	0.81	0.30
		Ca	2180	399	7.78	0.0001	24.3
	$CaSO_4$ / KCl	Cl	9530	399	1.14	0.00	0.00
		Ca	9530	399	1.37	0.00	0.00
Pivot Major	Distilled water	Cl	6617	364	1.00	0.00	0.00
		Ca	-	-	-	-	-
	$CaSO_4$ / KCl	Cl	-	-	-	-	-
		Ca	-	-	-	-	-

2.3.1.6. Gypsum precipitation characteristics

Four trials were performed with estimated gypsum precipitation loading of approximately 8, 30, 75 and 90 Mg ha^{-1} per 30 cm column height. A series of qualitative observations and a few quantitative estimates of the effect of the gypsum on the soil pore system were performed.

The gypsum precipitation columns were sectioned and the quantity of gypsum actually present in each trial estimated. Since this estimation required reference to a calibration of solution electrical conductivity (EC) versus mass precipitation gypsum per mass of solid material, the quantities derived are approximate and are used here for comparative purposes.

Scanning Electron Microscope (SEM) and Energy Dispersive X-ray (EDX) analyses were used to positively identify gypsum crystals in the pore system of thin sections prepared from the columns. However, these analyses were not able to quantify the volumes of pore space occupied.

Injection of mercury, using a mercury porosimeter, into the pore systems of samples from the columns revealed similar average pore sizes for samples prepared from the 8 Mg ha^{-1} and 30 Mg ha^{-1} columns. Differences between the volumes of pore space could not be discerned.

An outflow cell was used to develop liquid retention characteristics of a sample taken from the 8 Mg ha^{-1} column and another from the 30 Mg ha^{-1} column. These are shown in Figure 2.18. The data exhibited similar pore size distribution characteristics as determined for a range of undisturbed soil core samples taken from pivot Major at 0.5 m below surface. The dashed lines are the upper and lower bound of the water retention functions (Figure 2.8). The sample from the 30 Mg ha^{-1} column had a looser pore structure (lower water retention at the same matric pressure head) than that of the sample from the 8 Mg ha^{-1} column. However, the water retention in the same ranges of matric pressure head was not very different in the two columns, indicating that gypsum clogged a wide range of pore sizes.

There is no evidence, therefore, that the additional precipitated gypsum affected the water retention capacity adversely. Further research is required to confirm these findings and determine changes in pore size distribution and water retention capacity for larger amounts of gypsum precipitated in the soil.

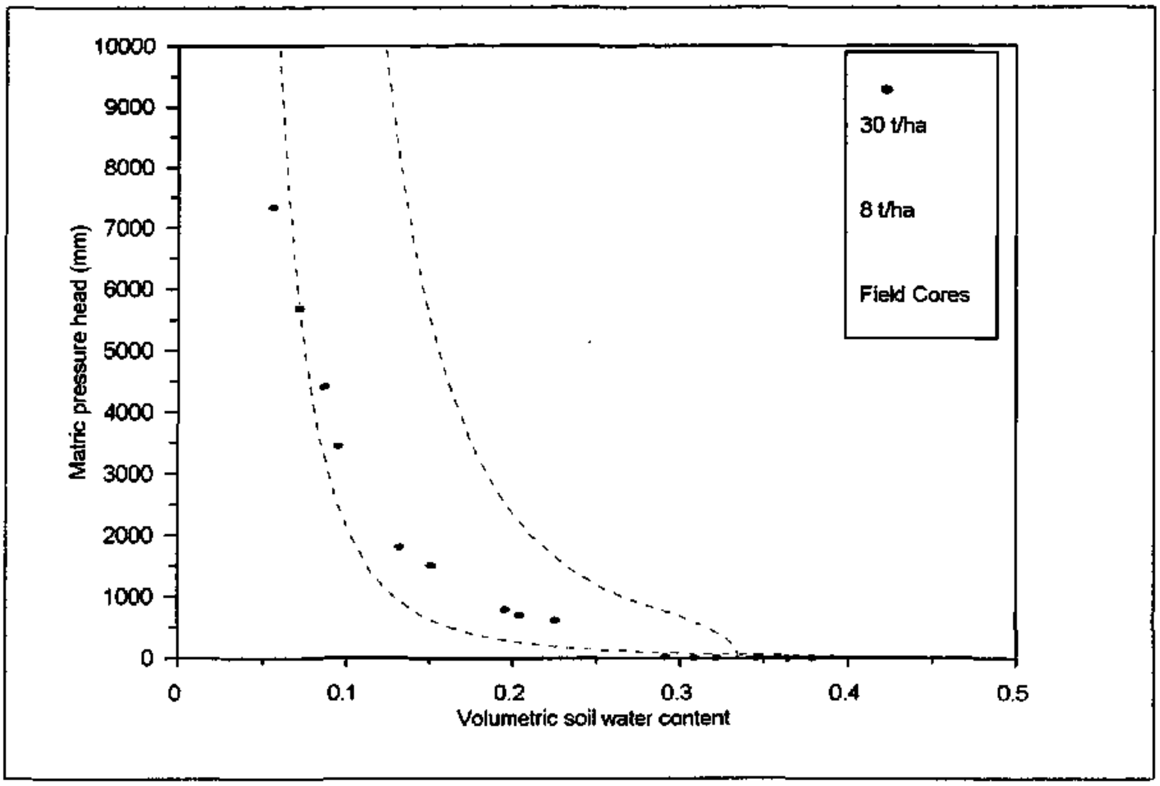


Figure 2.18. Water retention characteristics of samples from gypsum precipitation columns of 8 and 30 Mg ha^{-1}. The field cores (dashed lines) represent the upper and lower bound water retention functions (Figure 2.8).

2.3.2. Crops

2.3.2.1. Yield

Harvestable dry matter production (HDM, dried in oven at 60°C for two days) obtained for each pivot and treatment is summarized in Table 2.3. It is evident that the differentiation of water treatments was generally successful depending on seasonal rainfall. Higher yields were generally obtained with higher water applications. No symptoms of foliar injury due to sprinkler irrigation with gypsiferous water were noted for all crops.

Although comparable yield data with good quality water are not available, the yield of sugarbeans obtained under irrigation with mine water on virgin soil was comparable to yields registered in the area, and definitely higher than under dry land conditions (Table 2.3). Yields of sugarbeans on rehabilitated land were, however, low compared to virgin land, likely due to late planting dates, soil compaction, low soil pH (H_2O) and nutritional deficiencies. Pivot Jacuzzi also did not operate for a large part of the 1997/98 summer season due to mechanical and electrical problems and the crop suffered severe water stress. There was also waterlogging in certain areas of the field. Hail damage also occurred at pivot Jacuzzi during the vegetative stage of the crop in the 1997/98 season. Yield reductions were experienced due to waterlogging at pivot Tweefontein. The yield of sugarbeans on rehabilitated land was not better in the 1998/99 summer season compared to 1997/98, even after levelling works were carried out and waterways built to prevent waterlogging in certain areas of the field. Sugarbeans were, therefore, replaced by maize during the 1999/00 season.

Particular attention is therefore required in managing irrigations on rehabilitated soil profiles on top of a spoil profile. The hydraulic conductivity of the spoil layer is generally at least one order of magnitude lower than that of the overlying soil (Lorentz et al., 1999). This can prevent free percolation of water and leaching of salts, and has significant ramifications with respect to waterlogging and the lateral flow process. Ponding occurred during the rainy summer season, probably due to subsurface drainage from higher areas. A spatial variability study and a two-dimensional model are recommended to accurately predict crop growth and water use, as well as the water and salt balance under such conditions. In the rehabilitation process, the spoil material should be packed on a slight slope to minimize lateral flow accumulation, if rehabilitated land is to be used for crop production under irrigation. Spoil slumping over time is likely to remain problematic.

Excellent yields of wheat were obtained on both virgin and rehabilitated land (Table 2.3). Wheat is reportedly more tolerant to soil salinity than beans (Maas, 1986). The yield of the short-season cultivar of maize was also good on virgin land (1998/99 season).

The maize crops were damaged in the beginning of the 1999/00 season, 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 yield losses (Table 2.3). The expected yields were between 6 and 10 Mg ha^{-1} for the short-season cultivar. It was therefore decided to investigate the effect of mine water on herbicide activity. The results are presented in Section 2.4.2. of this report. The high rainfall experienced during the cropping season also affected the crops by causing some waterlogging and flooding in the pivot areas. This was particularly evident at Tweefontein pivot (rehabilitated ground), but also occurred at pivot Major. This resulted in areas of poor yield and localized flooding with associated crop death. The maize hybrid used in the short cropping season was chosen for the BT-gene, which is supposed to limit insect damage. However, it appears that this hybrid is very susceptible to Northern Leaf Blight (rust). This proved to be the case and extensive rust was noted on the crops near the end of the season. A neighbouring farmer planted the same hybrid early in the season, which served as a source of infection for the pivots with the Northern Leaf Blight. This was also a reason for the reduced yield obtained. Fungicide applications were required to control the spread of the Northern Leaf Blight within the pivots.

In October 2000, a hail storm completely wiped out the wheat crops at pivots Fourth and Tweefontein. The estimated loss in crop at pivot Major was 40%. The hail storm occurred during the grain filling stage of wheat. The potential yield at all three pivots was 8 Mg ha^{-1}.

In conclusion, commercial production of crops under irrigation with gypsiferous mine water is feasible. Higher yields can be achieved with higher mine water applications, in particular compared to dry land cropping. The major problem experienced was waterlogging in certain areas of rehabilitated land, especially during the summer months, when control over the soil water regime is difficult due to rainfall. This problem is related to the physical nature of rehabilitated land, where levelling of the spoil material and overlying soil is essential due to the low hydraulic conductivity of the spoil layer. The problem is not related to the chemistry of the water used for irrigation.

Table 2.3. Measured yield for each crop, pivot and treatment.

Season	Pivot	Crop	Yield (Mg ha^{-1})			
			Leaching fraction treatment	Field capacity treatment	Deficit irrigation treatment	Dry land treatment
Summer 1997/98	Major	Sugarbeans (pods)	3.23 ± 0.24	3.03 ± 0.31	2.61 ± 0.25	1.12 ± 0.10
	Tweefontein	Sugarbeans (pods)	1.26 ± 0.48	1.14 ± 0.33	1.12 ± 0.17	-
	Jacuzzi	Sugarbeans (pods)	1.37 ± 0.32	0.58 ± 0.15	0.55 ± 0.20	-
Winter 1998	Major	Wheat (ears)	5.04 ± 0.21	5.28 ± 0.62	4.43 ± 0.40	-
	Tweefontein	Wheat (ears)	4.98 ± 0.12	5.14 ± 0.32	3.75 ± 0.49	-
	Jacuzzi	Wheat (ears)	5.17 ± 0.06	4.11 ± 0.55	3.92 ± 0.13	-
Summer 1998/99	Major	Maize (cobs)	7.83 ± 1.66	7.17 ± 0.43	3.77 ± 0.50	-
	Tweefontein	Sugarbeans (pods)	1.37	1.09	1.05	-
	Jacuzzi	Sugarbeans (pods)	1.23	0.77	0.53	-
Winter 1999	Major	Wheat (ears)	6.40 ± 1.12	6.19 ± 1.05	4.70 ± 0.35	-
	Fourth	Wheat (ears)	6.73 ± 0.13 (repl. 1) 8.08 ± 0.71 (repl. 2)	6.51 ± 2.05 (repl. 1) 6.45 ± 0.94 (repl. 2)	5.51 ± 1.57 (repl. 1) 6.35 ± 0.63 (repl. 2)	-
	Tweefontein	Wheat (ears)	-	6.34 ± 0.67	-	-
Summer 1999/00	Major	Maize (grain)	4.04 ± 0.39	4.22 ± 0.96	4.14 ± 0.47	-
	Fourth	Maize (grain)	3.76 ± 0.14 (repl. 1) 2.81 ± 0.24 (repl. 2)	3.49 ± 0.67 (repl. 1) 2.26 ± 0.28 (repl. 2)	3.85 ± 0.29 (repl. 1) 3.05 ± 0.50 (repl. 2)	-
	Tweefontein	Maize (grain)	-	3.51 ± 0.74	-	-
Winter 2000	Major	Wheat (grain)	3.52 ± 0.37	4.29 ± 0.45	3.09 ± 0.16	-
	Fourth	Wheat (grain)	Total loss to hail	Total loss to hail	Total loss to hail	-
	Tweefontein	Wheat (grain)	Total loss to hail	Total loss to hail	Total loss to hail	-

2.3.2.2. Plant nutrition

Chemical analyses of plant material were carried out in order to indicate possible nutrient deficiencies during the growth of the crops, and correct these deficiencies through fertilization. This was done on wheat, lucerne, sugarbeans and maize. The complete results of analyses of plant material are presented in Tables A9 to A15 (Appendix A). In these tables, normal ranges for each analysis are also reported.

In 1998, the N contents of wheat were normal at the early stage. They became fairly high 70 to 80 days after planting and were normal again towards the end of the growing season. K contents on most samples were on the lower end of the normal range and were low towards the end of the growing season on pivots Jacuzzi and Major. The remaining analyses of wheat plant material were normal. In September 1998, the P contents of lucerne were low and the K contents were very low. The remaining analyses were normal.

In February 1999, the plant analysis values for sugarbeans were generally normal. Stunted growth was, however, observed at pivot Jacuzzi and this could be due too a low P content. Chlorotic symptoms were also observed at pivot Jacuzzi and could be due to low N content. This can be possibly due to the poor drainage at pivot Jacuzzi.

In 2000, the N and P contents during the early growth stages (tillering) of wheat were low at pivot Major. At later stages, these values were in the adequate range. The K content was higher than normal throughout the different growth stages. S was also higher than normal. The remaining analyses were normal.

At pivot Tweefontein, N was low during the tillering stage of wheat (winter 2000 season), but became normal to high at the latter growth stages. K and S were higher than normal. The contents of Fe, Mn and Zn were higher than normal and this could be due to wet conditions caused by periodic waterlogging.

At pivot Fourth, the N contents of wheat (winter 2000 season) were on the low side throughout the growing season. K was high and became very high towards the later stages of the growing season. S was also high. The remaining analyses were normal.

In conclusion, specific fertilization and monitoring of the nutrient status of the crop is required under irrigation with gypsiferous mine water. Waterlogging should be avoided because of the negative effect not only on the plants due to high concentrations of SO_4 and Ca as well as Fe, Mn and Zn in the soil solution, but also on gypsum precipitation. Further, the possibility that other sulphate minerals can precipitate (or might have) must be investigated.

2.3.3. Soils

2.3.3.1. Chemical properties

In this Section of the report, the general trends of soil chemical properties are reported in graphical format based on chemical analyses carried out at regular intervals on soil samples collected in the field. The complete results of soil chemical analyses are reported in Appendix A (Tables A16 to A39 in chronological order). Due to dry soil profiles, it was generally not possible to extract enough soil water with the ceramic cups for chemical analysis at the deficit strategy intensive monitoring stations. For this reason, soil samples were taken in the deficit treatments on 19/10/1998 for analysis (Table A25, Appendix A). In Tables A16 to A39 (Appendix A), the cation exchange capacity was calculated as the sum of exchangeable Ca^{2+}, K^+, Mg^{2+} and Na^+. The charge balances are also reported in the right column of each Table. The positive sign of the charge balance indicates excess of cations.

These differences could be due to the presence of other ions in solution that were not analysed.

The values of soil pH(H_2O) generally showed a slight tendency to increase during the course of the trial at all pivots (Figures 2.19 to 2.22). The electrical conductivity and the soluble ions in the saturated soil extract fluctuated depending on seasonal rainfall as well as on the irrigation and rainfall events prior to soil sampling. They did not, however, reach levels deleterious to the plants as the main ions in the soil solution precipitated in the form of $CaSO_4$ and due to the dilution effect of rainfall. The general tendencies are shown in the examples in Figures 2.23 to 2.37 for pivot Major, which was irrigated throughout the duration of the field trial. The electrical conductivity and soluble Ca^{2+}, Mg^{2+} and SO_4^{2-} generally showed a tendency to increase with time at all four pivot sites, due to the relatively high concentrations of these ions in irrigation water. The values of soluble K^+ did not show any particular trend and they were lower by one order of magnitude than the other cations (Figures 2.32 to 2.34), as the irrigation water has a low K^+ concentration.

Exchangeable Ca^{2+} and Mg^{2+} increased with time, whilst K^+ decreased at all four pivot sites. Examples are shown for exchangeable Ca^{2+} and K^+ at pivot Major (Figures 2.38 to 2.43). This indicates that Ca^{2+} and, to a certain extent Mg^{2+}, replace K^+ on the cation exchange complex. If loss of K^+ through leaching causes nutrient deficiencies to the crop, corrective fertilization should be applied as symptoms appear. Field monitoring of crop nutrient status is therefore essential at this stage of the research. Very low values of exchangeable Na^+ were measured during the course of the trial. The cation exchange capacity, calculated as the sum of adsorbed Ca^{2+}, Mg^{2+}, Na^+ and K^+, showed a slight tendency to increase during the course of the trial. An example is shown for pivot Major and three irrigation treatments in Figures 2.44 to 2.46.

Deep soil sampling was carried out before the beginning of the winter 2000 season (June 2000). This was done in order to explore whether any salt breakthrough originating from irrigation could be identified deeper in the soil profile. Replicate sub-samples were analysed by both the Department of Geology (University of Cape Town) and the Soil Science Laboratory at the University of Pretoria for double-checking purposes. Some of the results of the analyses carried out at the University of Pretoria are summarized in Figures 2.47 to 2.58. It is clear that, at pivot Major, most soluble salts were confined to the upper 1 m, probably due to the presence of the plinthic layer at 1.1 m limiting free drainage. At pivot Fourth, there was a more uniform distribution of salts in the soil profile, with a slight peak between 1.5 and 2 m down in the profile indicating leaching of salts below the root-zone. The deep soil sampling at pivot Tweefontein included a sample in the spoil material (deepest data points in Figures 2.49, 2.52, 2.55 and 2.58). The detailed analysis results obtained at the University of Pretoria, can be found in Tables A34 to A36 (Appendix A). The detailed analyses of deep soil samples carried out at the University of Cape Town are presented in Appendix I. Similar trends in the results of the analyses were observed in both laboratories.

Chemical analyses of soil water extracted with ceramic cup soil water samplers are shown in Tables A40 to A49 (Appendix A). The results of the analyses confirmed that soil salinity is a very dynamic property as it depends on many factors, mainly rainfall, irrigation amounts and quality, and evapotranspiration. The data generally indicated higher soil salinity in the topsoil layers (ceramic cups placed at 0.4 m soil depth) compared to deeper layers (ceramic cups placed at 1.0 and 1.4 m soil depth). This proves that salt, in particular gypsum, accumulates and precipitates where the rooting system is most dense. During the 1999/00 summer season, high salinity was recorded at pivot Fourth at 1.0 m, particularly in the deficit irrigation treatment (Table A48, Appendix A). This was due to salt leaching caused by heavy rainfall.

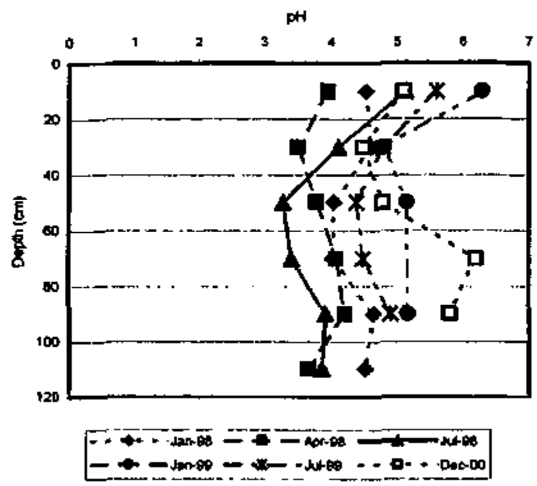


Figure 2.19. Soil pH(H_2O) at pivot Major (field capacity treatment) taken at seasonal intervals as a function of depth (cm).

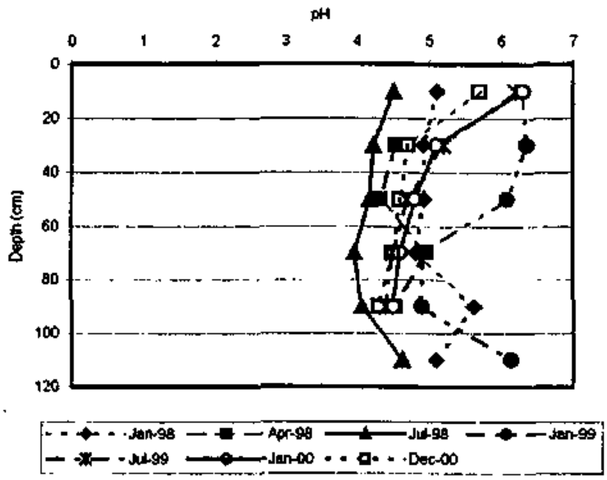


Figure 2.20. Soil pH(H_2O) at pivot Tweefontein (field capacity treatment) taken at seasonal intervals as a function of depth (cm).

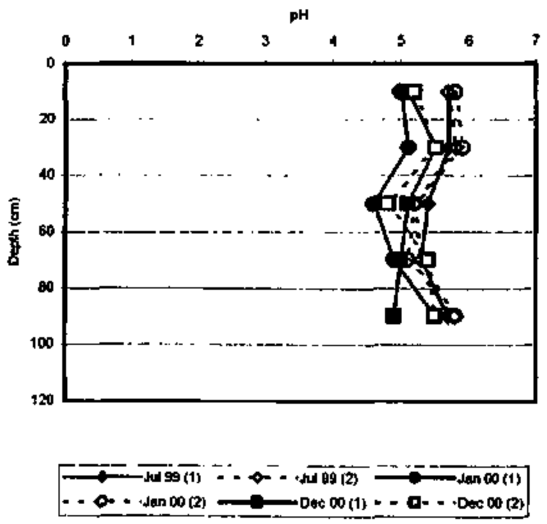


Figure 2.21. Soil pH(H_2O) at pivot Fourth (field capacity treatment) taken at seasonal intervals as a function of depth (cm).

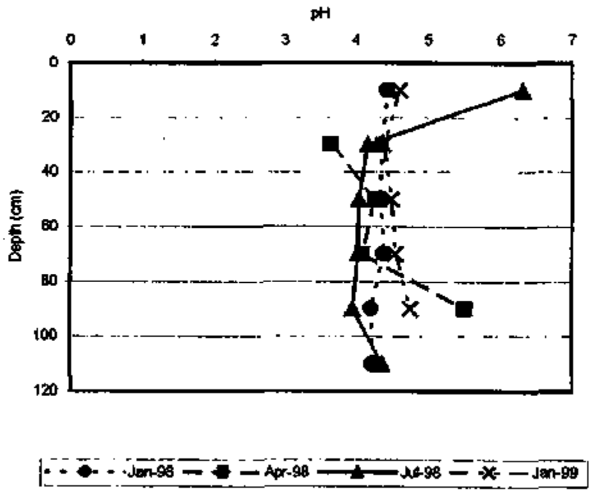


Figure 2.22. Soil pH(H_2O) at pivot Jacuzzi (field capacity treatment) taken at seasonal intervals as a function of depth (cm).

The graphs above indicate that pH(H_2O) had a slight tendency to increase during the trial due to irrigation with gypsiferous mine water. There is therefore potential to increase the pH(H_2O) of acidic soils through irrigation with water rich in gypsum.

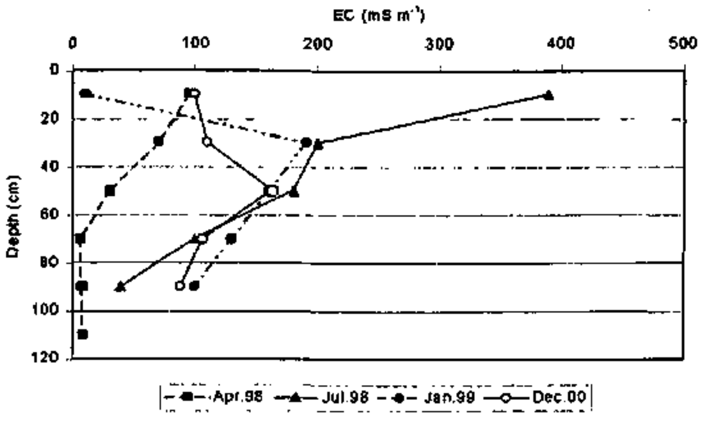


Figure 2.23. Electrical conductivity (mS m^{-1}) of the saturated soil extract at pivot Major (leaching fraction treatment) taken at seasonal intervals as a function of depth (cm).

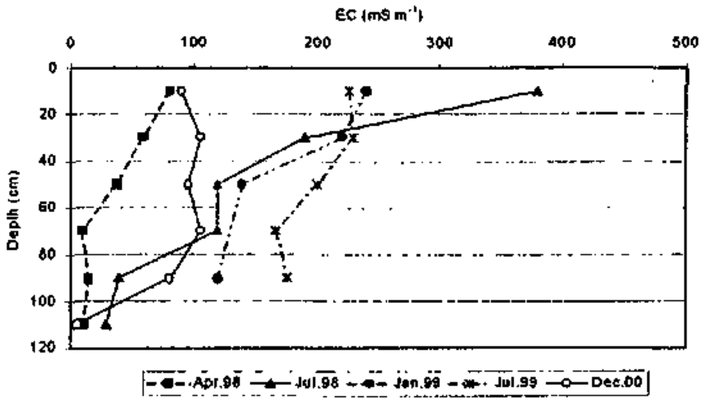


Figure 2.24. Electrical conductivity (mS m^{-1}) of the saturated soil extract at pivot Major (field capacity treatment) taken at seasonal intervals as a function of depth (cm).

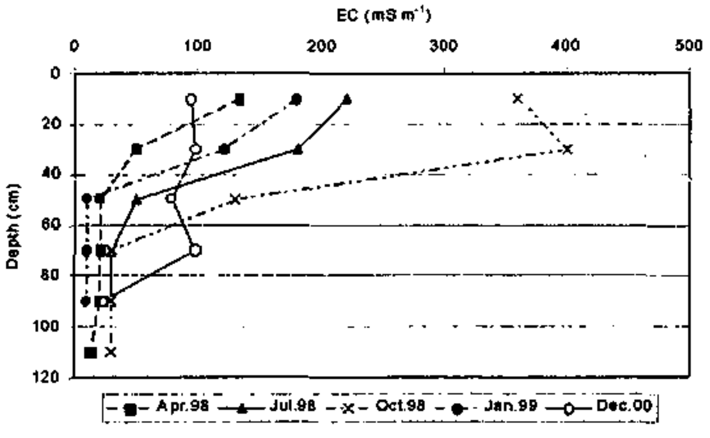


Figure 2.25. Electrical conductivity (mS m^{-1}) of the saturated soil extract at pivot Major (deficit treatment) taken at seasonal intervals as a function of depth (cm).

The electrical conductivity of the saturated soil extract increased compared to the beginning of the trial due to irrigation with saline water. The salinity levels, however, were not deleterious to the plants because gypsum is not highly soluble and precipitated in the soil profile. The values of electrical conductivity fluctuated depending on seasonal rainfall. For example, a decrease in electrical conductivity was observed in December 2000 due to heavy rainfall. During this period, portion of the salts was possibly leached from the soil profiles were measurements were taken, or removed through lateral flow of water above the plinthic layer.

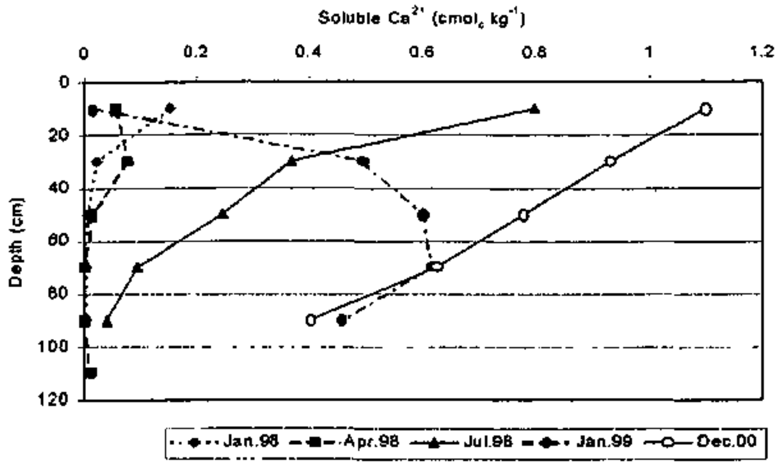


Figure 2.26. Soluble calcium content (cmol$_c$ kg^{-1}) of the saturated soil extract at pivot Major (leaching fraction treatment) taken at seasonal intervals as a function of depth (cm).

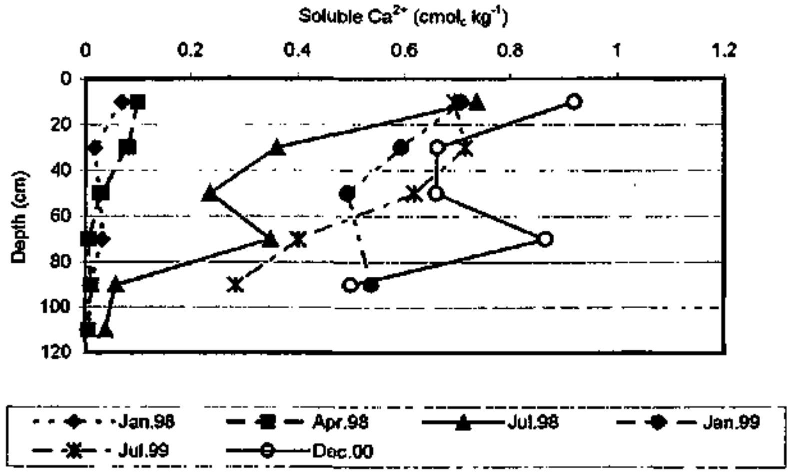


Figure 2.27. Soluble calcium content (cmol$_c$ kg^{-1}) of the saturated soil extract at pivot Major (field capacity treatment) taken at seasonal intervals as a function of depth (cm).

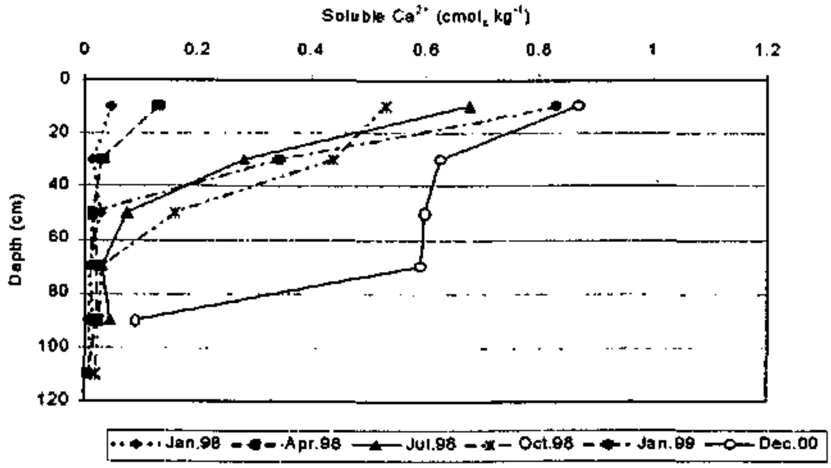


Figure 2.28. Soluble calcium content (cmol$_c$ kg^{-1}) of the saturated soil extract at pivot Major (deficit treatment) taken at seasonal intervals as a function of depth (cm).

Soluble Ca^{2+} increased compared to the beginning of the trial due to the high concentration of Ca^{2+} in mine water used for irrigation. The values of soluble Ca^{2+} fluctuated depending on seasonal rainfall.

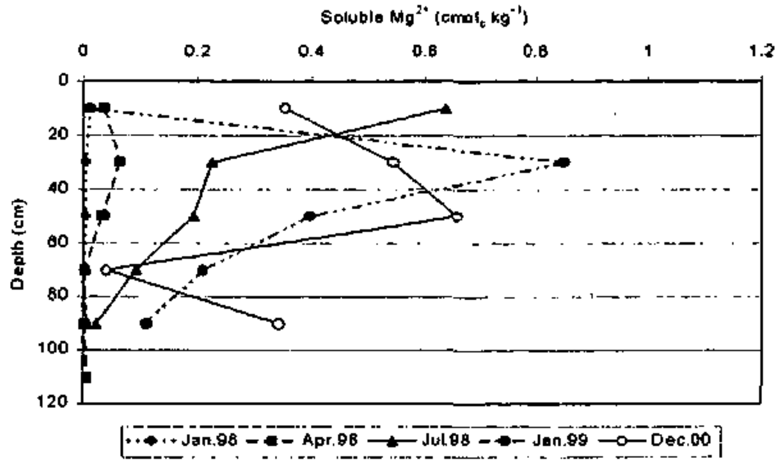


Figure 2.29. Soluble magnesium content (cmol$_c$ kg^{-1}) of the saturated soil extract at pivot Major (leaching fraction treatment) taken at seasonal intervals as a function of depth (cm).

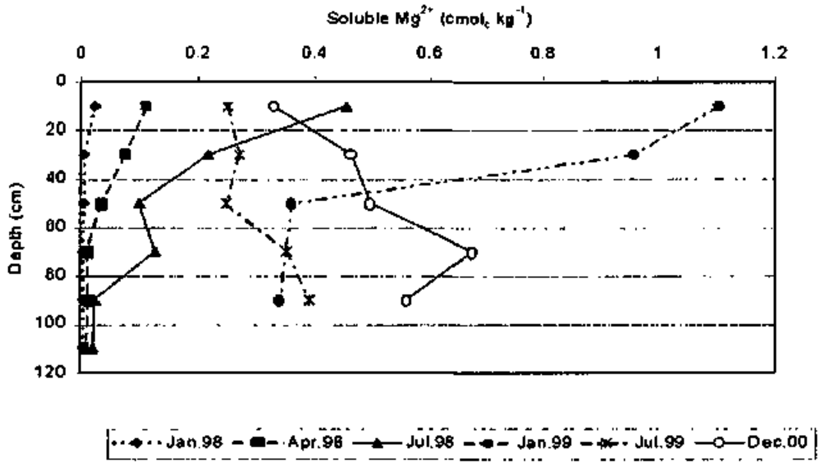


Figure 2.30. Soluble magnesium content (cmol$_c$ kg^{-1}) of the saturated soil extract at pivot Major (field capacity treatment) taken at seasonal intervals as a function of depth (cm).

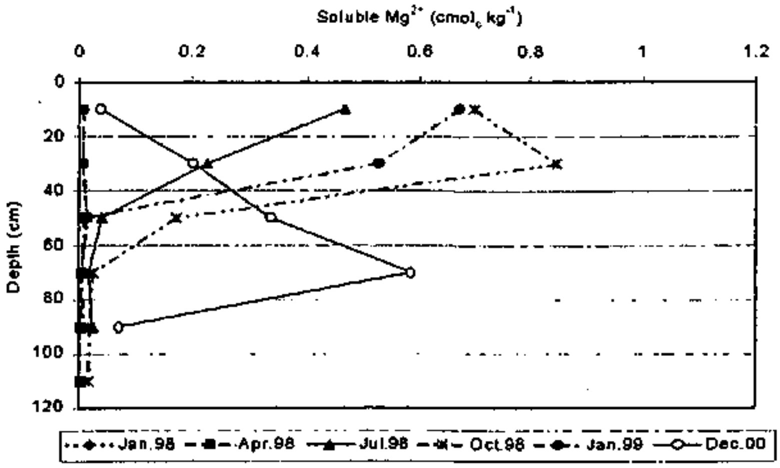


Figure 2.31. Soluble magnesium content (cmol$_c$ kg^{-1}) of the saturated soil extract at pivot Major (deficit treatment) taken at seasonal intervals as a function of depth (cm).

Soluble Mg^{2+} increased compared to the beginning of the trial due to the relatively high concentration of Mg^{2+} in mine water used for irrigation. The values of soluble Mg^{2+} fluctuated depending on seasonal rainfall. It is also interesting to note that soluble Mg^{2+} decreased in the topsoil layers in December 2000 due to heavy rainfall. This was not the case with soluble Ca^{2+} (Figures 2.26 to 2.28), indicating that Mg^{2+} moves through the soil profile and gets leached quicker than Ca^{2+}, which tends to precipitate in the form of gypsum.

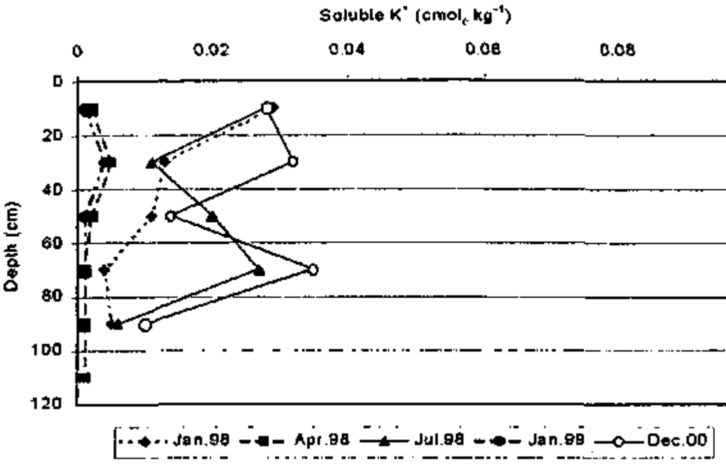


Figure 2.32. Soluble potassium content (cmol$_c$ kg^{-1}) of the saturated soil extract at pivot Major (leaching fraction treatment) taken at seasonal intervals as a function of depth (cm).

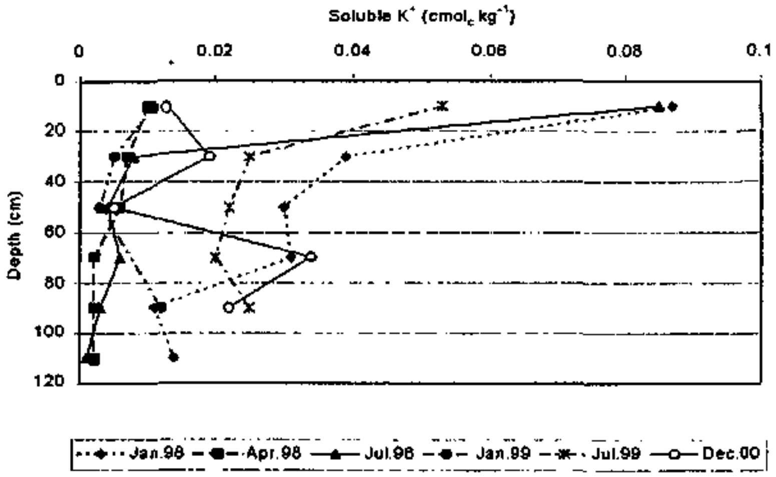


Figure 2.33. Soluble potassium content (cmol$_c$ kg^{-1}) of the saturated soil extract at pivot Major (field capacity treatment) taken at seasonal intervals as a function of depth (cm).

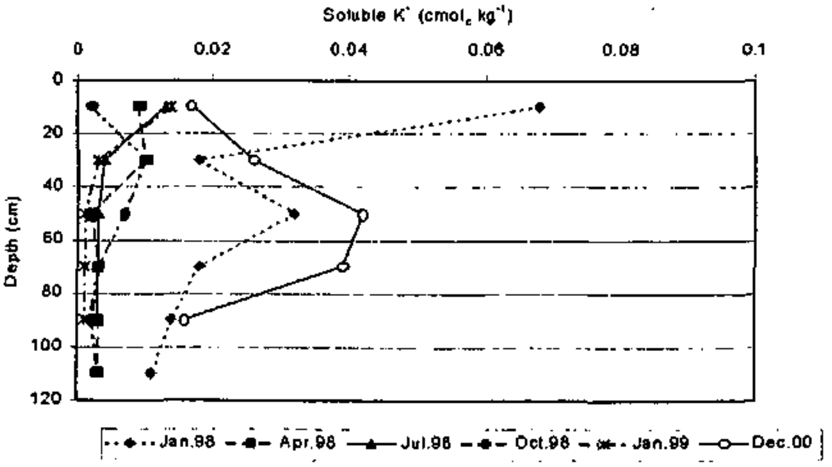


Figure 2.34. Soluble potassium content (cmol$_c$ kg^{-1}) of the saturated soil extract at pivot Major (deficit treatment) taken at seasonal intervals as a function of depth (cm).

Soluble K^+ did not show any particular trend during the trial. The values of soluble K^+ fluctuated depending on seasonal rainfall. They were lower by one order of magnitude compared to soluble Ca^{2+} and Mg^{2+} due to the low concentration of K^+ in mine water used for irrigation.

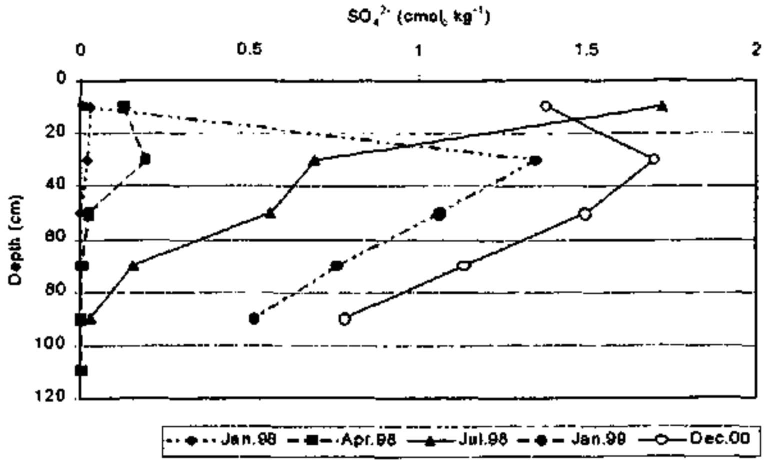


Figure 2.35. Sulphate content (cmol$_c$ kg^{-1}) of the saturated soil extract at pivot Major (leaching fraction treatment) taken at seasonal intervals as a function of depth (cm).

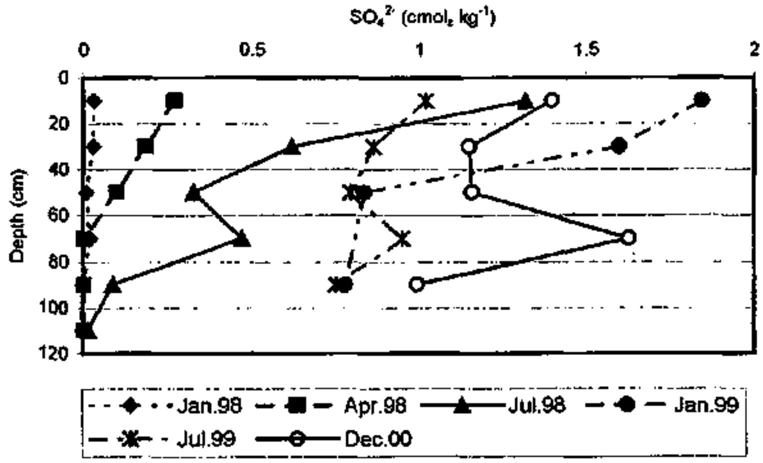


Figure 2.36. Sulphate content (cmol$_c$ kg^{-1}) of the saturated soil extract at pivot Major (field capacity treatment) taken at seasonal intervals as a function of depth (cm).

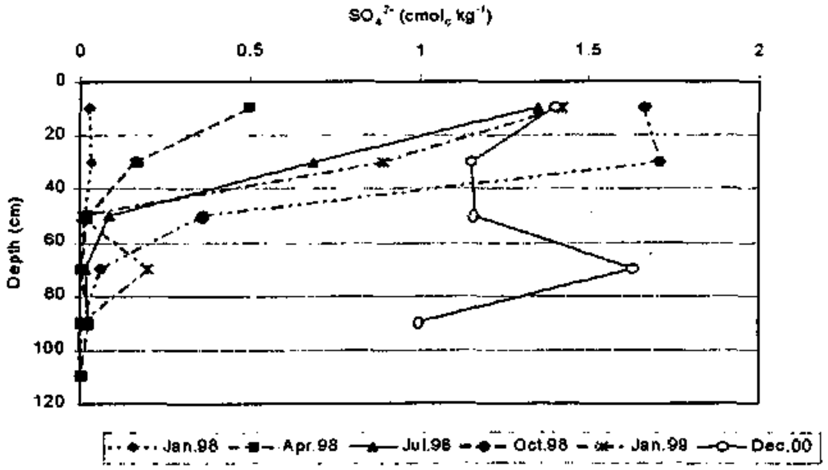


Figure 2.37. Sulphate content (cmol$_c$ kg^{-1}) of the saturated soil extract at pivot Major (deficit treatment) taken at seasonal intervals as a function of depth (cm).

Soluble SO_4^{2-} increased compared to the beginning of the trial due to the high concentration of SO_4^{2-} in mine water used for irrigation. The values of soluble SO_4^{2-} fluctuated depending on seasonal rainfall.

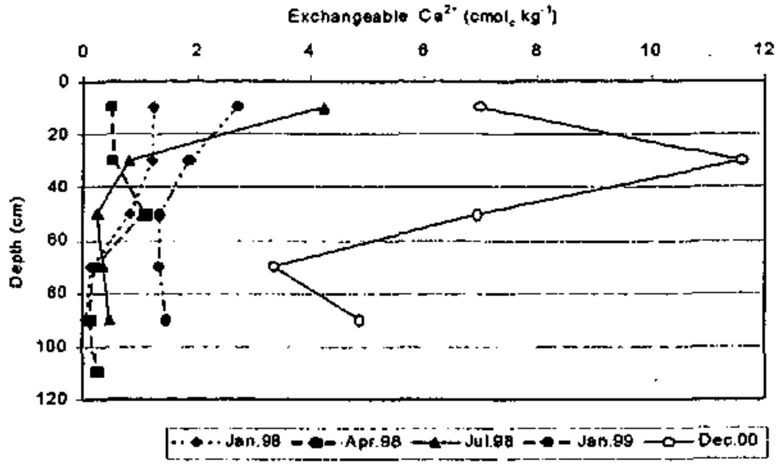


Figure 2.38. Exchangeable calcium content (cmol$_c$ kg^{-1}) of the saturated soil extract at pivot Major (leaching fraction treatment) taken at seasonal intervals as a function of depth (cm).

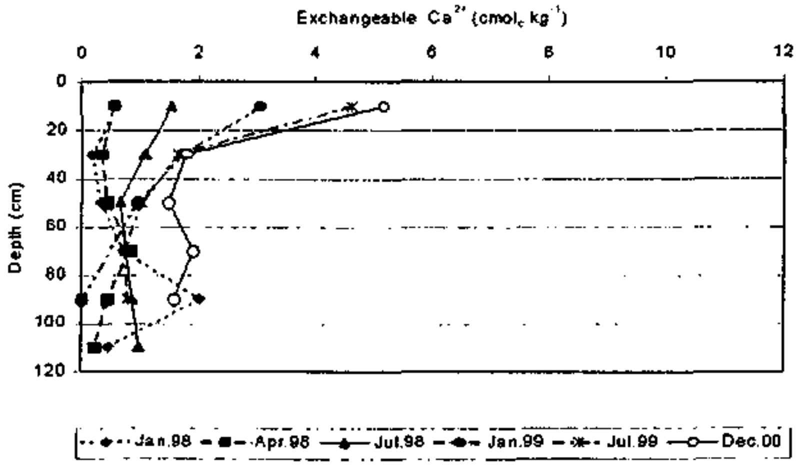


Figure 2.39. Exchangeable calcium content (cmol$_c$ kg^{-1}) of the saturated soil extract at pivot Major (field capacity treatment) taken at seasonal intervals as a function of depth (cm).

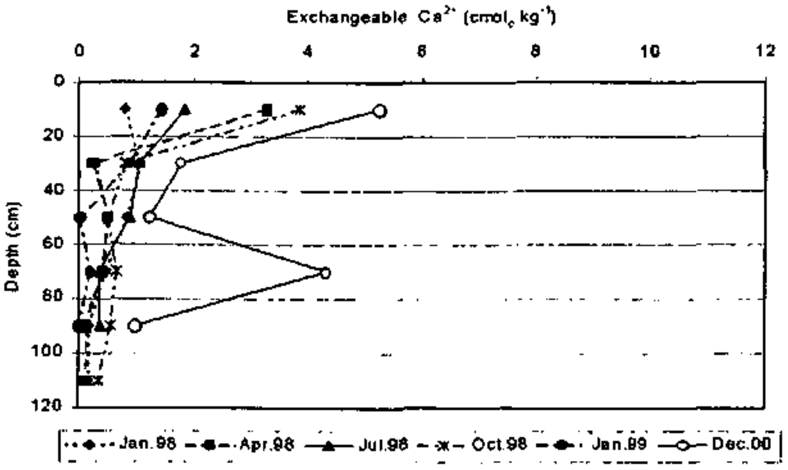


Figure 2.40. Exchangeable calcium content (cmol$_c$ kg^{-1}) of the saturated soil extract at pivot Major (deficit treatment) taken at seasonal intervals as a function of depth (cm).

Exchangeable Ca^{2+} increased compared to the beginning of the trial indicating that Ca^{2+} became the dominant cation on the soil exchangeable complex. This was due to the high concentration of Ca^{2+} in mine water used for irrigation.

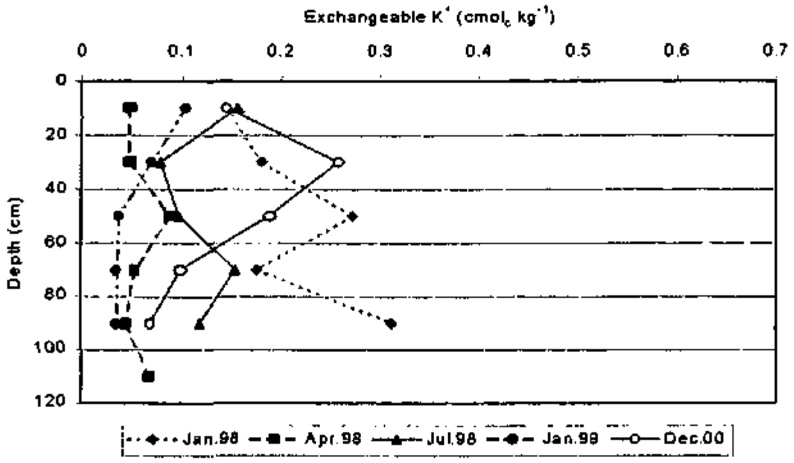


Figure 2.41. Exchangeable potassium content (cmol$_c$ kg^{-1}) of the saturated soil extract at pivot Major (leaching fraction treatment) taken at seasonal intervals as a function of depth (cm).

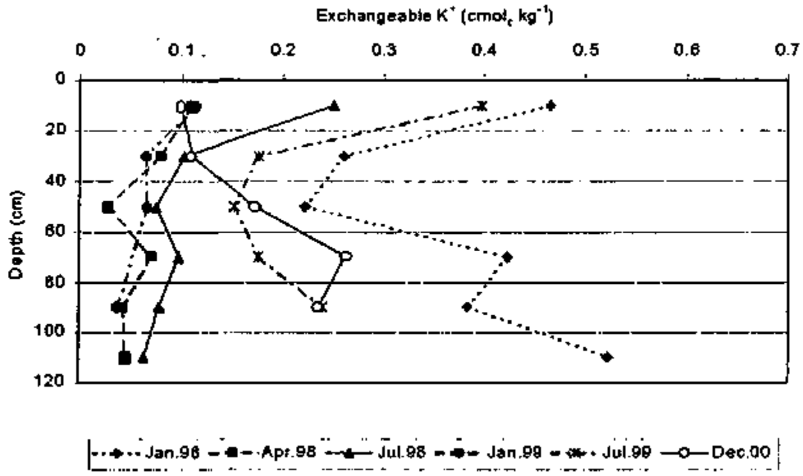


Figure 2.42. Exchangeable potassium content (cmol$_c$ kg^{-1}) of the saturated soil extract at pivot Major (field capacity treatment) taken at seasonal intervals as a function of depth (cm).

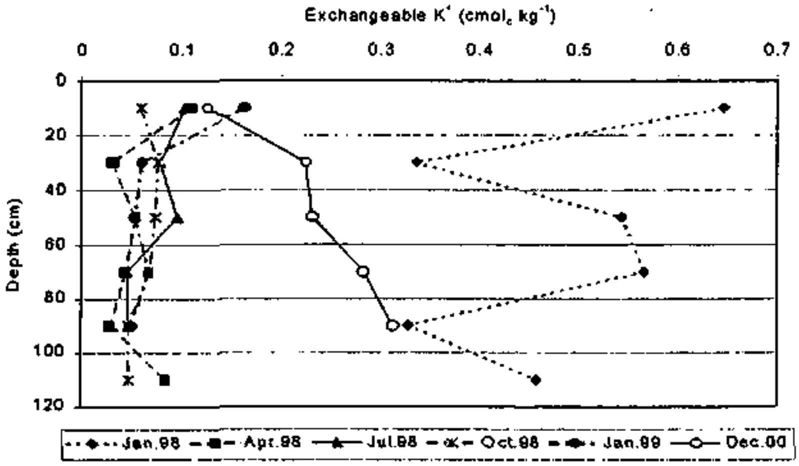


Figure 2.43. Exchangeable potassium content (cmol$_c$ kg^{-1}) of the saturated soil extract at pivot Major (deficit treatment) taken at seasonal intervals as a function of depth (cm).

Exchangeable K^+ decreased compared to the beginning of the trial indicating that K^+ was displaced, mainly by Ca^{2+}, on the soil exchangeable complex. This was due to the high concentration of Ca^{2+} and low concentration of K^+ in mine water used for irrigation. As K^+ is not retained by the soil adsorptive complex, there is a potential risk of K^+ leaching and the nutrient status of the plants should be monitored and corrected through fertilization.

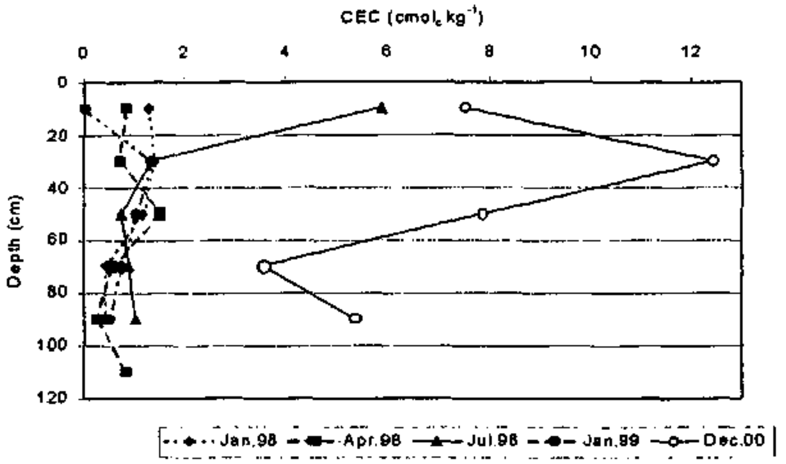


Figure 2.44. Calculated CEC (cmol$_c$ kg^{-1}) at pivot Major (leaching fraction treatment) taken at seasonal intervals as a function of depth (cm).

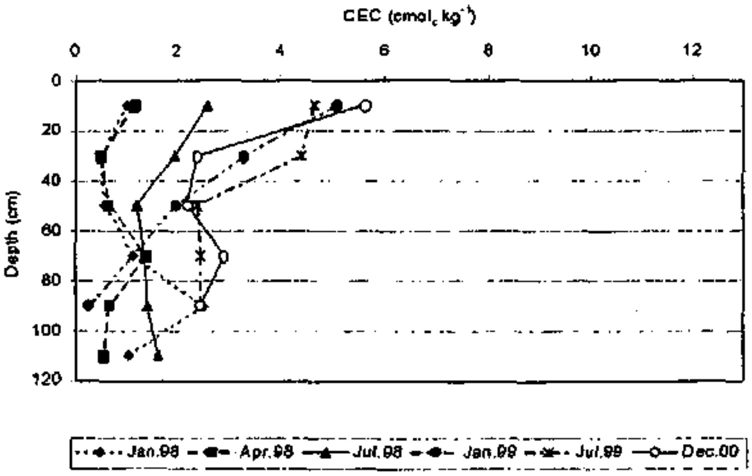


Figure 2.45. Calculated CEC (cmol$_c$ kg^{-1}) at pivot Major (field capacity treatment) taken at seasonal intervals as a function of depth (cm).

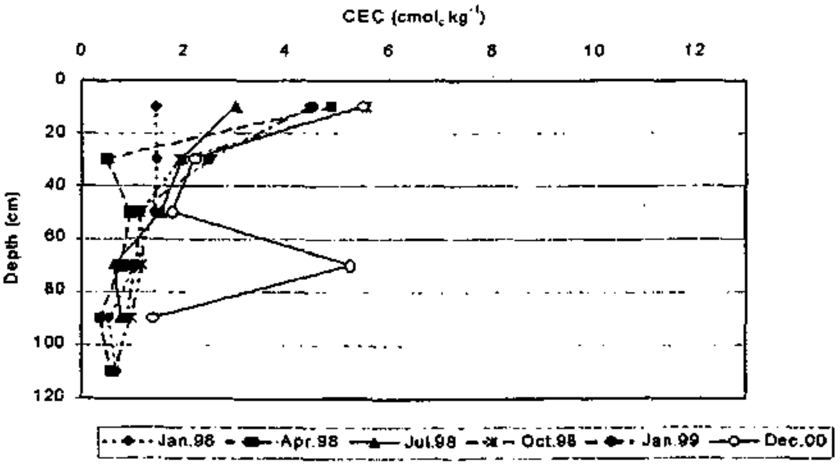


Figure 2.46. Calculated CEC (cmol$_c$ kg^{-1}) at pivot Major (deficit treatment) taken at seasonal intervals as a function of depth (cm).

Soil cation exchange capacity (CEC), calculated as the sum of adsorbed cations, showed a slight tendency to increase during the trial. This measurement is, however, susceptible to errors (e.g. dissolution of gypsum during the soil sample preparation). Methods should, therefore, be investigated and adapted for measurement of CEC in gypsiferous soils to confirm these findings.

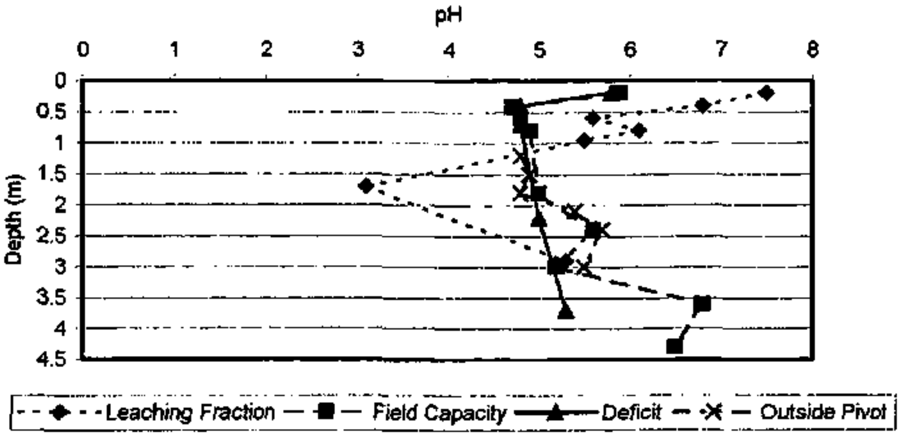


Figure 2.47. Soil pH(H_2O) at pivot Major as a function of depth (m) in June 2000.

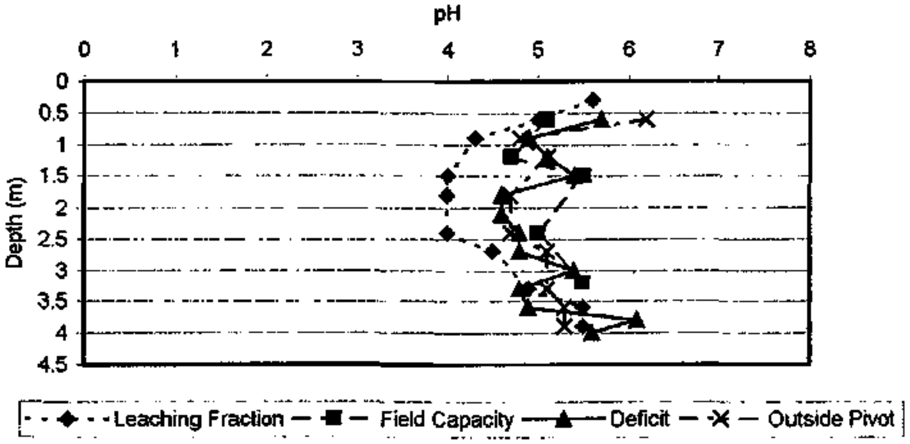


Figure 2.48. Soil pH(H_2O) at pivot Fourth as a function of depth (m) in June 2000.

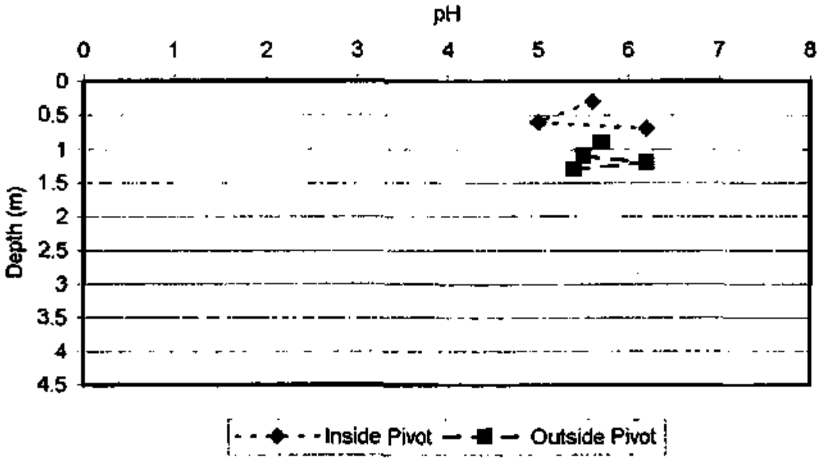


Figure 2.49. Soil pH(H_2O) at pivot Tweefontein as a function of depth (m) in June 2000.

Soil pH(H_2O) was generally higher in the root-zone compared to deeper layers due to irrigations with mine water. It was difficult to indicate any differences in pH(H_2O) between the irrigated and non-irrigated profiles.

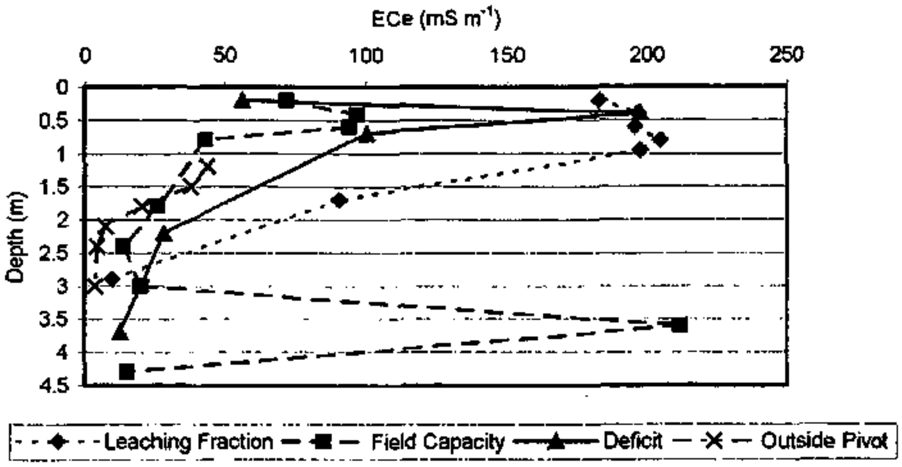


Figure 2.50. Electrical conductivity (mS m^{-1}) of the saturated soil extract at pivot Major as a function of depth (m) in June 2000.

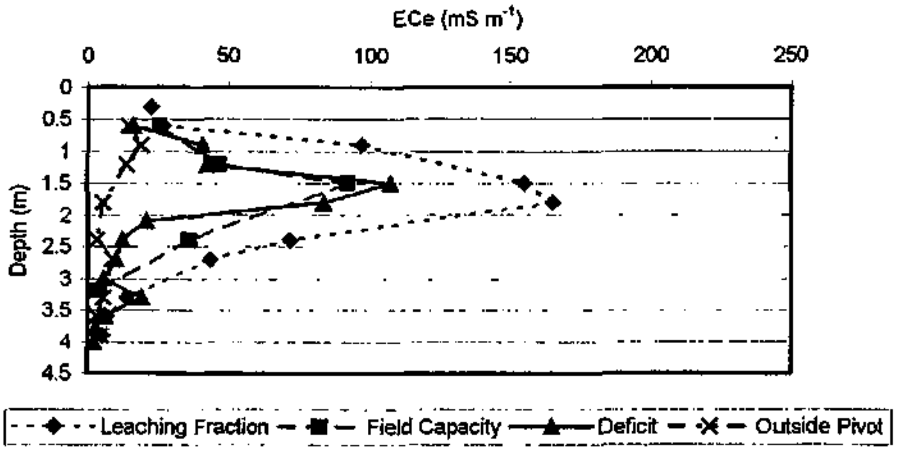


Figure 2.51. Electrical conductivity (mS m^{-1}) of the saturated soil extract at pivot Fourth as a function of depth (m) in June 2000.

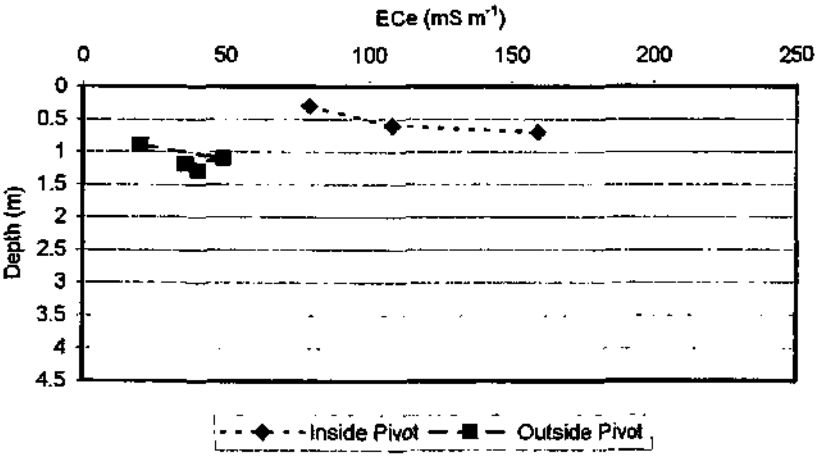


Figure 2.52. Electrical conductivity (mS m^{-1}) of the saturated soil extract at pivot Tweefontein as a function of depth (m) in June 2000.

At pivots Major and Tweefontein, electrical conductivities of the saturated soil extracts were higher in the topsoil layers, where salts were mainly confined due to the plinthic and spoil layer limiting drainage and leaching. At pivot Fourth, electrical conductivity had a peak between 1.5 and 2 m indicating leaching of salts below the root-zone.

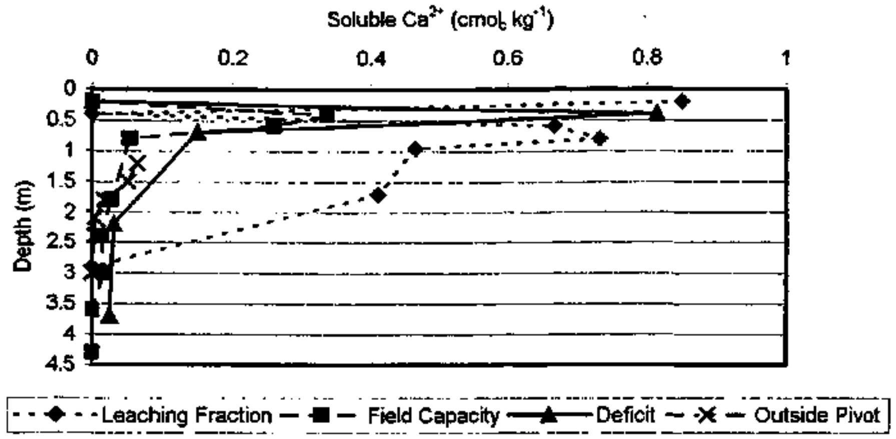


Figure 2.53. Soluble calcium content (cmol$_c$ kg^{-1}) of the saturated soil extract at pivot Major as a function of depth (m) in June 2000.

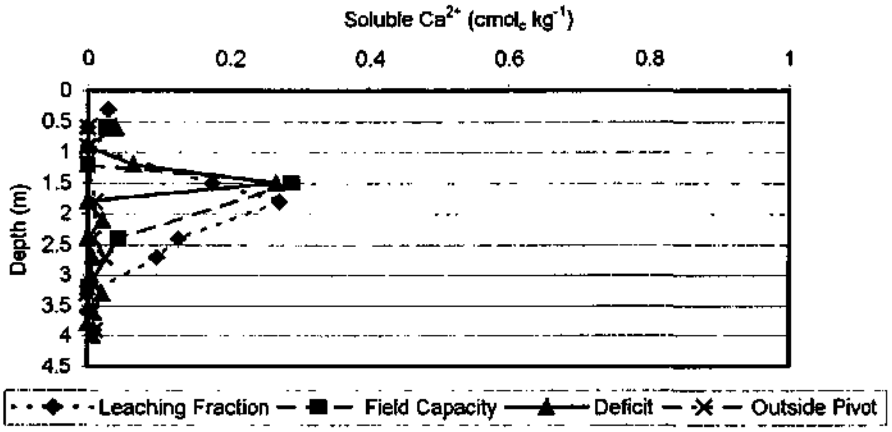


Figure 2.54. Soluble calcium content (cmol$_c$ kg^{-1}) of the saturated soil extract at pivot Fourth as a function of depth (m) in June 2000.

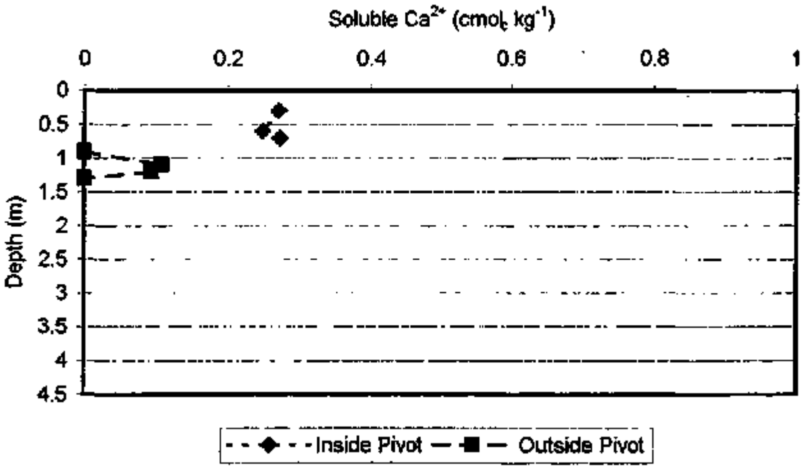


Figure 2.55. Soluble calcium content (cmol$_c$ kg^{-1}) of the saturated soil extract at pivot Tweefontein as a function of depth (m) in June 2000.

At pivots Major and Tweefontein, soluble Ca^{2+} was higher in the topsoil layers, where it was mainly confined due to the plinthic and spoil layer limiting drainage and leaching. At pivot Fourth, soluble Ca^{2+} had a peak between 1.5 and 2 m indicating leaching of salts below the root-zone. These trends are similar to those observed for electrical conductivity of the saturated soil extract (Figures 2.50 to 2.52).

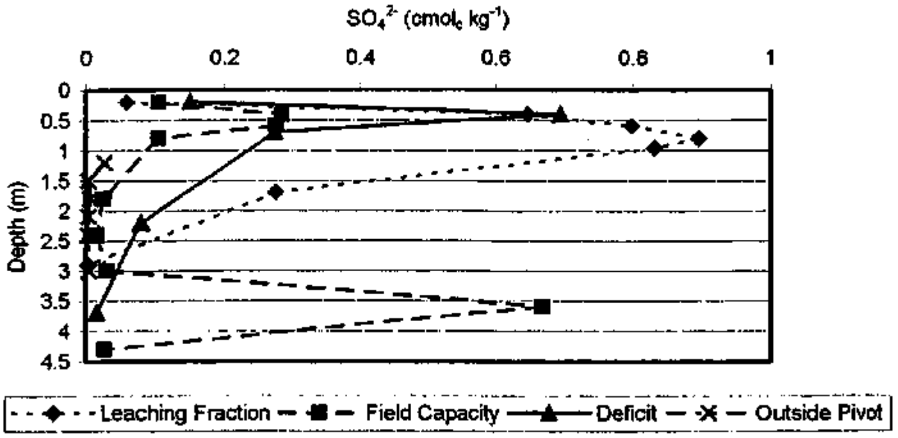


Figure 2.56. Sulphate content (cmol$_c$ kg^{-1}) of the saturated soil extract at pivot Major as a function of depth (m) in June 2000.

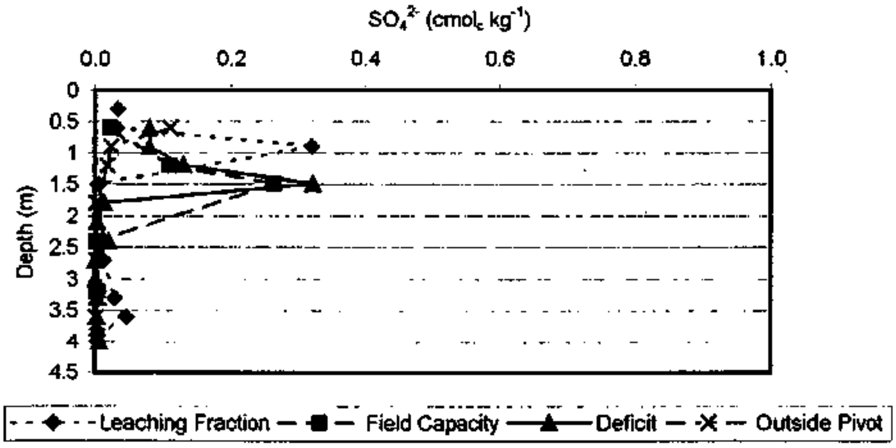


Figure 2.57. Sulphate content (cmol$_c$ kg^{-1}) of the saturated soil extract at pivot Fourth as a function of depth (m) in June 2000.

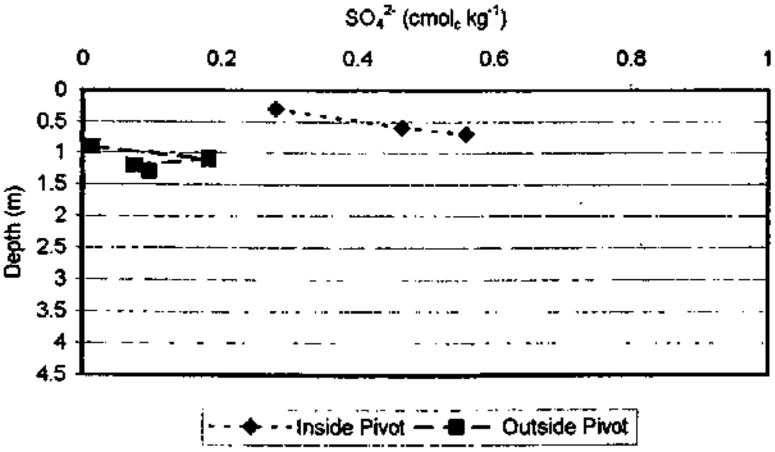


Figure 2.58. Sulphate content (cmol$_c$ kg^{-1}) of the saturated soil extract at pivot Tweefontein as a function of depth (m) in June 2000.

At pivots Major and Tweefontein, soluble SO_4^{2-} was higher in the topsoil layers, where it was mainly confined due to the plinthic and spoil layer limiting drainage and leaching. At pivot Fourth, soluble SO_4^{2-} had a peak between 1.5 and 2 m indicating leaching of salts below the root-zone. These trends are similar to those observed for electrical conductivity of the saturated soil extract (Figures 2.50 to 2.52).

2.3.3.2. Spatial variability of soil salinity

General features

Soil salinity levels were found to increase over the monitoring period of three years and seven months compared to the initial conditions. Measurements made with the EM-38 sensor show a progressive increase in the magnitude of EM_v, EM_h and EM_{mean} values (Table 2.4). The mean EC_e for the upper crop-rooting depth (0-60 cm) estimated using calibration equations show the EC_e to have reached mean levels that could be described as slightly saline.

Table 2.4. Comparison of the means of the soil salinity measurements (adjusted to 25°C) for the various salinity surveys conducted.

Centre pivot	Sampling date	Number of measurements	EM_v (mS m^{-1})	EM_h (mS m^{-1})	EMmean (mS m^{-1})	Estimated EC_e (0-60 cm) (mS m^{-1})
Major	May 1997	55	3	6	5	113
	Aug 1998	103	9	13	11	172
	Sep 1999	117	14	14	14	276
	Dec 2000	405	23	23	23	294
Tweefontein	May 1997	58	7	10	9	209
	Aug 1998	111	9	22	15	239
	Sep 1999	125	14	26	20	264
	Dec 2000	315	26	34	30	314
Fourth	Sep 1999	14	1	21	11	146
	Dec 2000	292	15	22	19	192

As a representation of the soil salinity status at the end of this project, salinity parameters are given for December 2000 in Table 2.5 for the sites used for calibration of the EM readings. These data show that salinity levels are generally fairly similar down the profile to a depth of 90 cm. This is reflected by the general similarity of EM_v and EM_h values. Where the EC_e is higher near the soil surface one expects to record a higher EM_h value, and *vice versa*. This is illustrated at sites 1 and 2.

Spatial distribution

In producing Figures 2.59 to 2.61, the geographic co-ordinates were established for the measurement points for the surveys conducted prior to 2000, which originally had no co-ordinates, but grid points relative to a reference "master line". The data was plotted using ArcView on the same basis (scale and salinity class intervals) as those used in 2000 (Figures 2.59 to 2.61).

The changes in the distribution of salinity in the upper soil profile (EC_e 0-60 cm), is shown for the three pivots over the monitoring period in Figures 2.59 to 2.61. Soon after commencement of irrigation, the salinity levels (EC_e 0-60 cm) at the Tweefontein pivot did not exceed 300 mS m^{-1} and over approximately one third of the area the values were less than 250 mS m^{-1} (May 1997 survey in Figure 2.59). Salinity increased slightly over the following two years (1998 and 1999), and evidence is shown of higher salinity levels towards the centre of the pivot. This is presumably a result of the progressively wetter irrigation regime towards the centre. For the 1998 and 1999 surveys, the highest salinity (EC_e 0-60 cm) categories were 300-350 mS m^{-1} and 350-400 mS m^{-1} respectively. A fairly substantial increase was shown for the 2000 sampling, when levels of 400 - 500 mS m^{-1} occurred in the higher salinity categories. The highest salinity occurred in an area North-West of the centre which was prone to waterlogging, apparently as a result of limited drainage of the soil, and fairly flat topography in a localized area (contour lines are shown on Figure 2.59).

Table 2.5. *Soil salinity levels for various sites sampled as reflected by the EC_e, EM_v and* EM_h at each centre pivot in December 2000.

Tweefontein			Major			Fourth		
Site No. depth (cm)	EC_e (mS m^{-1})	EM values (mS m^{-1})	Site No. depth (cm)	EC_e (mS m^{-1})	EM values (mS m^{-1})	Site No. depth (cm)	EC_e (mS m^{-1})	EM values (mS m^{-1})
1. 0-30	428	EMv=39 EMh=45	**11.** 0-30	331	EMv=29 EMh=30	**21.** 0-30	173	EMv=28 EMh=33
30-60	438		30-60	209		30-60	263	
60-90	325		60-90	259		60-90	337	
2. 0-30	576	EMv=22 EMh=35	**12.** 0-30	320	EMv=19 EMh=19	**22.** 0-30	293	EMv=33 EMh=43
30-60	389		30-60	341		30-60	302	
60-90	430		60-90	260		60-90	345	
3. 0-30	336	EMv=34 EMh=34	**13.** 0-30	418	EMv=26 EMh=25	**23.** 0-30	257	EMv=27 EMh=37
30-60	350		30-60	306		30-60	277	
60-90	454		60-90	279		60-90	332	
4. 0-30	370	EMv=30 EMh=44	**14.** 0-30	493	EMv=35 EMh=40	**24.** 0-30	357	EMv=20 EMh=28
30-60	358		30-60	460		30-60	255	
60-90	413		60-90	429		60-90	265	
5. 0-30	312	EMv=42 EMh=56	**15.** 0-30	636	EMv=41 EMh=50	**25.** 0-30	101	EMv=18 EMh=27
30-60	417		30-60	490		30-60	132	
60-90	398		60-90	312		60-90	239	
6. 0-30	405	EMv=56 EMh=78	**16.** 0-30	408	EMv=35 EMh=41	**26.** 0-30	148	EMv=13 EMh=21
30-60	325		30-60	368		30-60	184	
60-90	286		60-90	232		60-90	241	
7. 0-30	369	EMv=41 EMh=56	**17.** 0-30	324	EMv=35 EMh=30	**27.** 0-30	345	EMv=15 EMh=24
30-60	379		30-60	319		30-60	297	
60-90	334		60-90	355		60-90	245	
8. 0-30	177	EMv=19 EMh=19	**18.** 0-30	186	EMv=18 EMh=14	**28.** 0-30	188	EMv=10 EMh=21
30-60	326		30-60	335		30-60	206	
60-90	342		60-90	353		60-90	286	
9. 0-30	491	EMv=40 EMh=71	**19.** 0-30	282	EMv=24 EMh=21	**29.** 0-30	47	Emv= 0 EMh=10
30-60	432		30-60	255		30-60	63	
60-90	419		60-90	223		60-90	51	
10. 0-30	197	EMv=13 EMh=21	**20.** 0-30	130	EMv=6 EMh=7	-	-	-
30-60	276		30-60	45		-	-	-
60-90	303		60-90	34		-	-	-

Note: Sites 20 and 29 are situated outside the perimeter of the pivots.

At the Major pivot progressive soil salinization over time has also occurred (Figure 2.60). For the initial survey (May 1997), salinity levels (EC_e 0-60 cm) were less than 150 mS m^{-1} over the whole pivot area. In August 1998 approximately two thirds of the pivot had salinity levels in the 150-200 mS m^{-1} range. By September 1999, the central part had reached levels of 250-350 mS m^{-1}. The survey in December 2000 showed a further increase in salinity, with approximately half the area of the pivot having EC_e (0-60 cm) levels in the range of 300-450 mS m^{-1}. At this sampling there is strong evidence of salt accumulation in the south-eastern portion of the pivot. The rather sudden development of this distribution is somewhat surprising, but it is consistent with the normal process of water and salt movement downslope. The contour lines in Figure 2.60 indicate an area of reduced slope where salt accumulation has taken place.

At the Fourth pivot, EM measurements were made on a transect across the pivot in September 1999 fairly soon after irrigation had commenced. The calibration relationship established for the 2000 survey was used to convert the EM_{mean} values to EC_e (0-60 cm). The highest value obtained was 182 mS m^{-1} (Figure 2.61). The December 2000 survey showed a substantial increase in salinity levels, with approximately half the area having salinity levels of 200-350 mS m^{-1}. There is clear evidence for both surveys of higher salinity near the centre of the pivot. Again, this is presumably a result of higher water (and salt) application towards the centre.

In general, the Tweefontein and Major pivots show higher levels of salinity than the Fourth pivot, which is to be expected due to their longer duration of irrigation (Table 2.4 and Figures 2.59 to 2.61). These salinity levels are unlikely to have an adverse effect on the growth of a moderately tolerant crop like wheat, for which the critical threshold EC_e is given by Maas (1986) as 600 mS m^{-1}. A more sensitive crop like maize, with a critical EC_e of 180 mS m^{-1}, could currently be expected to show a yield decline in approximately half of the area of the Major and Tweefontein pivots. This decline is, however, likely to be no more than 15 - 20% in the most saline category, i.e. where EC_e (0-60 cm) exceeds 350 mS m^{-1}. In the Fourth pivot very little yield decline in maize could be expected, and no more than about a 10% decline in the worst affected area (EC_e > 250 mS m^{-1}).

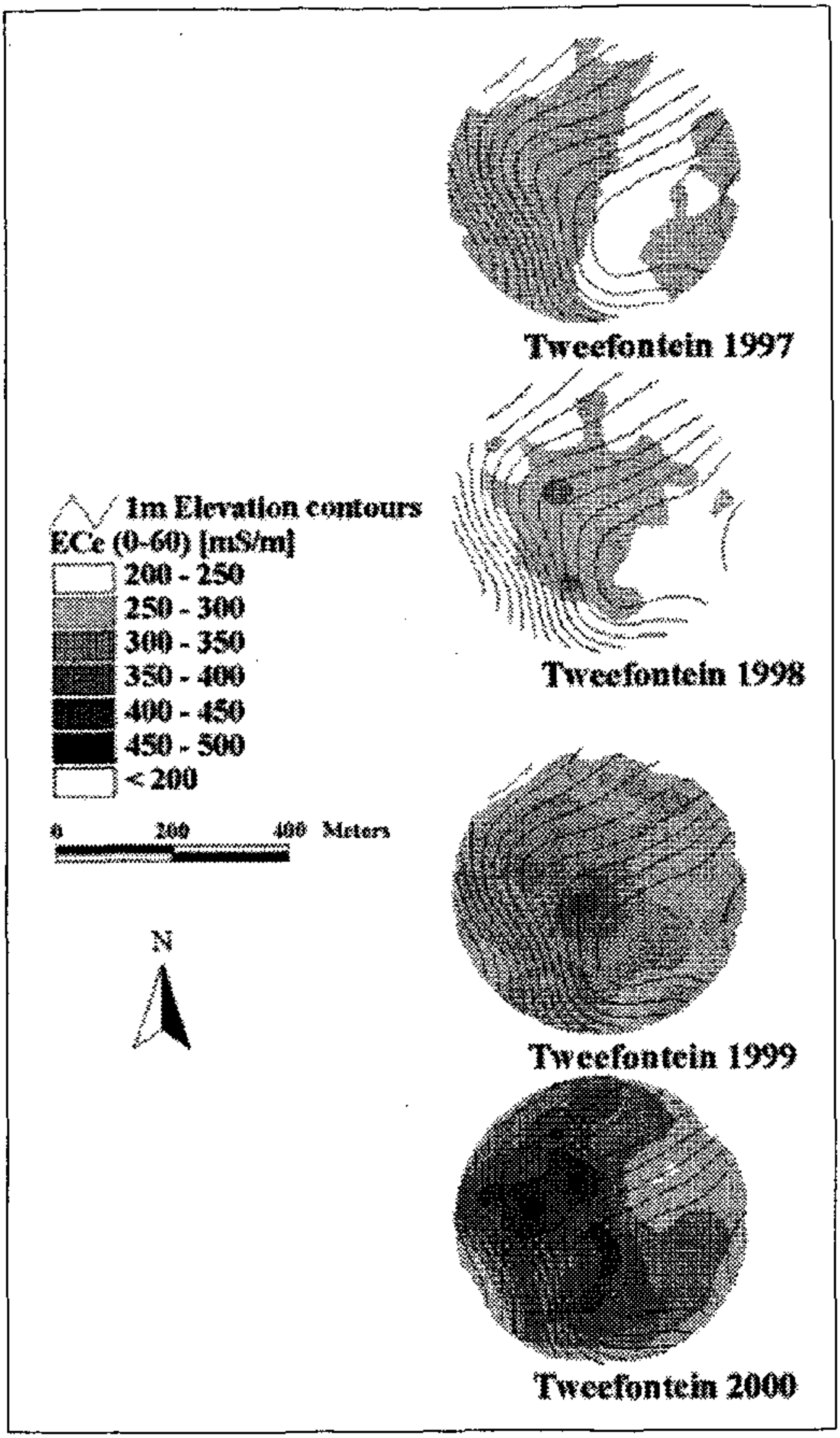


Figure 2.59. Spatial distribution of salinity in the upper soil profile (EC_e over 0-60 cm) of the Tweefontein centre pivot, showing changes over the study period. The 1 m contour lines illustrate a downward slope from West to East.

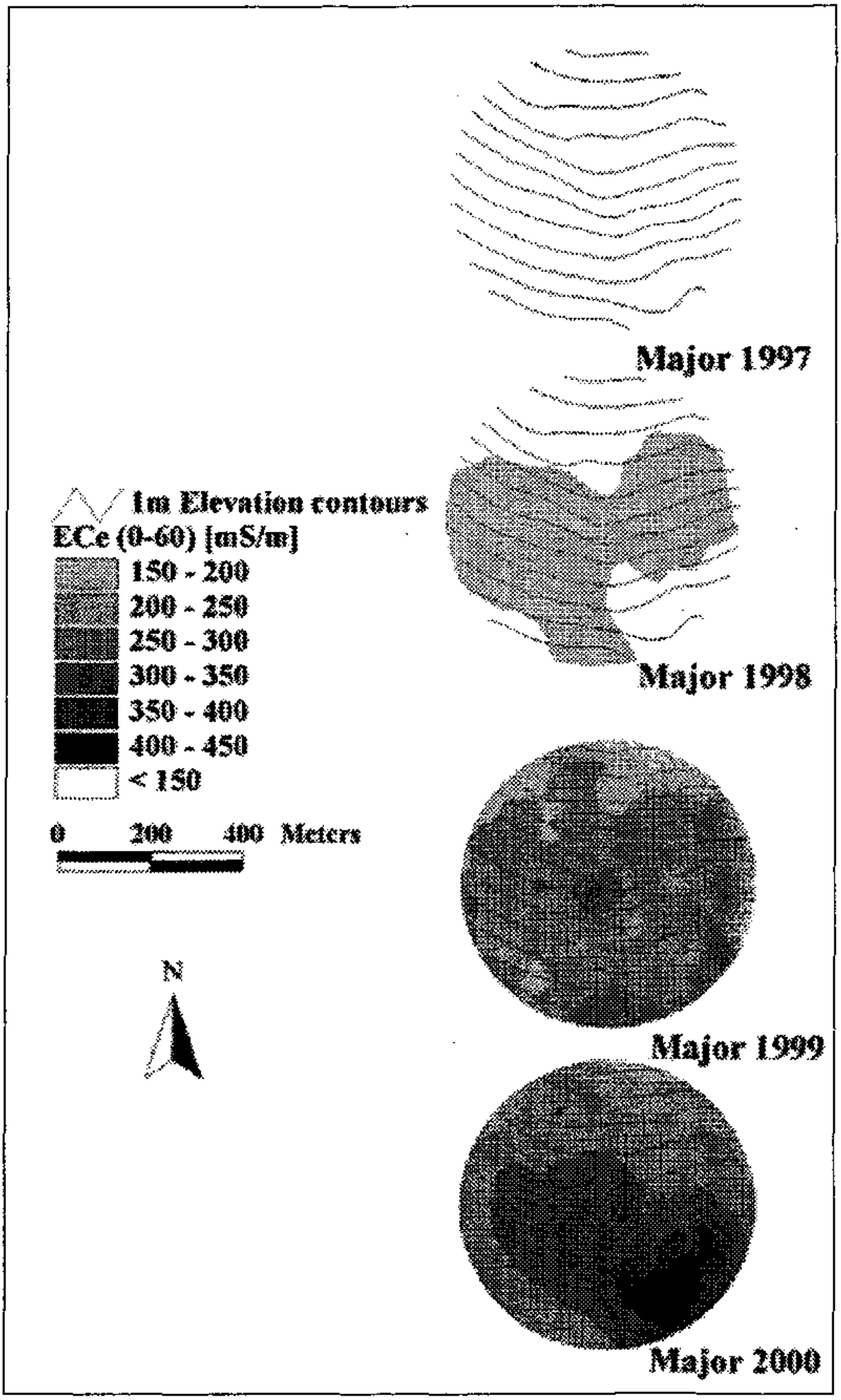


Figure 2.60. Spatial distribution of salinity in the upper soil profile (EC_e over 0-60 cm) of the Major centre pivot, showing changes over the study period. The 1 m contour lines illustrate a downward slope from North to South.

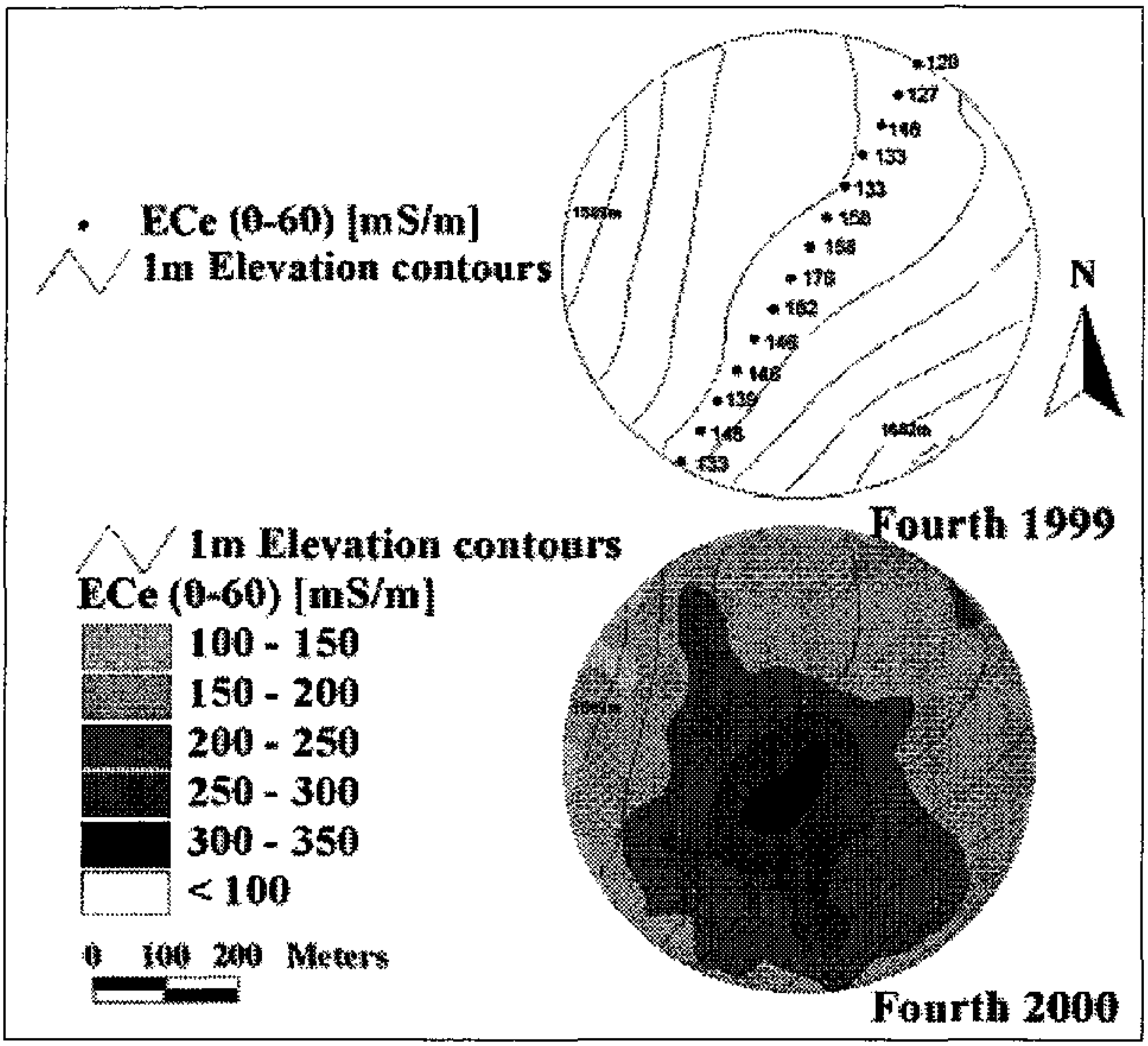


Figure 2.61. Spatial distribution of salinity in the upper soil profile (EC_e over 0-60 cm) of the Fourth centre pivot, showing changes over the study period. Individual figures on the transect for 1999 are in mS m^{-1}. The 1 m contour lines illustrate a downward slope from North-West to South-East.

2.3.4. Waters

2.3.4.1. Irrigation water quality

Irrigation water quality analyses are summarized in Tables A50 to A53 (Appendix A). The data were obtained from Kleinkopje Colliery and from the Soil Science Laboratory at the University of Pretoria. The water samples analysed by the Soil Science Laboratory were collected from the pivot nozzles. The analyses indicated that Jacuzzi and Tweefontein waters were similar. Seasonal fluctuations in irrigation water salinity can be expected. These data were used in the SWB model, which was improved to allow for variable irrigation water quality input during the simulation.

Jacuzzi water from the mine was used for irrigation. Water was taken from the mine itself, but some of this water was also pumped into a holding dam (Figure 2.4), South-West of irrigation pivot Major. In theory, therefore, the irrigation water quality should be similar to that in the dam. This dam has been newly constructed during the course of the irrigation project and has a considerable holding capacity. An approximate stage curve for the dam is included in Figure 2.62. The residence time of the mine water pumped into the dam is high and precipitation of particularly iron, is possible.

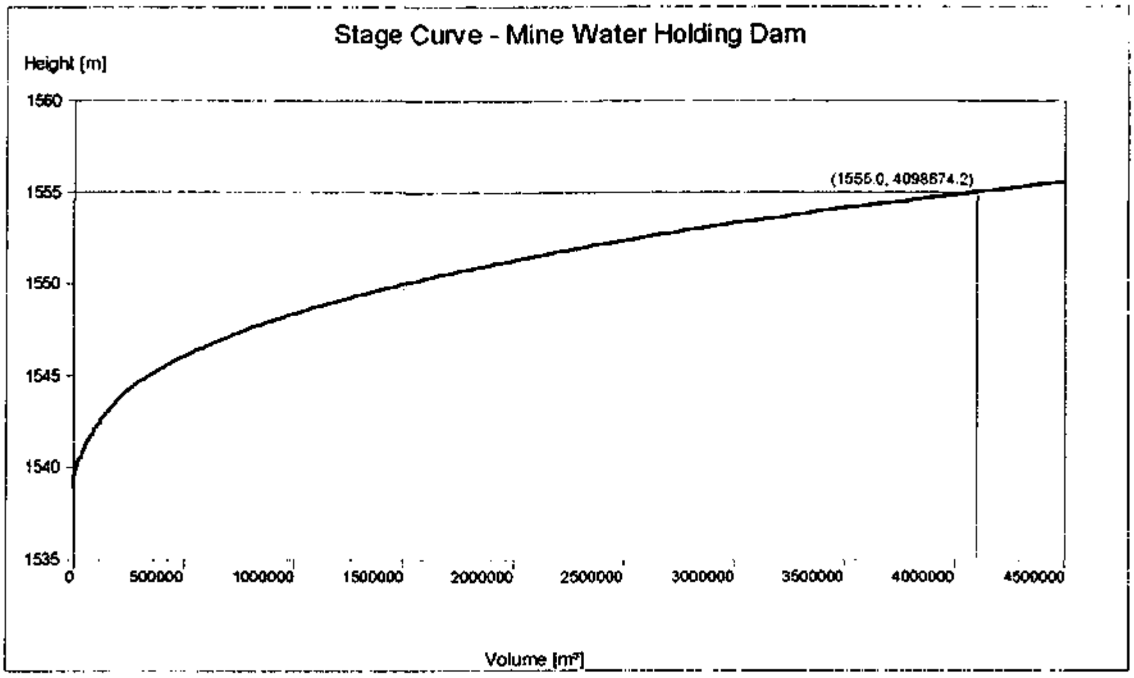


Figure 2.62. Approximate stage curve for the mine water holding dam.

Water from the holding dam was analyzed three times during this investigation by the Institute for Groundwater Studies (University of the Free State). The results are presented in Table A54 (Appendix A). The main conclusions from this information were:

- The pH-levels were variable, but generally in the range of calcium/magnesium buffering. This was confirmed by the high calcium and magnesium content, associated with the low sodium and total alkalinity of the water.
- Sulphate levels were typical of what was expected of opencast mine water in a dynamic regime. The water was removed from the mine before gypsum saturation was reached.
- Heavy metal concentrations were generally low due to near neutral pH-levels of the water. Exceptions were iron and manganese that, from time to time, reflected high concentrations. This was clearly dependent on the residence time of the mine water in the dam and also its pH.
- Nitrate concentrations were low in the mine water. In terms of identifying possible tracer constituents from the irrigation process, nitrate, which was introduced through fertilisers, should have been the first to migrate through the soil and rock profile.
- Other possible tracers were sulphate, magnesium and calcium. All three, however, were retarded as they passed through soil and therefore were not expected to arrive in the groundwater during the early stages of irrigation.

- The quality of water in the dam was consistent with the irrigation water qualities shown in Tables A50 and A53 (Appendix A).

2.3.4.2. Runoff

From spring 1999, runoff amounts and quality were measured at the weirs at pivot Major and Tweefontein. Runoff events and quality of runoff water are summarized in Tables 2.6 (pivot Major) and 2.7 (pivot Tweefontein). Water flow over the weir (Q) was calculated with the following formula:

$$Q = 1.585 \times 5 \times h^{2.5}$$

where h is the water level above the weir in m, whilst 1.585, 5 and 2.5 are coefficients depending on the shape and size of the weir and used to express flow in $m^3 s^{-1}$. Each reading of h recorded with the pressure transducer and the data logger, was used to calculate Q. This was then multiplied by 120 s (reading interval) and summed in order to calculate the total amount of runoff.

The amount of salts in runoff was calculated using the following equation:

$$TDS = 10 EC$$

where TDS is total dissolved salts in g m^{-3} and EC is the electrical conductivity measured with the salinity sensor in mS m^{-1}. The factor "10" is commonly used in the conversion for waters rich in SO_4^{2-}. Each reading of EC recorded with the salinity sensor and the data logger was used to determine TDS. This was then multiplied by the amount of water in m^3 flowing over the weir in 120 s (reading interval) and summed in order to calculate the amount of salts leaving the field in a runoff event. The average EC values in Tables 2.6 and 2.7 are weighted by the water flow during each measurement interval.

The results indicated that less than 2% of the salts added since the beginning of the trial (Tables 3.5 and 3.6) were lost from the irrigated fields through surface and subsurface runoff from November 1999 until April 2000. More runoff was recorded at pivot Tweefontein compared to pivot Major, due to the restricted soil depth of the rehabilitated land. Due to impervious soil layers at pivots Major and Tweefontein, it is likely that runoff and salts in runoff could have mainly originated from lateral movement of soil water.

Table 2.6. Runoff events measured at the weir at pivot Major (pivot area: 30 ha).

Duration (date - time)		Average electrical conductivity ($mS.m^{-1}$)	Amount of water discharged		Amount of salts discharged (t)	Note
From	To		(m^3)	(mm)		
19/11/1999; 13h16min	19/11/1999; 16h58min	41.0	429.55	1.43	0.17	Rainfall
16/01/2000; 0h44min	17/01/2000; 9h52min	21.0	1595.51	5.32	0.33	Rainfall
08/02/2000; 12h26min	08/02/2000; 18h42min	12.0	260.71	0.87	0.03	Rainfall
10/02/2000; 13h44min	16/02/2000; 6h4min	80.4	10749.79	35.83	8.64	Rainfall
25/02/2000; 9h42min	25/02/2000; 11h10min	280.3	0.10	0.0003	0.0003	Rainfall
12/03/2000; 4h10min	13/03/2000; 17h28min	195.5	589.04	1.96	1.16	Rainfall
18/03/2000; 18h08min	19/03/2000; 8h14min	28.4	86.01	0.29	0.03	Rainfall
31/03/2000; 18h30min	01/04/2000; 11h30min	103.3	535.01	1.78	0.56	Rainfall
06/04/2000; 21h00min	07/04/2000; 6h14min	59.2	66.62	0.22	0.04	Rainfall
07/04/2000; 16h10min	09/04/2000; 13h06min	10.2	2487.97	8.29	0.26	Rainfall
15/04/2000; 17h42min	16/04/2000; 11h22min	2.7	1181.77	3.94	0.006	Rainfall
Total (from 19/11/1999 to 16/04/2000)		62.5	17982.08	59.93	11.23	-

Table 2.7. Runoff events measured at weir at pivot Tweefontein (pivot area: 20 ha).

Duration (date - time)		Average electrical conductivity (mS m^{-1})	Amount of water discharged		Amount of salts discharged (t)	Note
From	To		(m^3)	(mm)		
01/11/1999; 4h13min	02/11/1999; 10h33min	342.9	1116.20	5.58	3.83	Over-irrigation
19/11/1999; 13h20min	19/11/1999; 18h04min	44.1	151.75	0.76	0.07	Rainfall
22/12/1999; 5h10min	22/12/1999; 10h22min	30.8	56.88	0.28	0.01	Rainfall
23/12/1999; 1h18min	23/12/1999; 12h46min	37.7	700.36	3.50	0.26	Rainfall
28/12/1999; 18h56min	29/12/1999; 10h02min	10.1	3073.59	15.37	0.31	Rainfall
06/01/2000; 16h10min	06/01/2000; 22h32min	16.6	74.80	0.37	0.01	Rainfall
16/01/2000; 2h00min	17/01/2000; 14h40min	12.5	7607.28	38.04	0.94	Rainfall
08/02/2000; 13h18min	08/02/2000; 22h26min	7.3	271.98	1.36	0.01	Rainfall
10/02/2000; 12h46min	12/02/2000; 10h46min	11.6	6380.33	31.90	0.74	Rainfall
13/02/2000; 5h56min	13/02/2000; 23h40min	12.1	1143.91	5.72	0.14	Rainfall
16/03/2000; 19h30min	17/03/2000; 4h36min	2.7	1325.47	6.63	0.04	Rainfall
18/03/2000; 19h34min	19/03/2000; 5h50min	5.9	151.36	0.76	0.009	Rainfall
21/03/2000; 1h14min	21/03/2000; 8h40min	43.8	83.43	0.42	0.04	Rainfall
26/03/2000; 18h34min	27/03/2000; 5h34min	47.2	497.30	2.49	0.23	Rainfall
31/03/2000; 13h20min	01/04/2000; 14h18min	59.2	1338.35	6.69	0.79	Rainfall
07/04/2000; 16h34min	08/04/2000; 21h00min	39.6	2974.45	14.87	1.17	Rainfall
15/04/2000; 18h50min	16/04/2000; 6h28min	29.9	523.62	2.62	0.16	Rainfall
Total (from 01/11/1999 to 16/04/2000)		23.2	27471.06	137.36	8.76	-

2.3.4.3. Groundwater

2.3.4.3.1. Groundwater quality

Piezometer installations are done through the introduction of foreign material into the boreholes. Great care is usually taken to ensure that groundwater is not unduly contaminated during these installations. A certain degree of contamination is, however, unavoidable, since sodium bentonite is one of the prime materials used to hydraulically isolate one horizon from another.

After the installation of a bentonite plug, boreholes have to be flushed, usually over a period of months, to ensure that all free salts from the bentonite are leached.

In the case of the monitoring holes in the irrigation area, periodic flushing was necessary for three months after piezometer installation. The results from chemical analyses during this period have therefore been ignored, since they do not reflect the true composition of the groundwater. Even after this period, traces of abnormal sodium levels were still detected in boreholes BH4 and BH7.

The results from the chemical analyses are presented in Appendix J. Figures 2.63 to 2.65 summarize some of the relevant information.

Conclusions from this information are:

- Boreholes BH2 and BH8 showed an increase in nitrate concentrations. Nitrate was the most mobile constituent available in the irrigation system and was derived from fertilizer. The mine water did not contain nitrate concentrations at these levels.
- Boreholes BH2, BH3, BH5, BH8 and BH9 showed a general but small increase in calcium, magnesium and sulphate.
- Boreholes BH4, BH6 and BH7 showed no increase in any of its constituents.
- These response patterns are typical of what can be expected in a geological environment such as the irrigation pivot. Water from the irrigated area will infiltrate along preferred pathways, thus contaminating the aquifer in a patchy manner.

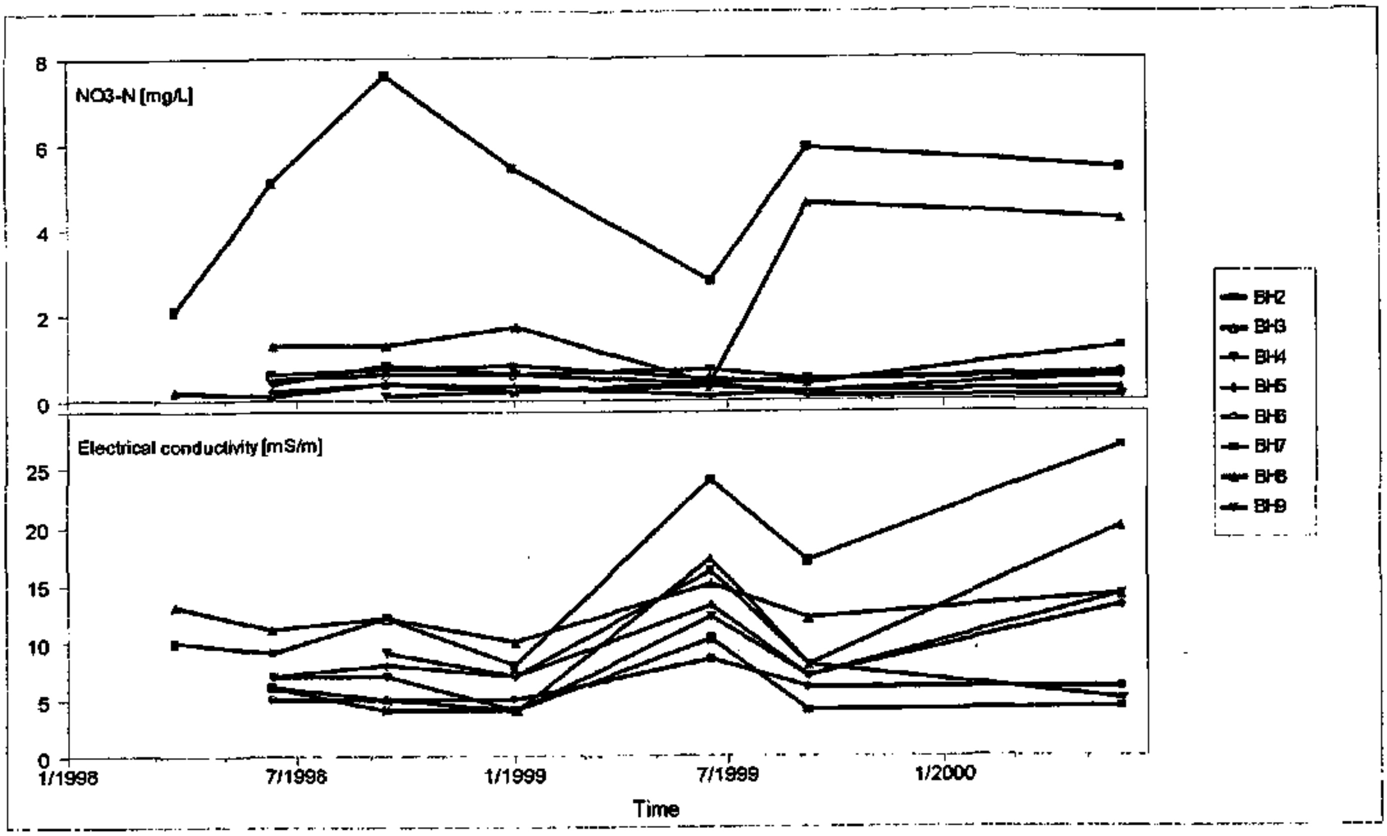


Figure 2.63. Results from chemical analyses on water samples from monitoring boreholes at pivot Major for NO_3^- and electrical conductivity.

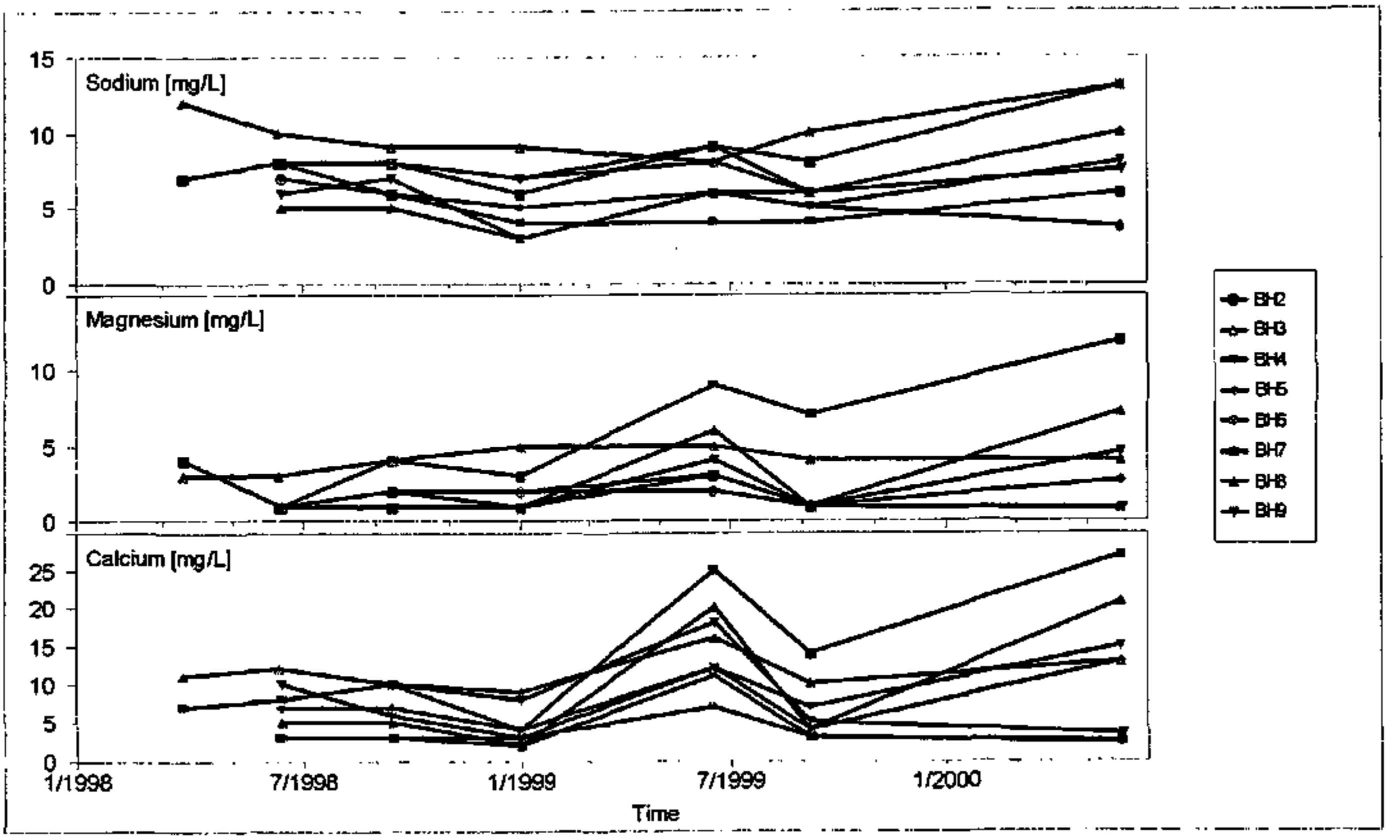


Figure 2.64. Results from chemical analyses on water samples from monitoring boreholes at pivot Major for Na^+, Mg^{2+} and Ca^{2+}.

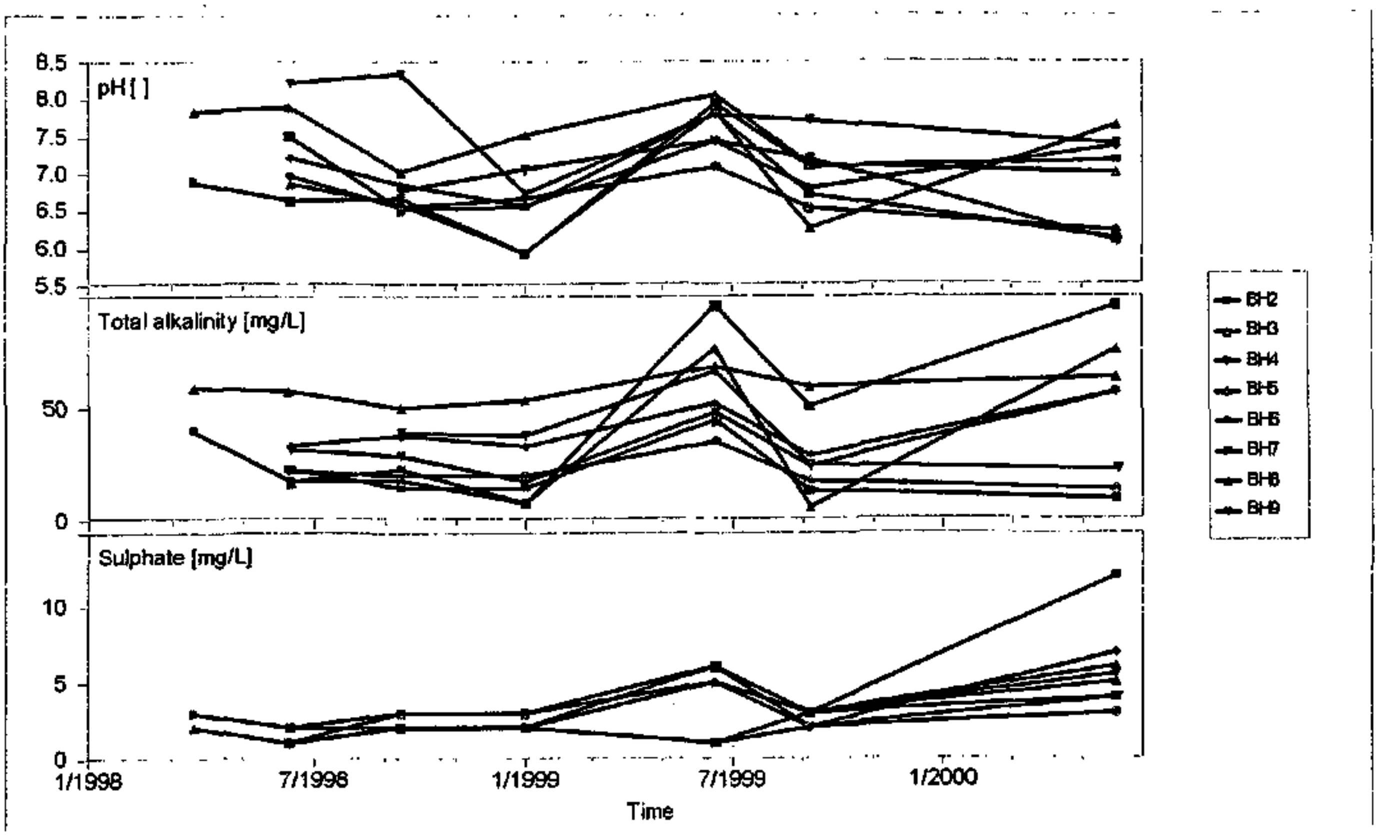


Figure 2.65. Results from chemical analyses on water samples from monitoring boreholes at pivot Major for pH, total alkalinity and SO_4^{2-}.

2.3.4.3.2. Groundwater levels

Figure 2.66 shows the groundwater levels in the monitoring boreholes. The original water levels ranged from 2.5 – 4.8 m below surface; BH5 was the exception with a water-level depth of 7 m.

Due to seasonal fluctuations, water levels raised by approximately 1 m during summer. The only borehole that showed an abnormal rise in its water level over the first 18 months of irrigation was BH5, where a consistent rise of 1.5 m was observed. It is inferred from this information that:

- The annual rise in the groundwater level of 1.0 m constituted approximately 30 000 m^3 of water that reached the water table in the irrigation area. This was about 7% of the average crop water demand for two crops per annum, but significantly greater than the 6 500 m^3 that was estimated to be naturally replenished from rainfall at a recharge rate of 3% per annum.
- The deeper water level in BH5 was explained by the local higher transmissivity of the aquifer (0.83 $m^2 d^{-1}$), and thus the greater compatibility to drain water from this point. The initial rise in the water level at BH5 was significant and suggested that more water reached the water table than in the past, before irrigation.

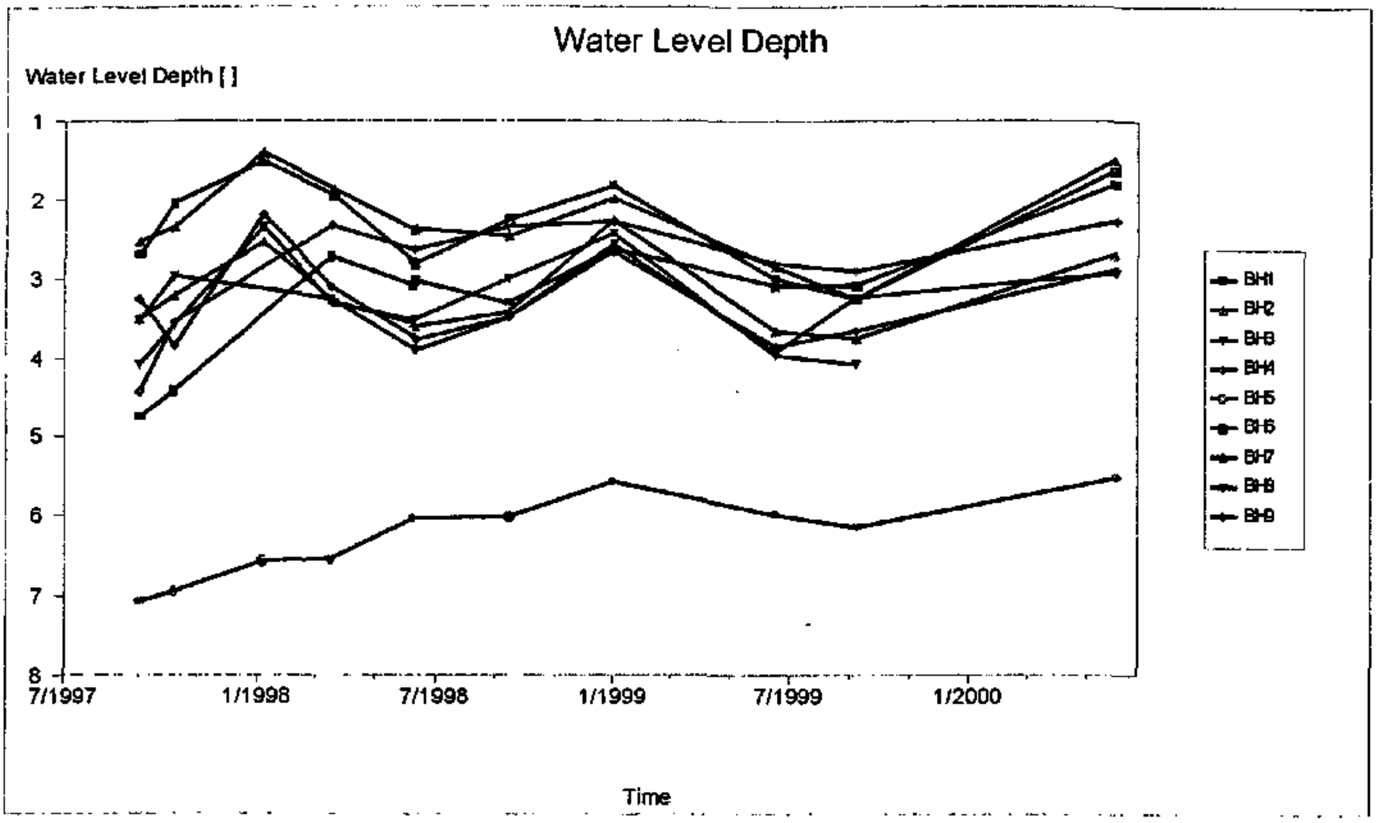


Figure 2.66. Water levels in monitoring boreholes at the irrigation site.

2.4. Glasshouse and laboratory experiments

2.4.1. Plant nutrition

Wheat (*Triticum aestivum* L. cv. SST 825) was grown in calcium and magnesium sulphate salinized solutions (Ca:Mg 2:1) with differential levels of NO_3, NH_4, P and K to investigate the effect of these nutrients on vegetative biomass and nutrient composition under sulphate salinity. The dry matter yield and plant analysis results are presented in Tables 2.8 and 2.9, respectively.

Table 2.8. Mean root and top dry matter yields of wheat plants.

Mean dry mass per pot (g)	Treatments (mmol l^{-1})										
	Control	Salinized control	7 NO_3	20 NO_3	7 NH_4	9 NH_4	0.25 P	0.75 P	3 K	8 K	10 K
Roots	1.38	1.23	1.26	1.08	1.46	1.22	1.01	1.04	1.40	1.52	1.30
Tops	6.12	3.85	4.86	4.09	6.01	4.19	3.79	3.86	4.28	5.69	4.29

Root growth $p = 0.167$, c.v. 21.7%; Top growth $p = 0.029$, c.v. 24.8%

Table 2.9. Nutrient concentrations in top growth of wheat.

Treatment (mmol l^{-1})	N	P	K	Ca	Mg	SO_4	Fe	Mn	Cu	Zn
	(%)						(mg kg^{-1})			
Control	4.19	0.86	5.23	0.39	0.13	1.17	47.6	81	10.5	34.5
7 NO_3	4.11	0.93	4.90	0.50	0.34	1.53	59.6	153	15.0	69.0
14 NO_3	5.90	1.12	4.55	0.61	0.39	1.98	28.1	165	13.5	58.5
20 NO_3	3.93	0.83	4.85	0.70	0.43	1.49	56.6	165	12.0	55.5
1 NH_4	5.90	1.12	4.55	0.61	0.39	1.98	28.1	165	13.5	58.5
7 NH_4	5.95	1.06	4.84	0.41	0.32	1.48	28.1	135	16.5	61.5
9 NH_4	6.10	1.16	4.94	0.38	0.29	1.50	92.6	132	18.0	69.0
0.25 P	5.70	0.88	5.20	0.67	0.44	1.99	25.1	194	16.5	84.0
0.5 P	5.90	1.12	4.55	0.61	0.39	1.98	28.1	165	13.5	58.5
0.75 P	4.18	0.98	5.18	0.62	0.42	1.69	20.6	210	18.0	84.0
3 K	5.95	1.13	5.27	0.71	0.41	1.86	65.6	171	13.5	79.5
6 K	5.90	1.12	4.55	0.61	0.39	1.98	28.1	165	13.5	58.5
8 K	4.08	0.82	5.12	0.64	0.39	2.00	50.6	177	15.0	69.0
10 K	3.45	0.65	4.97	0.57	0.38	2.00	32.6	179	15.0	73.5

Salinity decreased the biomass production of wheat, mainly due to interactions of Mg and Mn with the uptake of Fe and K. Decreases in yield were also associated with significant increases in plant concentrations of SO_4 and Mg. The application of NO_3, NH_4, and K at rates different from the level considered beneficial for non-saline conditions (salinized control) improved wheat growth under sulphate saline conditions. Differential application levels of P had no effect on the yield of wheat. The extraordinary effect of a high NH_4 supply under sulphate salinity can be ascribed to the antagonistic effect that NH_4 exerted on Mg and Mn concentrations in plants and/or to NH_4 being a supplementary N source when large SO_4 concentrations suppressed NO_3 uptake by wheat. In practice this could mean that the inclusion of NH_4 fertilizers in a NO_3:NH_4 ratio of 2:1 could be advantageous when irrigating crops with water containing high levels of Ca and Mg sulphate. Further experimentation is needed to verify these results in soils under field conditions.

The detailed report on this experiment can be found in Appendix K.

2.4.2. Herbicide effects

The objectives of this investigation were to determine the influence of mine water on the three important performance criteria for herbicides, namely:

- Weed control efficacy;
- Herbicide selectivity; and
- Herbicide persistence and mobility in soil (incorporates risks of environmental pollution).

In addressing the above issues, it first needed to be determined whether the quality of water used for preparing tank mixtures for herbicide spraying affects the integrity, and thus, the potential biological activity of herbicides. Chemical analyses of selected herbicides (atrazine and 2,4-D) in a tank mixture were done by gas chromatography (GC) analysis. The results indicated that there is rapid transformation of the herbicides in the mine water, with atrazine having a higher inactivation rate. This suggested that the electrolytes found in the mine water interact with herbicide molecules to rapidly transform them. This could mean that mine water may not be a suitable carrier for herbicide spraying.

In a parallel investigation, bioassays were conducted in a greenhouse in order to assess whether the biological activity of selected herbicides (atrazine and metolachlor) is affected by the presence of gypsum in soil. The biological activity of atrazine was significantly increased in the presence of gypsum, whilst the activity of metolachlor was significantly reduced by the same treatment. The magnitude of activity change was far greater in the case of metolachlor than for atrazine, and in the case of the latter herbicide the activity difference probably does not hold any practical consequences in terms of herbicide efficacy, selectivity or persistence. In contrast, the performance of metolachlor was dramatically affected, and this has important practical consequences. Reduction of metolachlor activity in the presence of gypsum implies that weed control by the herbicide will be poor on soils irrigated with water containing high levels of calcium sulphate. In the case of metolachlor, the finding does not suggest that selectivity of the herbicide towards the crop would be a concern. The effect on herbicide selectivity is also not an issue in the case of the atrazine, because of the inherent high tolerance of the main crop in which it is used, namely maize.

The detailed report on this experiment can be found in Appendix L.

CHAPTER 3

3. SOIL WATER BALANCE MODEL

3.1. 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. In the case of the finite-difference model, salt redistribution is solved using a convection/dispersion equation. The salt redistribution subroutine of the finite-difference model is, however, currently being debugged, and was not therefore used in this report. 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). Critical assumptions of the chemical equilibrium model and the validation with lysimeter data are discussed in the same study. The model of Robbins (1991) solves chemical equilibrium by iteration. Within each iteration, activity coefficients and ion activities are calculated for Ca^{2+}, Mg^{2+}, Na^{+}, H^{+}, SO_4^{2-}, HCO_3^{-} and CO_3^{2-}, 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 the cascading water 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) need to be entered. The finite-difference model does not need inputs like drainage factor and maximum drainage rate, which are very difficult to estimate in particular for poorly drained soils, but a realistic assumption of the bottom boundary condition is required. If available, measured saturated hydraulic conductivity can be entered as input for each soil layer when the finite-difference water balance is run. Alternatively, the model estimates saturated hydraulic conductivity from field capacity and permanent wilting point using the function of Campbell (1985). The convection/dispersion equation also requires dispersivity factors for each ionic species.

The SWB model is written in Delphi v. 5.0 (Inprise Corp.) and runs in a user-friendly Windows 95 environment. A full description of the model before the improvements made during the course of this project, can be found in Annandale et al. (1999b). The SWB model includes specific crop growth parameters for a wide range of species (Annandale et al., 1999b).

Weather data are generated using CLIMGEN, a two-component weather generator developed by GS Campbell (Washington State University) and based on the work of Richardson and Wright (1984). The first component (CLIMPAR) determines statistical parameters required for long-term daily weather data generation, while the second component (CLIMGEN) generates weather data. CLIMGEN generates daily maximum and minimum air temperature, as well as precipitation from either historic daily weather data, if available, or from monthly averages. At least 20 years of rainfall and 10 years of historic temperature data are required in order to get a reliable simulation. The CLIMGEN weather data generator was assessed at South African sites by Clemence (1997), who showed the estimations to be quite satisfactory.

CLIMGEN is also written in Delphi v. 5.0 and runs in a user-friendly Windows 95 format. The database of CLIMGEN can be used as the weather database of SWB.

Improvements to the SWB model

The following improvements have been made to the SWB model during the course of this project:

i) The finite-difference water balance subroutine based on Richards' equation was included in the SWB model. This was done during the study leave of the project leader at CSIRO (Townsville, Australia). The finite-difference water redistribution improves the simulations as water moves both upwards and downwards driven by soil matric potential gradients. The theory of the finite-difference water redistribution model is reported in Appendix M.

ii) The salt redistribution in the finite-difference water balance model can be simulated using the convection/dispersion equation. The code was also written during the study leave of the project leader at CSIRO. The convection/dispersion equation is expected to improve the simulation of salt redistribution as salts are moved by mass flow or convection, as well as by diffusion in response to concentration gradients. The convection/dispersion equation is currently being debugged and was not used in this report. The theory of the salt redistribution subroutine based on the convection/dispersion equation is also reported in Appendix M.

iii) Introduction of the cation exchange subroutine from Robbins (1991). This subroutine can be enabled or disabled in order to test the effect of adsorption on soil salinity and leaching. The same cation exchange subroutine is performed on a daily basis for salt redistribution in both the cascading and finite-difference water balance model.

iv) Change in input data structure to allow variable irrigation water quality during the simulation.

v) Change in input data structure to allow input of initial salt contents per soil layer.

vi) Calculation of non-instantaneous drainage in the cascading water redistribution model. This was done by introducing a drainage factor, which can be entered by the user. The drainage factor is the fraction of water above field capacity that cascades to the next lower soil layer in the daily time step calculation of water redistribution.

vii) Simulation of perched water table formation in the cascading water redistribution model. This was done by introducing a drainage rate upper limit. The drainage rate upper limit is the maximum amount of water in mm that can be drained in one day.

viii) Calculation and output of parameters of the statistical analysis of measured and simulated data. This allows quick, efficient and quantitative evaluation of model accuracy.

ix) Graphical output of salt balance parameters.

x) Conversion of the CLIMGEN weather data generator to a user-friendly, Windows 95 format. The database of CLIMGEN can be used as the weather database of SWB.

xi) Import of weather data from spreadsheet files into the SWB or CLIMGEN model.

xii) Calculation of the soil water deficit from neutron water meter readings and graphical output. This facilitates real-time irrigation scheduling by neutron water meter measurements.

xiii) Compilation of a comprehensive help file that enables a better technical and operational understanding by users.

xiv) Improvements in user-friendliness.

3.2. 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 treatments, and compared to field measurements obtained at the intensive monitoring sites.

In this Section of the report, examples of simulations and comparisons with field measurements are presented in graphical format for the winter 1999 season of wheat grown at pivot Fourth and irrigated with a leaching fraction (Appendix A, Table A8, replication 2). This season was chosen because the most comprehensive data set of measurements was obtained, and no damage to the crop occurred (hail, herbicide etc.).

3.2.1. Soil water balance and crop growth

Daily weather data collected with the automatic weather station, irrigation water qualities (Table A51, Appendix A), soil physical properties, as well as initial soil chemical properties (Table A30, Appendix A) 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.

The soil water balance summary graph is shown in Figure 3.1. Root depth (RD), leaf area index (LAI), top (TDM) and harvestable dry matter (HDM), as well as the soil water deficit to field capacity are presented in Figure 3.2. The solid lines are simulations, whilst symbols are measured data points. SWB calculates parameters of the statistical analysis between measured and simulated data, and outputs them in the top right corner of each graph. This allows quick, efficient and quantitative evaluation of model performance. The parameters of the statistical analysis are:

i) Number of observations (N);
ii) Coefficient of determination (r^2);
iii) Index of agreement of Willmott (1982) (D);
iv) Root mean square error (RMSE); and
v) Mean absolute error (MAE).

These were recommended by de Jager (1994) to assess model accuracy. He also recommended as model prediction reliability criteria that r^2 and D should be > 0.8, whilst MAE should be < 20%. The statistical analysis shown in the TDM & HDM graph is only for measured and simulated total above ground dry matter production. All data used for calibration and validation are available in the SWB database.

More validation graphs of soil water balance and crop growth are shown in Figures N1 to N4 (Appendix N) for the same crop, but different irrigation treatments.

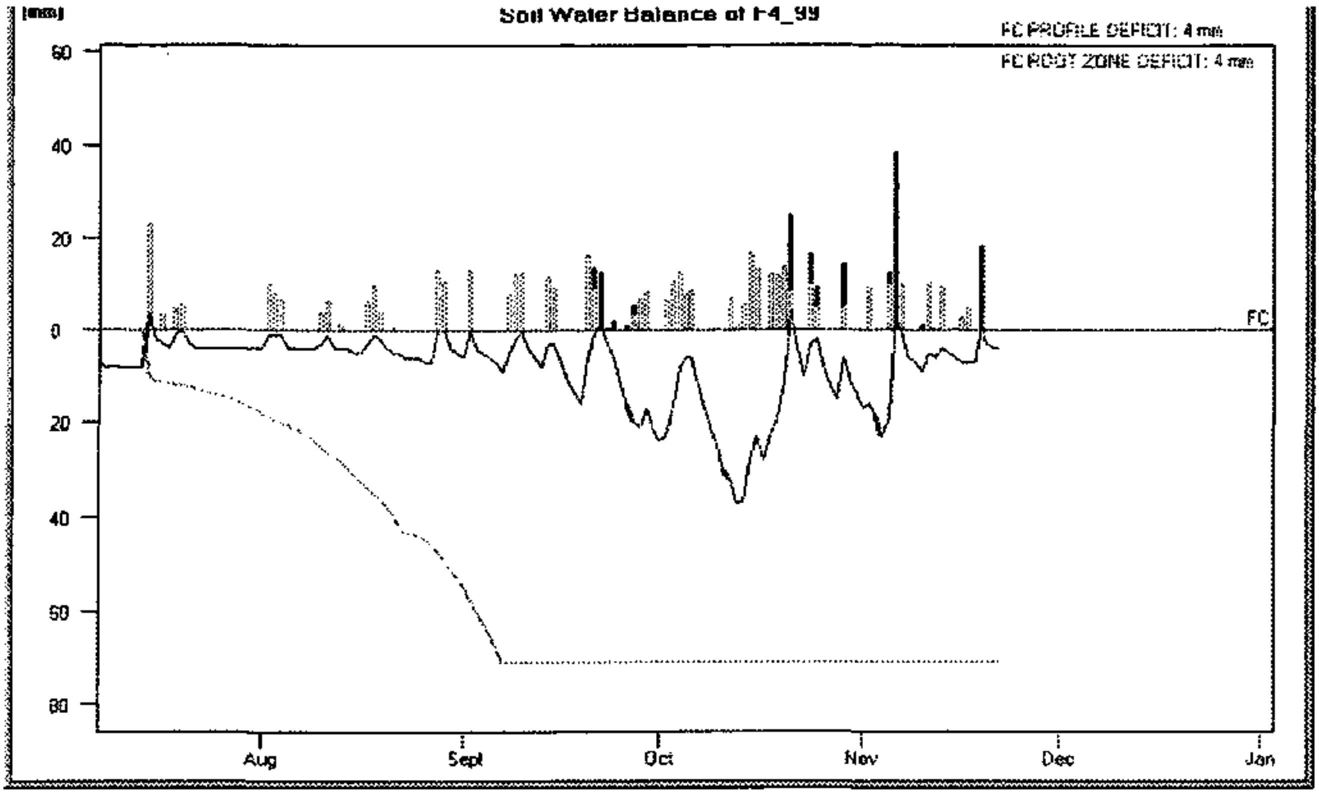


Figure 3.1. Soil water balance summary graph (wheat crop, winter 1999 season, pivot Fourth, leaching fraction treatment, replication 2).

Legend:

- Irrigation (blue, empty histograms) and rainfall (red, filled histograms) input data in the top part of the graph.
- Simulated soil water deficit to field capacity (blue/red bold line) and allowable depletion level (grey, thin line) in the bottom part of the graph.
- Simulated profile soil water deficit as well as root-zone deficit to field capacity at the end of the simulation in the top right corner of the graph.
- The horizontal (blue) line on the graph indicates the field capacity level (FC).

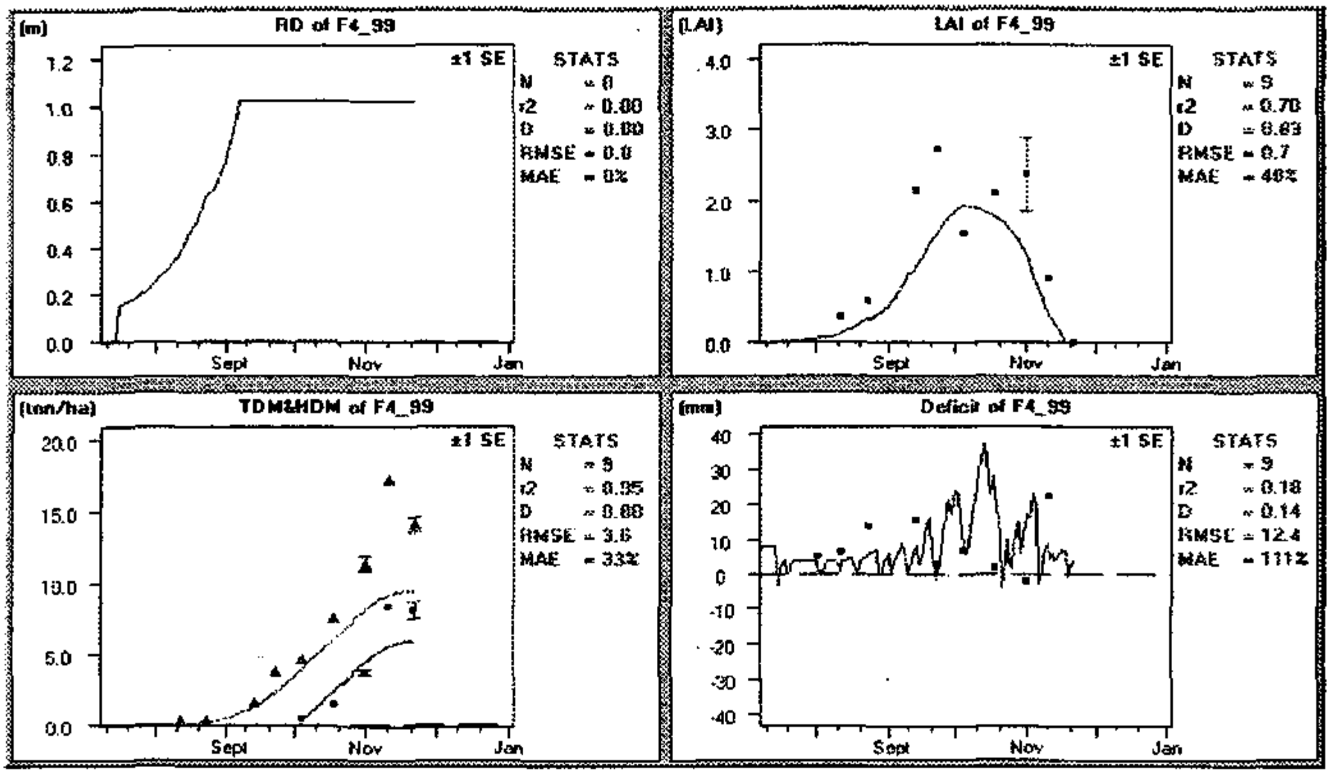


Figure 3.2. Simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), top and harvestable dry matter (TDM & HDM), as well as soil water deficit to field capacity (wheat crop, winter 1999 season, pivot Fourth, leaching fraction treatment, replication 2). The parameters of the statistical analysis are:

i) Number of observations (N);
ii) Coefficient of determination (r^2);
iii) Index of agreement of Willmott (1982) (D);
iv) Root mean square error (RMSE);
v) Mean absolute error (MAE); and
vi) Vertical bars are ± 1 standard error of the measurements.

The growth parameters for wheat used in these simulations were obtained from the database of SWB (Annandale et al., 1999b). A slight modification was introduced to correct the thermal time requirements for crop developmental stages, and dry matter partitioning in order to simulate more accurately the development and growth of the particular cultivar.

The statistical analysis indicated that the simulated and measured data were generally inside or marginally outside the established criteria. Discrepancies were mainly due to spatial variability for crop growth parameters (LAI, TDM and HDM). Large MAE was observed for soil water deficit to field capacity for the leaching fraction treatment (Figure 3.2), as the values were generally close to 0.

3.2.2. Soil water redistribution

A detailed validation of water redistribution was carried out by comparing simulated values of soil matric potential to those obtained with the heat dissipation sensors. The heat dissipation sensors were individually calibrated and their readings normalized for soil temperature at 20 °C using the procedure described by Campbell et al. (2001).

The CS-615 soil reflectometers, which were installed in the field in the first three seasons of the trial, proved to be unsuitable for this type of experiment, as it was impossible to separate out the effects of volumetric soil water content and soil salinity on their readings. The reflectometers were therefore replaced by the TDR system, which should provide measurement of volumetric soil water content and electrical conductivity of the soil solution separately. However, the TDR technique was still under development at the time of compilation of this report.

Figure 3.3 presents the comparison between simulated and measured soil matric potentials, where simulated values were obtained using both the cascading and the finite-difference model. The comparison was done for 16 cm soil depth, where soil water redistribution is more dynamic compared to deeper soil layers due to infiltration and evaporation fluxes. Simulated data of soil matric potential generally compared very well to field measurements. It is interesting to note the sensitivity of the sensors and the model response to irrigation and rainfall events. The finite-difference model proved to be more dynamic than the cascading model, as can be seen from the trend of the simulation line. The finite-difference model moves water both downwards and upwards according to matric potential gradients. The simulation with the finite-difference model, however, was carried out without any effect of salts, as the convection/dispersion salt redistribution subroutine is currently being debugged. The finite-difference model has potential to predict the soil and salt water balance more accurately than the cascading model, once the salt redistribution subroutine is included in SWB.

More validation data of soil water redistribution are shown in Appendix N (Figures N5 to N10) for the same crop, but different irrigation treatments and soil depths.

A summary of the seasonal soil water balances predicted with the cascading model for all pivots and treatments is included in Tables 3.1 to 3.4. Rainfall and irrigation were measured with tipping bucket rain gauges at all intensive monitoring stations. Less irrigation was generally applied during the rainy summer seasons. In particular, very little irrigation was applied during the 1999/00 season, which was extremely wet. The SWB model was used to split the water balance losses between soil evaporation, crop transpiration, drainage, canopy interception as well as surface and subsurface runoff. Soil evaporation and crop transpiration depended on plant species and canopy cover. Drainage varied at pivots Major and Fourth (Tables 3.1 and 3.4) depending on rainfall. In particular, considerable amounts of water were predicted to have drained during the summer 1999/00 season. At pivots Tweefontein (Table 3.2) and Jacuzzi (Table 3.3), which were located on rehabilitated land, no drainage was predicted as this was impeded by the spoil layer. Water intercepted by the canopy was predicted to be a minor component of the soil water balance. Measurements of runoff at the weirs were used to calibrate the runoff curve number of the SWB model for the specific fields. A runoff curve number of 65 was used for pivot Major. This value is typical for contoured row crops, good hydrologic condition and soils with a layer that impedes downward movement of water (USDA-SCS, 1988). The calibrated runoff curve number for the Tweefontein field was 38. This value was also used for pivot Jacuzzi. At pivot Fourth, in the absence of a weir, runoff was assumed to be 0. The change in soil water storage was generally negative as the crops were dried out before harvest.

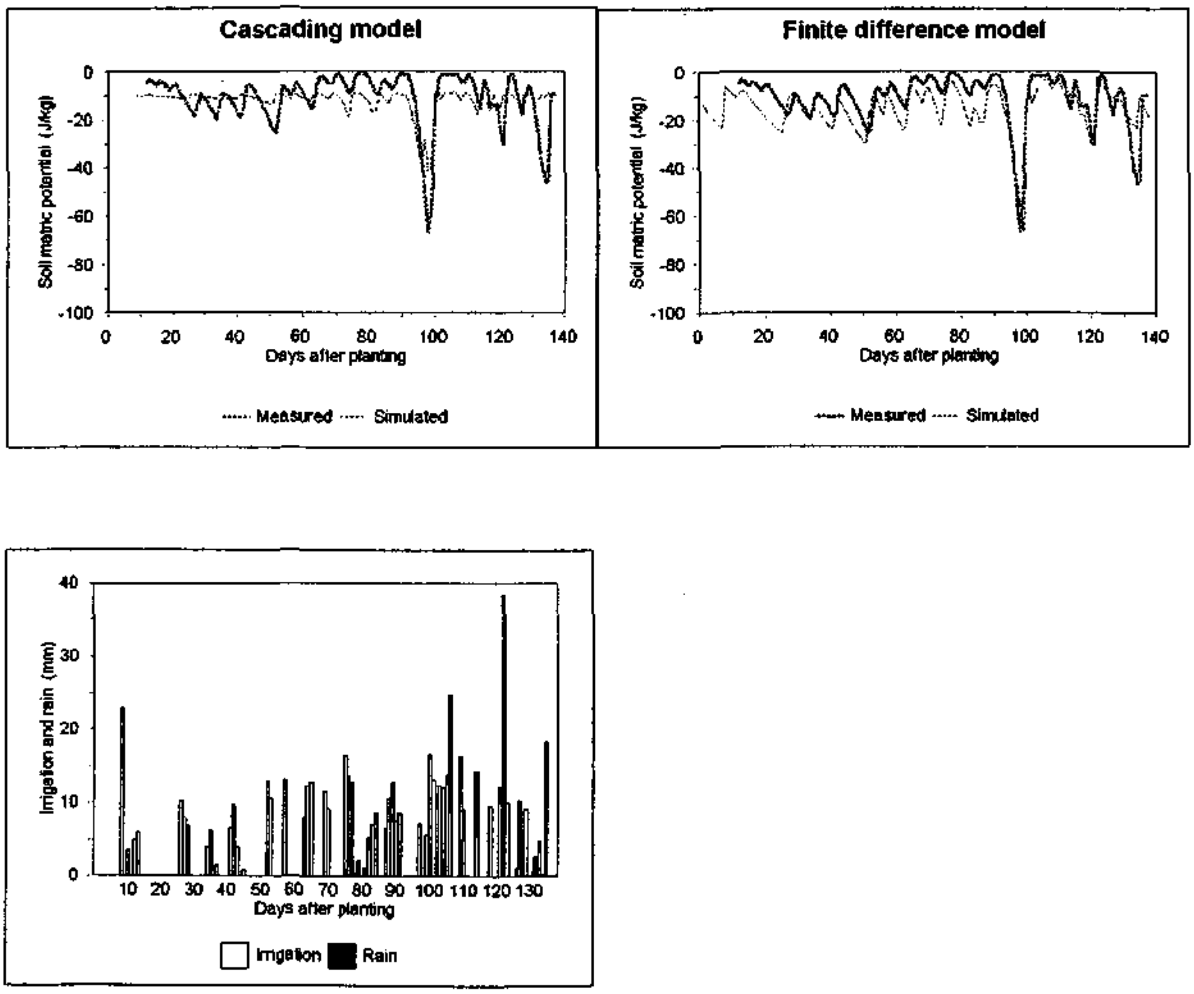


Figure 3.3. Measured and simulated soil matric potential with the cascading and finite-difference water balance model at 16 cm soil depth, as well as irrigation and rainfall (wheat crop, winter 1999 season, pivot Fourth, leaching fraction treatment, replication 2).

Table 3.1. Simulated seasonal values of the soil water balance components for each crop and treatment at pivot Major.

Crop and season	Strategy	Rainfall (mm)	Irrigation (mm)	Soil evaporation (mm)	Crop transpiration (mm)	Drainage (mm)	Canopy interception (mm)	Runoff (mm)	Change in soil water storage (mm)
Sugar beans 1997/98	Leaching fraction	345	113	271	164	0	17	16	-10
	Field capacity	338	82	274	143	0	14	16	-27
	Deficit	336	74	276	130	0	14	15	-25
	Dry-land	321	0	228	105	0	7	14	-33
Wheat 1998	Leaching fraction	234	419	360	158	55	27	7	-21
	Field capacity	226	329	296	158	74	27	7	-40
	Deficit	221	224	306	154	0	25	7	-47
Maize 1998/99	Leaching fraction	204	341	187	257	60	39	28	-26
	Field capacity	205	264	195	260	46	37	25	-94
	Deficit	190	198	204	185	37	30	17	-85
Wheat 1999	Leaching fraction	119	309	171	221	18	22	8	-12
	Field capacity	119	285	237	183	1	20	7	-44
	Deficit	119	197	164	157	0	19	8	-32
Maize 1999/00	Leaching fraction	630	77	274	244	129	27	57	-24
	Field capacity	621	41	274	231	111	26	65	-45
	Deficit	619	31	271	231	117	27	48	-44
Wheat 2000	Leaching fraction	2	404	235	236	35	30	3	-133
	Field capacity	2	354	218	215	32	27	6	-142
	Deficit	2	320	217	175	32	25	4	-131

Table 3.2. Simulated seasonal values of the soil water balance components for each crop and treatment at pivot Tweefontein.

Crop and season	Strategy	Rainfall (mm)	Irrigation (mm)	Soil evaporation (mm)	Crop transpiration (mm)	Drainage (mm)	Canopy interception (mm)	Runoff (mm)	Change in soil water storage (mm)
Sugarbeans 1997/98	Leaching fraction	192	82	188	70	0	9	22	-15
	Field capacity	191	70	189	70	0	9	20	-27
	Deficit	194	59	188	70	0	9	20	-34
Wheat 1998	Leaching fraction	184	444	386	153	0	26	25	38
	Field capacity	222	339	367	153	0	27	19	-5
	Deficit	201	208	309	150	0	25	22	-97
Sugarbeans 1998/99	Leaching fraction	161	278	288	134	0	19	39	-41
	Field capacity	154	237	287	106	0	16	34	-52
	Deficit	156	199	277	87	0	16	33	-58
Wheat 1999	Field capacity	132	458	314	222	0	22	47	-15
Maize 1999/00	Field capacity	668	13	264	225	0	26	130	36
Wheat 2000	Field capacity	2	615	260	236	0	29	63	29

Table 3.3. Simulated seasonal values of the soil water balance components for each crop and treatment at pivot Jacuzzi.

Crop and season	Strategy	Rainfall (mm)	Irrigation (mm)	Soil evaporation (mm)	Crop transpiration (mm)	Drainage (mm)	Canopy interception (mm)	Runoff (mm)	Change in soil water storage (mm)
Sugarbeans 1997/98	Leaching fraction	190	49	191	48	0	5	26	-31
	Field capacity	198	41	184	48	0	4	35	-32
	Deficit	199	29	173	48	0	5	28	-26
Wheat 1998	Leaching fraction	202	408	339	154	0	28	27	62
	Field capacity	202	368	355	154	0	28	22	11
	Deficit	207	315	323	154	0	28	24	-7
Sugarbeans 1998/99	Leaching fraction	152	428	253	139	0	22	68	98
	Field capacity	152	360	290	91	0	16	53	62
	Deficit	152	275	299	52	0	12	41	23

Table 3.4. Simulated seasonal values of the soil water balance components for each crop and treatment at pivot Fourth.

Crop and season	Strategy	Rainfall (mm)	Irrigation (mm)	Soil evaporation (mm)	Crop transpiration (mm)	Drainage (mm)	Canopy interception (mm)	Runoff (mm)	Change in soil water storage (mm)
Wheat 1999	Leaching fraction (repl. 1)	122	391	187	222	77	25	0	2
	Field capacity (repl. 1)	114	295	176	216	0	25	0	-8
	Deficit (repl. 1)	118	245	167	180	0	22	0	-6
	Leaching fraction (repl. 2)	119	446	171	221	148	22	0	3
	Field capacity (repl. 2)	109	283	171	220	0	22	0	-21
	Deficit (repl. 2)	115	265	175	186	0	20	0	-1
Maize 1999/00	Leaching fraction (repl. 1)	676	9	253	229	201	27	0	-25
	Field capacity (repl. 1)	643	9	251	237	158	29	0	-23
	Deficit (repl. 1)	660	23	252	226	189	29	0	-13
	Leaching fraction (repl. 2)	667	45	248	225	224	31	0	-16
	Field capacity (repl. 2)	666	30	248	225	205	30	0	-12
	Deficit (repl. 2)	660	23	252	226	189	29	0	-13
Wheat 2000	Leaching fraction (repl. 1)	2	525	232	241	0	22	0	32
	Field capacity (repl. 1)	2	414	226	234	0	22	0	-66
	Deficit (repl. 1)	2	314	183	201	0	20	0	-88
	Leaching fraction (repl. 2)	2	415	233	243	0	23	0	-82
	Field capacity (repl. 2)	2	450	236	241	0	23	0	-48
	Deficit (repl. 2)	2	338	217	223	0	23	0	-123

3.2.3. Salt redistribution

A detailed validation of salt redistribution was carried out by comparing simulated values and measurements of electrical conductivity of the soil solution. Measured data were obtained from soil water samples extracted with the ceramic cup soil water samplers. The comparison is shown in Figure 3.4 for three irrigation treatments. The model predicted EC values at different depths in the soil profile very well. The model also gave good predictions of the redistribution of single ionic species in the soil profile (Appendix N, Figures N11 to N13). The contents of solid phase gypsum in the soil profile at the beginning of the seasonal simulations were estimated. The major reason for discrepancies between measured and simulated data was spatial and temporal variability of salts. The samples collected with the ceramic cups for laboratory analyses generally represented the average quality of soil water in the few days before sampling. It was not possible to obtain more water samples for laboratory analysis, as air entry in the ceramic cup tube causes loss of vacuum. More frequent field visits were required, but this was not feasible due to logistical reasons.

A summary of the seasonal salt balances predicted with the cascading model for all pivots and treatments is included in Tables 3.5 to 3.8. The amount of salts added was calculated based on irrigation amounts and quality. Leached salts were predicted depending on drainage amount and quality. Leached salts were 0 for pivots Tweefontein (Table 3.6) and Jacuzzi (Table 3.7) where no drainage was predicted due to the presence of the spoil layer. Runoff of salts depended on the calculated runoff of water. This was 0 for pivot Fourth (Table 3.8) where no water runoff was predicted. Increase in soluble salts in the 1.1 m soil profile was generally predicted depending on irrigation and rainfall. Gypsum precipitation in the 1.1 m soil profile also depended on irrigation and rainfall. The highest amount of gypsum precipitated at the end of the trial was predicted for pivot Major, which was irrigated for the longest period.

During the course of the trial, soil salinity increased in the root-zone compared to the initial conditions (Appendix A, Tables A16 to A39). This increase in salinity was, however, limited due precipitation of gypsum and leaching of soluble salts. On the other hand, according to the borehole measurements presented in Section 2.3.4.3.1 for pivot Major, no salt breakthrough was detected in groundwater. The hypothesis was that, at the end of the trial, the centre of mass of salts leached out of the root-zone was located in the vadose zone between the root-zone and groundwater. In order to check this hypothesis, deep soil samples were collected in June 2000 and analysed in the laboratory. The results of these laboratory analyses are shown in Appendix A (Tables A34 to A36) and were discussed in Section 2.3.3.1. It was interesting to compare whether the mass of salts predicted to be leached by the model matches the mass of salts measured in deep soil samples. The comparison was done for pivots Major and Fourth and the results are presented in Table 3.9. The predicted mass of salts leached below the root-zone represents the sum of salts leached until June 2000 (Tables 3.5 and 3.8). The salts measured in deep soil samples represent the sum of soluble Ca^{2+}, Mg^{2+}, K^{+}, Na^{+} and SO_4^{2-} below the 1.1 m root-zone (Tables A34 and A35, Appendix A). These masses of soluble salts were reduced by the masses measured below 1.1 m outside the pivot areas. The predicted mass of salts leached was in the range of the mass of salts measured below the root-zone for pivot Major. This indicated that leached salts were most probably trapped in the vadose zone between the root-zone and groundwater. For pivot Fourth, the predicted mass of salts leached was higher than the mass of salts measured below 1.1 m. No borehole water quality measurements were available for pivot Fourth to investigate the possibility of groundwater contamination at this well-drained site. It is most likely that portion of the salts leached out of the root-zone was transported through groundwater into the Tweefontein pan, which was located near the irrigated area.

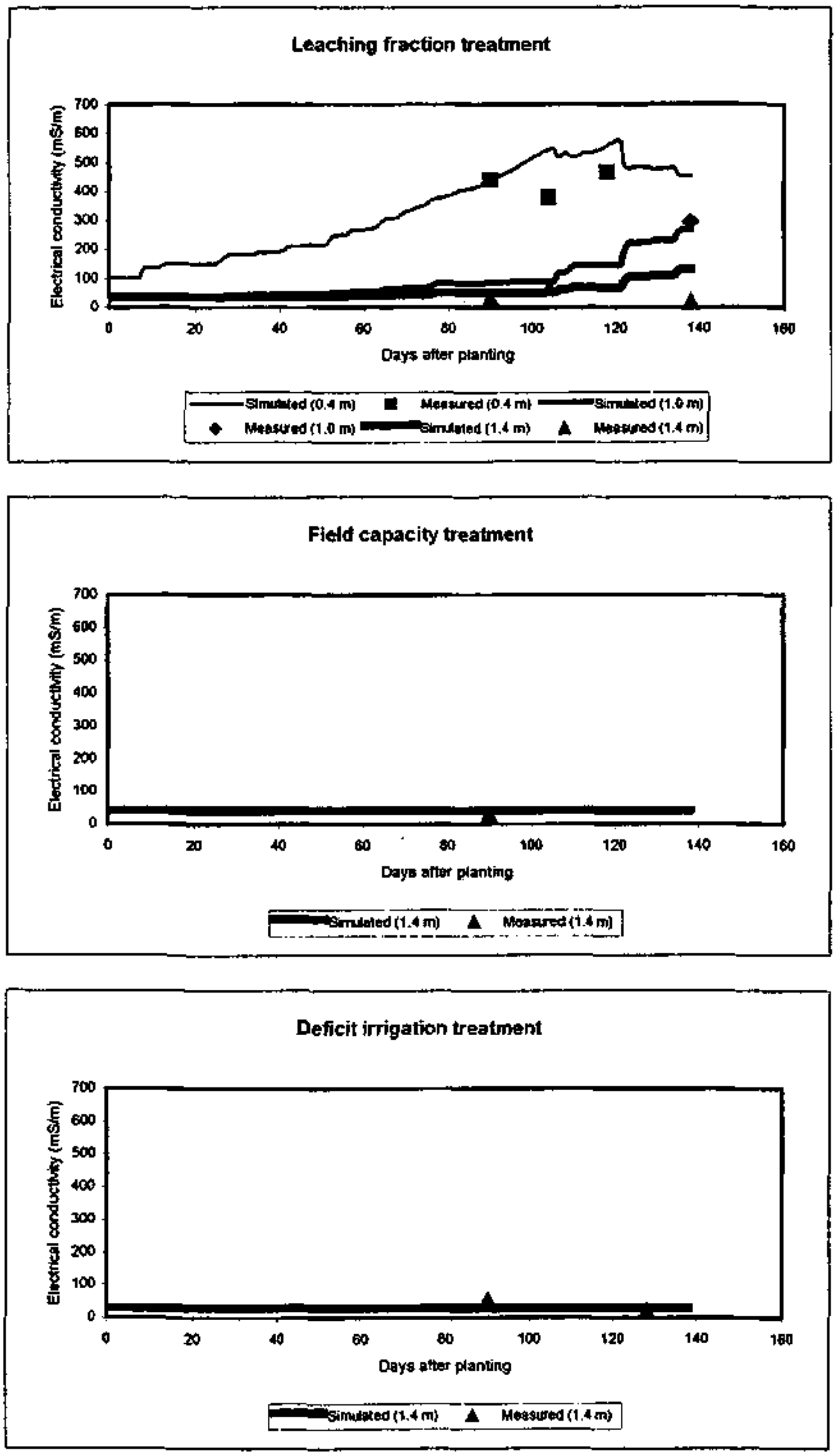


Figure 3.4. Measured and simulated electrical conductivity of the soil solution for three irrigation treatments (*wheat crop, winter 1999 season, pivot Fourth, replication 2*).

Table 3.5. Simulated seasonal values of the salt balance components for each crop and treatment at pivot Major.

Crop and season	Strategy	Salts added (measured) (Mg ha^{-1})	Salts runoff (simulated) (Mg ha^{-1})	Salts leached (simulated) (Mg ha^{-1})	Mass of salts in the 1.1 m soil profile at the beginning of season (measured) (Mg ha^{-1})	Mass of salts in the 1.1 m soil profile at the end of season (simulated) (Mg ha^{-1})	Gypsum precipitated in the 1.1 m soil profile at the beginning of season (simulated) (Mg ha^{-1})	Gypsum precipitated in the 1.1 m soil profile at the end of season (simulated) (Mg ha^{-1})
Sugarbeans 1997/98	Leaching fraction	3.23	0.01	0	0.29	2.31	0	1.2
	Field capacity	2.32	0	0	0.55	2.05	0	0.82
	Deficit	2.12	0	0	0.47	1.86	0	0.72
	Dry-land	0.02	0	0	0.52	0.54	0	0
Wheat 1998	Leaching fraction	11.38	0.30	0.12	6.24	12.29	2.50	7.41
	Field capacity	8.94	0	0.46	5.67	10.07	1.82	5.90
	Deficit	6.10	0	0	4.13	6.80	1.62	5.05
Maize 1998/99	Leaching fraction	9.90	0.20	0.60	8.24	10.93	8.77	15.18
	Field capacity	7.66	0.14	1.54	12.14	11.64	8.79	15.27
	Deficit	5.74	0.84	0.11	4.33	4.8	5.63	9.95
Wheat 1999	Leaching fraction	8.27	0.03	0.66	9.49	11.52	16.95	22.50
	Field capacity	7.67	0.02	0.04	9.49	11.01	17.03	23.12
	Deficit	5.33	0.04	0	9.49	10.57	11.89	16.10
Maize 1999/00	Leaching fraction	2.10	1.47	1.05	7.98	11.95	23.26	18.87
	Field capacity	1.14	0	1.27	11.53	13.54	24.74	22.60
	Deficit	0.87	0	0.38	4.05	6.01	14.84	13.37
Wheat 2000	Leaching fraction	11.29	0.09	0.84	7.67	7.23	20.05	30.85
	Field capacity	9.84	0.18	0.14	2.11	2.61	20.50	29.52
	Deficit	8.91	0.12	0.14	3.21	3.41	12.34	20.79

Table 3.6. Simulated seasonal values of the salt balance components for each crop and treatment at pivot Tweefontein.

Crop and season	Strategy	Salts added (measured) (Mg ha^{-1})	Salts runoff (simulated) (Mg ha^{-1})	Salts leached (simulated) (Mg ha^{-1})	Mass of salts in the 1.1 m soil profile at the beginning of season (measured) (Mg ha^{-1})	Mass of salts in the 1.1 m soil profile at the end of season (simulated) (Mg ha^{-1})	Gypsum precipitated in the 1.1 m soil profile at the beginning of season (simulated) (Mg ha^{-1})	Gypsum precipitated in the 1.1 m soil profile at the end of season (simulated) (Mg ha^{-1})
Sugarbeans 1997/98	Leaching fraction	1.89	0.09	0	0.46	2.16	0	0.10
	Field capacity	1.62	0.05	0	0.29	1.72	0	0.14
	Deficit	1.37	0.03	0	0.39	1.64	0	0.09
Wheat 1998	Leaching fraction	10.96	0.22	0	4.89	11.32	0.28	4.59
	Field capacity	8.34	0.01	0	3.10	8.44	0.71	3.70
	Deficit	5.05	0.02	0	3.46	6.14	1.03	3.38
Sugarbeans 1998/99	Leaching fraction	8.31	0.27	0	9.22	11.54	4.70	10.42
	Field capacity	7.09	0.18	0	6.44	9.26	4.70	8.79
	Deficit	5.95	0.13	0	4.40	6.12	3.76	7.86
Wheat 1999	Field capacity	12.87	0.52	0	10.98	16.60	10.80	17.53
Maize 1999/00	Field capacity	0.41	0.01	0	10.55	13.53	17.31	14.73
Wheat 2000	Field capacity	17.21	1.78	0	5.35	11.35	13.53	22.96

Table 3.7. Simulated seasonal values of the salt balance components for each crop and treatment at pivot Jacuzzi.

Crop and season	Strategy	Salts added (measured) (Mg ha^{-1})	Salts runoff (simulated) (Mg ha^{-1})	Salts leached (simulated) (Mg ha^{-1})	Mass of salts in the 1.1 m soil profile at the beginning of season (measured) (Mg ha^{-1})	Mass of salts in the 1.1 m soil profile at the end of season (simulated) (Mg ha^{-1})	Gypsum precipitated in the 1.1 m soil profile at the beginning of season (simulated) (Mg ha^{-1})	Gypsum precipitated in the 1.1 m soil profile at the end of season (simulated) (Mg ha^{-1})
Sugarbeans 1997/98	Leaching fraction	1.40	0.03	0	0.28	1.06	0	0.59
	Field capacity	1.17	0.01	0	0.70	1.34	0	0.52
	Deficit	0.82	0	0	0.80	1.44	0	0.18
Wheat 1998	Leaching fraction	10.87	0.27	0	1.12	8.13	1.07	4.66
	Field capacity	9.81	0.13	0	1.77	7.53	1.15	5.07
	Deficit	8.39	0.07	0	2.30	7.04	0.93	4.51
Sugarbeans 1998/99	Leaching fraction	13.46	1.18	0	3.75	11.41	5.36	9.98
	Field capacity	11.32	0.71	0	4.79	8.32	5.79	12.87
	Deficit	8.65	0.34	0	4.63	7.18	4.96	10.72

Table 3.8. Simulated seasonal values of the salt balance components for each crop and treatment at pivot Fourth.

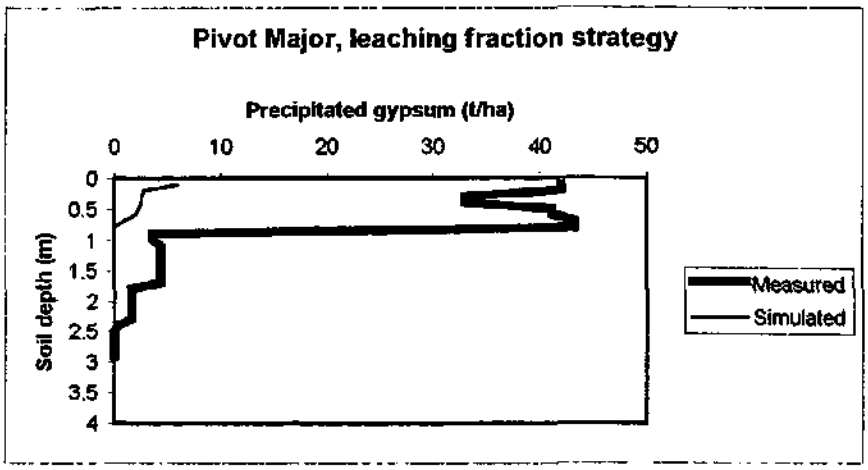
Crop and season	Strategy	Salts added (measured) (Mg ha^{-1})	Salts runoff (simulated) (Mg ha^{-1})	Salts leached (simulated) (Mg ha^{-1})	Mass of salts in the 1.1 m soil profile at the beginning of season (measured) (Mg ha^{-1})	Mass of salts in the 1.1 m soil profile at the end of season (simulated) (Mg ha^{-1})	Gypsum precipitated in the 1.1 m soil profile at the beginning of season (simulated) (Mg ha^{-1})	Gypsum precipitated in the 1.1 m soil profile at the end of season (simulated) (Mg ha^{-1})
Wheat 1999	Leaching fraction (repl. 1)	11.11	0	0.14	1.00	8.67	0	3.30
	Field capacity (repl. 1)	8.41	0	0	1.52	6.88	0	3.05
	Deficit (repl. 1)	6.96	0	0	0.83	5.43	0	2.36
	Leaching fraction (repl. 2)	12.60	0	0.41	2.20	10.69	0	3.70
	Field capacity (repl. 2)	8.00	0	0	1.93	6.81	0	3.12
	Deficit (repl. 2)	7.53	0	0	2.27	6.50	0	3.30
Maize 1999/00	Leaching fraction (repl. 1)	0.27	0	7.70	11.76	6.86	3.02	0.49
	Field capacity (repl. 1)	0.28	0	2.53	8.10	8.31	3.65	1.19
	Deficit (repl. 1)	0.67	0	2.25	5.71	6.63	2.73	0.23
	Leaching fraction (repl. 2)	1.29	0	7.60	10.58	6.84	3.46	0.89
	Field capacity (repl. 2)	0.87	0	4.15	9.60	9.01	4.60	1.91
	Deficit (repl. 2)	0.67	0	2.25	5.71	6.63	2.73	0.23
Wheat 2000	Leaching fraction (repl. 1)	14.63	0	0	1.34	8.72	0	7.25
	Field capacity (repl. 1)	11.56	0	0	0.93	5.65	0	6.84
	Deficit (repl. 1)	8.76	0	0	0.62	4.36	0	5.02
	Leaching fraction (repl. 2)	11.60	0	0	1.34	6.18	0	6.76
	Field capacity (repl. 2)	12.58	0	0	0.93	5.70	0	7.81
	Deficit (repl. 2)	9.46	0	0	1.34	4.83	0	5.97

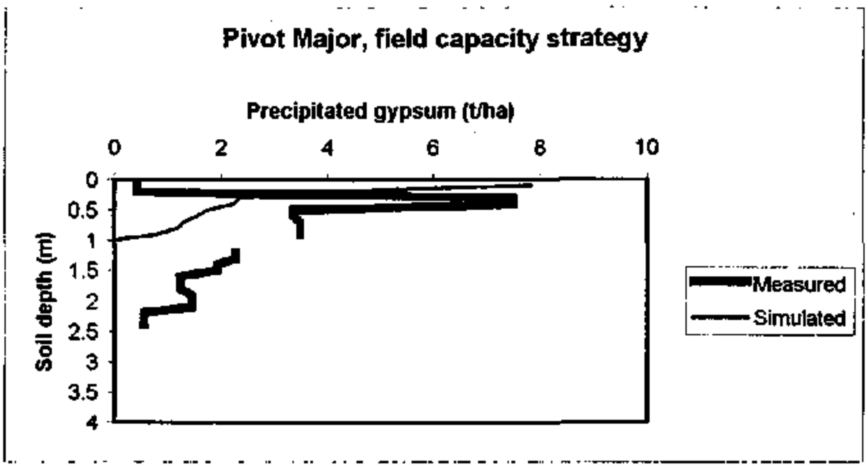
Table 3.9. Amount of salts predicted to be leached by the SWB model until June 2000 and amount of salts measured in deep soil samples collected in June 2000 below the root-zone for pivots Major and Fourth.

Pivot	Strategy	Salts leached (SWB simulations) (Mg ha^{-1})	Salts measured below the 1.1 m root-zone (deep soil samples) (Mg ha^{-1})
Major	Leaching fraction	2.43	2.27
	Field capacity	3.31	2.12
	Deficit	0.49	1.35
Fourth	Leaching fraction	7.84	1.40
	Field capacity	2.53	1.40
	Deficit	2.25	0.87

3.2.4. Gypsum precipitation

The amount of gypsum precipitated in the soil profile was measured only once during the course of the field trial. This was done on deep soil samples collected in June 2000. A comparison between measured and simulated values of precipitated gypsum is shown in Figure 3.5 for pivot Major and three irrigation treatments. Measured values of precipitated gypsum were much higher compared to the simulations, in particular for the leaching fraction and deficit irrigation strategies. It appears that the methodology used to measure gypsum in solid phase was not correct, as much higher values of measured precipitated gypsum were obtained than the amount of salts added through irrigation. For example, for the leaching fraction strategy, the measured amount of gypsum precipitated was 366.72 Mg ha^{-1}. However, from December 1997 to June 2000, only 34.88 Mg ha^{-1} of salts were added (Table 3.5), based on measured irrigation water quality and amount. The main source of error of the method used to measure gypsum in solid phase was adsorbed sulphate. In the method used, sulphate was measured in order to calculate gypsum in solid phase. However, sulphate in soils can originate both from dissolved gypsum and from the adsorptive complex. It is also possible that these soils already retained a certain amount of sulphate before irrigation started. In Figure 3.5, the measured amounts of gypsum were reduced by the amount of gypsum measured with the same methodology in samples collected outside the pivot area, which was never irrigated with gypsiferous water.





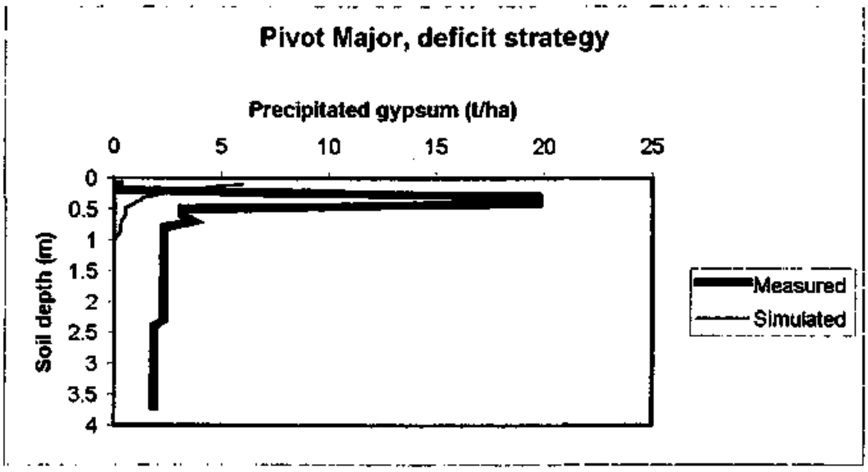


Figure 3.5. Measured and simulated values of gypsum precipitated in the soil profile in June 2000 at pivot Major.

3.2.5. Comparison between SWB and FAO-SWS

Simulations of gypsum precipitation in the soil profile with the SWB model were compared to the FAO-SWS model (Suarez et al., 2001). The FAO-SWS is a user-friendly modification to UNSATCHEM (Simunek et al., 2001) to be released by the FAO, and is the state-of-the-art model for simulating the effect of irrigation water quality on soil salinity and crop response. It includes one-dimensional, variably saturated water flow, CO_2 production and transport, as well as multi-component solute transport and major ion chemistry.

In order to compare the two models, one-year simulations were run for an imaginary crop with a constant root depth of 0.6 m, full canopy cover and a constant PET of 4 mm d^{-1}. Initial soil water content was at field capacity and bulk density was 1.5 Mg m^{-3}. Irrigation water quality typical for the Tweefontein dam (Appendix A, Tables A51 and A53) was used in the simulations. Rain water quality was taken from Bolt (1979). Initial cation (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) content in the soil was 1 meq kg^{-1}, whilst initial anion (SO_4^{2-} and Cl^{-}) content was 2 meq kg^{-1}. The soil profile was 1.1 m deep and free draining.

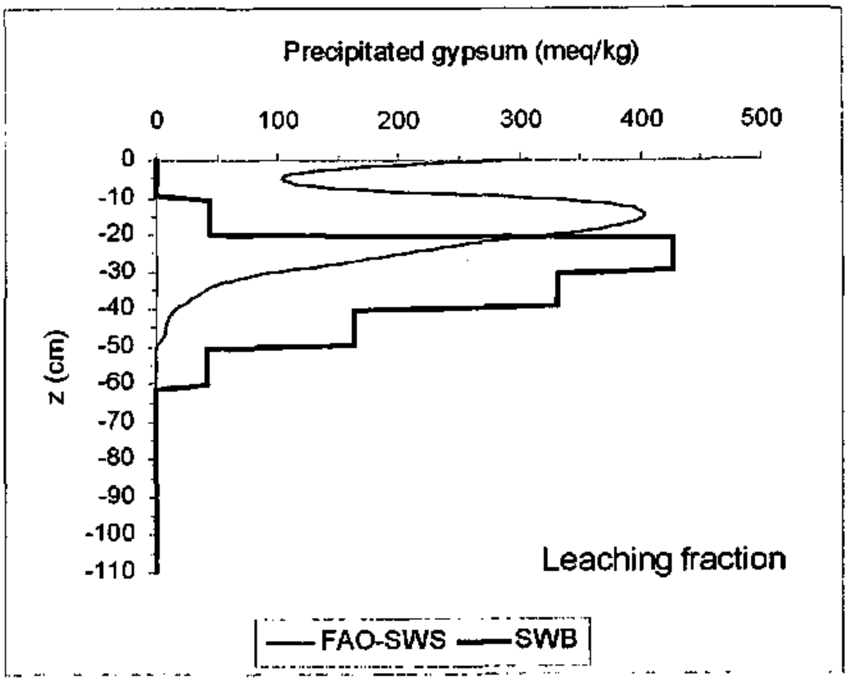
For the SWB model, the volumetric soil water content at field capacity was 0.2 m m^{-1}, the volumetric soil water content at permanent wilting point was 0.1 m m^{-1} and no runoff was simulated.

For the FAO-SWS model, the root system was assumed to have the same pattern computed by the SWB model (Campbell and Diaz, 1988), with no roots in the top 10 cm soil layer. Soil type was selected to be a loam with K_s = 24.96 cm d^{-1} (default value). Default values were used for all the other inputs required in FAO-SWS.

Simulations were carried out applying 2 mm d^{-1} of irrigation and assuming 2 mm d^{-1} of rain (irrigations up to field capacity), as well as applying 2.4 mm d^{-1} of irrigation and assuming 2 mm d^{-1} of rain (irrigations with 20% leaching fraction). Figure 3.6 represents the meq of gypsum precipitated per kg of soil at different depths in the soil profile at the end of the one-year simulations with SWB and FAO-SWS. The SWB output values were calculated per 10 cm soil layer, whilst the output of FAO-SWS is for 101 nodes in the 1.1 m deep soil profile. Both trends and absolute values of predicted gypsum precipitation matched well. The centre of mass of precipitated gypsum predicted with SWB was deeper in the soil profile compared to FAO-SWS predictions, as the cascading soil water balance of SWB assumes complete mixing of the infiltrating water with the soil solution and does not allow water and salts to move upwards. The simulations with SWB can, therefore, be seen as the worst-case scenario from the point of view of leaching.

It is interesting to note the peak in precipitated gypsum close to the soil surface predicted with FAO-SWS due to evaporation (Figure 3.6). The dip predicted with FAO-SWS at about 5 cm soil depth is due to the absence of roots in the top 10 cm. The peak in precipitated gypsum was between 20 and 30 cm soil depth for the SWB model and between 10 and 20 cm for the FAO-SWS model. At these depths, the root system is most dense and the soil solution gets most concentrated due to plant water uptake. Further down in the soil profile, the root system is less dense and the predicted values of precipitated gypsum were lower. Both models predicted a slightly deeper centre of mass of precipitated gypsum when a leaching fraction was applied.

This gave confidence that the cascading soil water balance and Robbins' (1991) chemical equilibrium used in the SWB model are accurate enough in gypsum-dominated systems. Caution should, however, be exercised in the simulation of chemical equilibrium in calcitic soils with Robbins' (1991) model (DL Suarez, Salinity Laboratory, Riverside, California, personal communication).



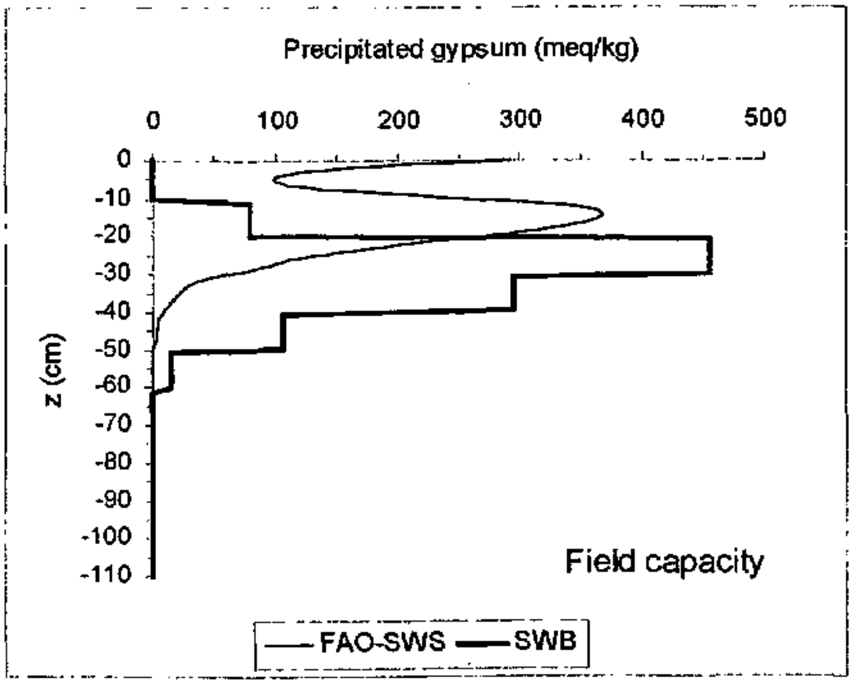


Figure 3.6. Amounts of gypsum precipitated in the soil profile simulated with SWB and FAO-SWS for an imaginary pasture crop after one year of irrigation with Tweefontein water.

CHAPTER 4

4. SCENARIO SIMULATIONS

4.1. Introduction

The validation of SWB presented in the previous Sections gave confidence that the model could be used for long-term scenario simulations in order to recommend the most suitable management practices.

Different cropping practices have different implications for water utilization, capital outlay, salt precipitation, and economic impacts. The managers are therefore faced with a decision-making problem defined by Massam (1988) as "*Given a set of alternate plans, each characterized by a set of assessments for selected criteria, and a set of interest groups whose opinions regarding the selection of criteria and the assessment have to be considered, provide an appropriate procedure to define the attractiveness of the alternate plans with a view to identifying the best one.*" All these factors have to be valued and harmonised to determine an optimal solution for the problem.

Although it was assumed that the cropping system is sustainable, it was still very important to verify this. When deciding what cropping system to adopt, it is important to consider not only which system uses the most water or which system precipitates the most salts but also to assess which system is the best economic option for the particular conditions. To do this, the economic feasibility of every cropping system must be evaluated before a decision is made. Multiple Criteria Decision-Making (MCDM) is both an approach and a body of techniques to assist people to relate their multiple, non-commensurate and conflicting criteria to optimal decisions (Bogetoft and Pruzan, 1991).

The objective of this Section was to investigate the long-term effects of different cropping systems on the volume of water used for irrigation, and the subsequent precipitation of salts in the profile. MCDM techniques were also used to advise Kleinkopje Collieries management on the most economical and environmentally sustainable cropping system for irrigation with gypsiferous mine water.

4.2. Materials and methods

4.2.1. Long-term effects of cropping systems and environmental impact

The long-term modelling approach used by Annandale et al. (1999a) showed that irrigation of agricultural crops with gypsiferous mine water is sustainable and that the soil can act as an effective salt sink. In this Section, the SWB model has been used to determine the long-term (30 years) water use and yields of different cropping systems. The water and salt balance for different crop rotations were simulated. The model required as inputs, soil, weather and crop data. Soil data for field Major were used as input. The specific plant growth parameters were determined in the field trial undertaken at Kleinkopje Colliery under centre pivot irrigation. Long-term weather data were generated for the region using the CLIMGEN weather data generator (Campbell, 1990) and used in the simulations. Water qualities used for both rain and irrigation can be seen in Table 4.1.

Table 4.1. Water qualities for both rain and irrigation as used in the simulations, concentrations are in mmol l^{-1}.

Ion	Irrigation	Rainfall
Ca^{2+}	14	0.002
Mg^{2+}	7	0.012
Na^{+}	1	0.086
K^{+}	0.0	0.008
Cl^{-}	1	0.102
SO_4^{2-}	21	0.006

It was assumed that double cropping would be feasible and SWB was programmed to irrigate when there was a 20 mm water deficit in the soil profile. Three different irrigation strategies were simulated:

- Irrigations to field capacity and then adding a 20 % leaching fraction,
- Irrigating to field capacity, and
- Leaving a 20% room for rain.

Three different cropping strategies were simulated, a perennial pasture, annual pastures and cash crops. Long-term simulations were carried out for the following farming systems:

- Cash crops: wheat/beans, wheat/maize and wheat/soybeans rotations.
- Annual pastures: rye/babala, ryegrass/babala and oats/babala rotations.
- Perennial pastures: lucerne/fescue mixture.

For the long-term simulations, SWB was modified to simulate the harvesting of the pastures.

Irrigations were simulated for 30 years, and the water use and average yield of the different rotations were determined for every irrigation strategy.

4.2.2. Modelling the decision process with MCDM techniques

The methodology applied to this particular problem was the 'prior articulation of alternatives' model (Bogetoft and Pruzan, 1991) where the analyst undertakes an extensive investigation of the set of feasible alternatives ($X=\{x^1,x^2,\ldots x^n\}$) and presents them to the decision-maker as:

$$\max F[f_1(x), f_2(x), \ldots, f_n(x)]$$

$$\text{s.t.} \quad x \in X$$

where X is the set of feasible alternatives, $f_1,\ldots,f_n$ functions measuring the value of each criterion to the decision-maker, and F the unknown preference function of the decision-maker.

The general problem is restated in the criterion space Y:

$$Y = \{[f_1(x), f_2(x), \ldots, f_n(x)] \mid x \in X\}$$

and the objective function therefore becomes:

$$\max F(y) \qquad \text{s.t.} \quad y \in Y$$

In this notation, $f_1(x)$, $f_2(x)$,...,$f_n(x)$ becomes the criterion value generated by evaluating the different alternatives and associated criteria. The decision-maker consequently inspects the set of alternatives, clarifies his preferences and makes a choice to maximize utility (Bogetoft and Pruzan, 1991, and Massam, 1988).

The management of Kleinkopje Colliery was faced with 11 possible agricultural activities $(x_1,x_2,\ldots,x_8)$, see Table 4.2. The analyst evaluated the agricultural activities on the basis of four criteria, specifically:

WU - Water utilisation in m^3 over a period of 30 years
CR - Total capital requirement per m^3 water used for the specific farming alternative
EA - Net present value for the specific farming alternative over 30 years
PCM - Precipitation of salts in Mg ha^{-1} over 30 years

These criteria are used in the calculations of the value of $f_1(x)$ to determine the derived utility for the specific option and criterion. Water utilization (WU) indicates the quantity of water utilized by the specific farming alternative. The colliery supplies the capital to establish the agricultural operation, which is presented by CR (capital requirement). Net Present Value is used as an indicator of economic sustainability of the farming activities. Precipitation of salts PCM was introduced to estimate the environmental impact of the project.

4.2.3. Economic impact

The volume of polluted water produced by the mine and the long-term water use of the cropping system (determined from the long-term simulations) were used to determine the area to be irrigated to utilize the required volume of water. The capital required to install the irrigation system was calculated assuming a cost of R 15 000 ha^{-1} for the installation of the irrigation system. The cost of livestock and machinery was not included in the capital requirement.

Budgets for the different crops used in the farming activities were obtained from the COMBUD budgets for the region and adapted according to the yield obtained from the simulations. Running cost of irrigation was calculated using the long-term average water use of the crop.

Pasture crops were assumed to be utilized in combination with one of the following:

- Dairy cow system. Average production of 18 l cow^{-1} d^{-1} and a dry matter intake of 15 kg cow^{-1} d^{-1}.
- Beef system. Average daily gain (ADG) of 1 kg and a dry matter intake of 8 kg d^{-1}.

An investment analysis was done for all the different rotations, where the rotation was evaluated over a period of 30 years, assuming an interest component of 15% based on the economic conditions (Government long bond yield). This analysis was done to assess which rotation is the best option from the farm operating company's point of view.

4.2.4. Analysis

The farming alternatives and the calculated values per criteria are represented in Table 4.2.

Table 4.2. Farming alternatives and values per criterion.

Farming Activity	Water utilization (Million m^3)	Capital requirement (Million R)	Economic analysis (Million R)	Salt precipitation ($Mg\ ha^{-1}$)
Wheat/Soybeans	14.13	16.8	12.6	256
Wheat/Maize	16.53	14.4	10.2	301
Wheat/Beans	13.92	17.1	12.1	252
Rye/Babala: Milk	15.58	28.0	26.8	277
Rye/Babala: Beef	15.58	19.6	7.0	277
Oats/Babala: Milk	21.44	23.1	27.9	388
Oats/Babala: Beef	21.44	17.6	8.9	388
Ryegrass/Babala: Milk	14.32	28.3	25.2	256
Ryegrass/Babala: Beef	14.32	16.8	17.0	256
Lucerne/Fescue: Milk	27.07	17.3	21.2	501
Lucerne/Fescue: Beef	27.07	13.7	13.3	501

The Conflict Analysis Method (CAM) is used because it successfully combines the main features of various well-known methods like ELECTRE, PROMETHEE, ORESTE, and AHP (van Huylenbroeck, in El-Swaify and Yakowitz, 1998). In this method preference indicators are calculated for each pair of alternatives, which take into account both the scores for each criterion as well as the relative importance of the criteria.

To measure the relative difference in value between two alternatives $\hat{e}_j(a,b)$, the original data is transformed into a linear preference function (see Massam, 1988 and van Huylenbroeck, 1995 for other functions). On the basis of these preference scores, aggregate preference indices are calculated with the following formula:

$$P(a,b) = \frac{100}{n}\sum_{j=1}^{n} g_j . \hat{e}_j(a,b)$$

with:

$\hat{e}_j(a,b)$ - Difference in impact score on criterion j for those criteria for which a is better than b
g_j - Relative importance of criterion j
n - Number of criteria

The relative importance of each criterion needs to be determined. Often decision-makers are unable to give specific preference scores for the different criteria. In this case a feasible alternative is the Average Value Ranking (AVR) method as discussed in van Huylenbroeck (1990). In this approach the g_j factor is calculated with the following formula:

$$g_j = \sum_{i=k}^{n} \frac{1}{i}$$

where k = the ranking for criterion j (with k = 1 for the most important and k = n for the least important criterion).

The mine management ranked economic impact (EA) as the most important criterion, followed by salt precipitation (PCM), water usage (WU), and capital requirement (CR).

4.3. Results and discussions

The major elements of the water and salt balances, namely total rainfall (R), irrigation (I), evaporation (E), transpiration (T), evapotranspiration (ET), drainage (D), salts added to the profile, salts leached from the profile and salts precipitated in the profile as simulated over a 30-year period for the three irrigation strategies, are given in Tables 4.3, 4.4 and 4.5.

It is clear that the permanent pasture uses the most water followed by the annual pastures and then the cash crops. The reason for this is that with a perennial pasture there is a full cover canopy throughout the year and thus transpiration is high, as opposed to cash crops where a drying off period is required during which no irrigation takes place. Annual pastures use more water than the cash crops because no drying off period is required.

Salts precipitated followed the same trend with the most precipitating under the permanent pasture and the least under the cash crop rotations. The salts that neither leached nor precipitated were those still in the soil solution and those that were intercepted, which was negligible.

The Lucerne/Fescue: Milk farming combination is the most preferred farming alternative (see Table 4.6). Value adding through the use of animal production systems (milk and beef) increases farming profitability. Since farming profitability received the highest ranking from the mine management, this is the most important determining factor in the results. Capital requirement's low ranking caused a positive bias towards capital intensive farming activities. The reason for the low ranking of the capital requirement criterion is the exorbitant cost of the next best option to manage environmental pollution, which is reverse osmosis. Therefore, mine management gave a higher priority to the economic sustainability of the farming option that is measured by the EA or Net Present Value.

The year-round green canopy of the pasture crops increases water usage (WU) and salt precipitation (PCM). Cash crops require a drying-off period of two to three months during which no water is required, thus reducing water use. This fact combined with smaller margins in cash crop alternatives, leads to relatively lower rankings for these traditional irrigation-farming systems.

Table 4.3. 30-year water and salt balances for the leaching fraction strategy.

Rotation	R (m)	I (m)	E (m)	T (m)	ET (m)	D (m)	Salts Added (Mg ha^{-1})	Salts Leached (Mg ha^{-1})	Salts Precipitated (Mg ha^{-1})
Lucerne/Fescue^1	20.9	45.2	15.5	30.1	45.6	18.0	1271	741	493
Wheat/Soybeans^2	20.9	30.5	19.3	15.6	34.9	15.0	858	556	282
Wheat/Maize^2	20.9	22.5	12.5	15.8	28.3	13.3	632	458	154
Wheat/Beans^2	20.9	20.9	12.9	14.4	27.3	13.0	588	439	130
Rye/Babala^3	20.9	33.2	13.1	24.1	37.2	14.9	933	572	329
Ryegrass/Babala^3	20.9	36.1	9.8	28.6	38.4	16.1	1014	619	360
Oats/Babala^3	20.9	39.9	11.7	30.2	41.9	16.5	1120	622	422

Table 4.4. 30-year water and salt balances for the field capacity strategy.

Rotation	R (m)	I (m)	E (m)	T (m)	ET (m)	D (m)	Salts added (Mg ha^{-1})	Salts Leached (Mg ha^{-1})	Salts Precipitated (Mg ha^{-1})
Lucerne/Fescue^1	20.9	38.5	10.9	35.2	46.1	10.4	1081	521	517
Wheat/Soybeans^2	20.9	25.4	19.3	15.6	34.9	9.9	716	405	289
Wheat/Maize^2	20.9	18.4	12.0	16.1	28.1	9.8	518	348	152
Wheat/Beans^2	20.9	17.4	12.9	14.4	27.3	9.5	490	335	136
Rye/Babala^3	20.9	27.7	13.1	24.1	37.2	9.3	777	407	337
Ryegrass/Babala^3	20.9	30.0	9.7	28.6	38.3	10.1	844	440	368
Oats/Babala^3	20.9	33.2	11.7	30.2	41.9	9.8	933	465	431

Table 4.5. 30-year water and salt balances for the room for rain strategy.

Rotation	R (m)	I (m)	E (m)	T (m)	ET (m)	D (m)	Salts added (Mg ha^{-1})	Salts Leached (Mg ha^{-1})	Salts Precipitated (Mg ha^{-1})
Lucerne/Fescue^1	20.9	36.6	15.7	30.1	45.8	9.0	1028	477	508
Wheat/Soybeans^2	20.9	27.1	21.8	15.6	37.4	9.0	763	398	340
Wheat/Maize^2	20.9	18.7	13.3	15.8	29.1	8.8	526	327	174
Wheat/Beans^2	20.9	17.3	13.6	14.4	28.0	8.7	488	317	150
Rye/Babala^3	20.9	27.4	13.7	24.1	37.8	8.3	769	381	349
Ryegrass/Babala^3	20.9	29.1	9.9	28.6	38.5	8.9	819	405	372
Oats/Babala^3	20.9	32.6	12.3	30.2	42.5	8.5	918	430	444

1 - Perennial pasture
2 - Cash crops
3 - Annual pasture

Table 4.6. Calculated preference values for the alternative farming activities.

Farming Activity	Criterion				
	Water Utilization	Capital Requirement	Economic Analysis	Salt Precipitation	Preference
Wheat/Soybeans	0.01	0.20	0.23	0.01	0.44
Wheat/Maize	0.07	0.24	0.11	0.10	0.52
Wheat/Beans	0.00	0.19	0.21	0.00	0.40
Rye/Babala: Milk	0.04	0.01	0.95	0.05	1.04
Rye/Babala: Beef	0.04	0.15	0.00	0.05	0.24
Oats/Babala: Milk	0.19	0.09	1.00	0.27	1.55
Oats/Babala: Beef	0.19	0.18	0.05	0.27	0.69
Ryegrass/Babala: Milk	0.01	0.00	0.87	0.01	0.88
Ryegrass/Babala: Bee	0.01	0.20	0.45	0.01	0.67
Lucerne/Fescue: Milk	0.33	0.19	0.66	0.50	1.68
Lucerne/Fescue: Beef	0.33	0.25	0.27	0.50	1.35

4.4. Conclusions

From this study, it is clear that all cropping systems yielded a net present value > 0, which means that the utilization of mine water through irrigation is profitable and value can be added through agricultural production.

The cropping system that has the biggest year round canopy will use the most water and precipitate the most salts. These systems will require animal production systems to utilize the fodder produced and although this might be a very attractive option economically, the company managing the irrigation must be geared to animal production systems. These systems tend to be more labour intensive and are therefore often not preferred.

Cash crop systems lend themselves to mechanization and are therefore often preferred by bigger farming companies.

For this reason, each system must be evaluated individually to determine the best economic option for use under irrigation with gypsiferous mine water. A risk analysis should also be included in the calculation.

Irrigation management practices also contributed to the sustainability of the system. Simulated yields were the highest for the leaching fraction strategy, however, with this strategy more salts were leached (64% of the applied salts) compared to the room for rain strategy where only 53% of applied salts where leached.

A balance between agriculture and environment must be found. This will be a management practice that precipitates an acceptable fraction of the applied salts and where yields are still acceptable to the farming company. It is clear form this study that large quantities of gypsum can be precipitated in the soil and therefore removed from the water system. However, careful management of this delicate system is needed to minimize leaching and still achieve satisfactory yields.

CHAPTER 5

5. GROUNDWATER MODELLING

In this Chapter of the report, a case study of groundwater modelling is presented for pivot Major. This modelling study was carried out by the Institute for Groundwater Studies of the University of the Free State using modelled values from the SWB model.

Firstly, the SWB model was run to generate input data for the groundwater model. The simulation was run for the period of the field trial (from December 1997 to November 2000) followed by 50 years of scenario simulation. The scenario simulation was done for a short season maize-wheat rotation irrigated to field capacity on days when the calculated soil water deficit was 8 mm (the application rate of pivot Major is 8 mm d^{-1}). Drainage and leaching were assumed from a depth of 3 m (depth at which hard rock was generally encountered during the deep sampling in June 2000 (Section 2.3.3.1)). The water retention and chemical properties of the layer below the root-zone (from 1 m to 3 m) were assumed to be similar to those of the bottom layer of the root-zone (from 0.8 m to 1 m). The generated data for the groundwater model were:

- Monthly volume of water drained
- Monthly tonnage of salts leached
- Concentrations of the major ionic species expected to be leached (Ca^{2+}, SO_4^{2-} and Mg^{2+}) in mg l^{-1}

No significant pollution was detected in the groundwater at pivot Major during the irrigation period (Section 2.3.4.3.1). It is, however, expected that pollution will start reporting if irrigations with mine water continue. A finite element model of the groundwater flow and potential pollution migration was therefore run for pivot Major assuming a worst-case scenario where groundwater pollution started to occur. This was done to ensure that:

- Monitoring boreholes BH8 and BH9 are placed in localities where they are likely to intercept pollution once it arrives in the groundwater.
- The migration rate and mechanism of water and salt flow along the aquifer are sufficiently understood.
- The modelling capability exists, if required.

A description of the groundwater model and the results for this case study are presented in the following Sections.

5.1. Model description and scenario modelling

The first step in constructing such a model is the subdivision of the area to be modelled into elements where the characteristics are similar. Considerations for subdivision of the area are typically:

- The surface geometry, such as topography, streams, dams and the irrigation area.
- The hydraulic characteristics of the underlying aquifer.
- The potential groundwater quality distribution.

The simulated area constitutes an area of 2 400 x 2 000 m. It covers the whole pivot area, including the dam to the west, into which mine water is pumped. Other features included in the design of the finite element network are the streams and furrow that run North of the stream (Figure 2.4). The finite element network consists of 21 176 elements.

5.2. Governing equations for modelling pollution transport

To predict pollution movement across an area, several sets of equations are to be solved. These are for instance:

- The interpolation of groundwater levels across the whole area (Figure 5.1) using Bayesian interpolation.
- The solution of the groundwater flow equation for the whole area, which is a second order partial differential equation, determines groundwater gradients, seepage velocity and the response of the aquifer due to external influences such as seepage and recharge from rainfall. This equation may be written as follows:

  $$T(\partial^2h/\partial x^2) + T(\partial^2h/\partial y^2) + T(\partial^2h/\partial z^2) = S\partial h/\partial t - Q$$

  where

  S - Storage coefficient
  $\partial h/\partial t$ - Change in hydraulic head with time (m d^{-1})
  T - Transmissivity (m^2 d^{-1})
  $(\partial^2h/\partial x^2)$, $(\partial^2h/\partial y^2)$, $(\partial^2h/\partial z^2)$ - Flux directions
  Q - Abstraction/Recharge (m^3 d^{-1})

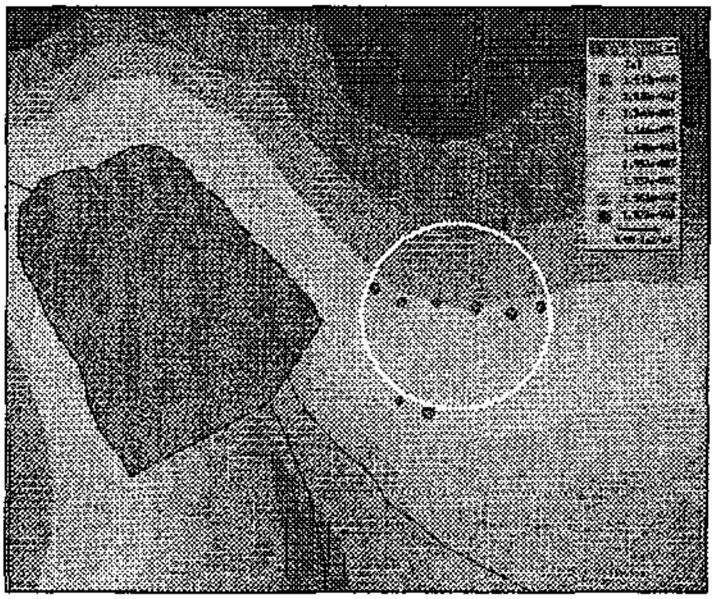


Figure 5.1. Groundwater level distribution, also showing the irrigation pivot Major and dam.

This equation describes the three-dimensional flow of groundwater through substrata, calculating the water table response. The equation may be solved analytically for simple problems, though for the irrigation problem, which is more complex, piece-wise approximation of the equation is obtained through the finite element method.

Once the water level distribution is available over the whole area, the seepage velocity and direction can be calculated, using the following equation:

$$v \quad - \quad k(\partial h/\partial l)/n$$

where

v - Seepage velocity (m d^{-1})
k - Hydraulic conductivity (m d^{-1})
n - Effective porosity
$\partial h/\partial l$ - Groundwater gradient (m m^{-1})

On the basis of the hydraulic gradients and flow velocities, the movement of pollutants through the aquifer is calculated next. The mass transport equation is used and is of the following type in its one-dimensional form:

$$D_x(\partial^2 c/\partial x^2) - V_x(\partial c/\partial x) = R(\partial c/\partial t)$$

where

D_x - Dispersion coefficient in the x-direction (m^2 d^{-1})
$\partial^2 c/\partial x^2$ - Flux direction
V_x - Seepage velocity (m d^{-1})
$\partial c/\partial x$ - Change in concentration with distance
R - Retardation coefficient
$\partial c/\partial t$ - Change in concentration with time (decay)

This equation may be expanded into two or three dimensions, depending on requirements.

It is clear from the above that the coupling of the mass transport equation with the flow equation becomes rather complex because of the additional variables present. The dispersive properties of the soil and aquifer, degree of convection in these systems, as well as chemical reactions that take place, must be known before the mass transport equation can be applied successfully.

Certain simplifying assumptions may be made regarding the problem to be modelled, without jeopardizing the value of the model. Examples of assumptions that have been applied for this modelling exercise are:

- The vertical dimension in the equations may be eliminated by simulating only pollution movement once it reaches the water table. At the irrigation site, the water table is within a few metres from the surface (1 – 4 m). The vertical dimension for groundwater flow is therefore very small compared to the lateral dimension, which from the centre of the pivot to the nearest stream is 700 m. After three years of monitoring, the pollution plume has not yet arrived in the aquifer below the irrigated site. It is assumed, however, that this will happen at some stage in the future. The time that it takes for the pollution front to travel through the unsaturated zone should therefore be added to the simulated times for the lateral dispersion of the pollution plume, as described in this exercise.

- The concentrations of potential pollutants beneath the irrigation site are expressed as 100% in the model, rather than a specific concentration in mg l^{-1}. This is convenient since any constant concentration can thus be accommodated. For instance, simulations of the salt transfer through the soil at the irrigation site suggest that constituent levels will stabilise at certain levels, depending on the constituent availability and initial concentration. Sulphate concentrations, for instance, will be around 3 600 mg l^{-1}, magnesium at 700 mg l^{-1} and calcium at 430 mg l^{-1} (Figure 5.2). Constant concentrations are therefore assumed in modelling pollution migration from the irrigation site. A 100% value for sulphate would therefore be 3 600 mg l^{-1}, for magnesium 700 mg l^{-1} and for calcium 430 mg l^{-1}.

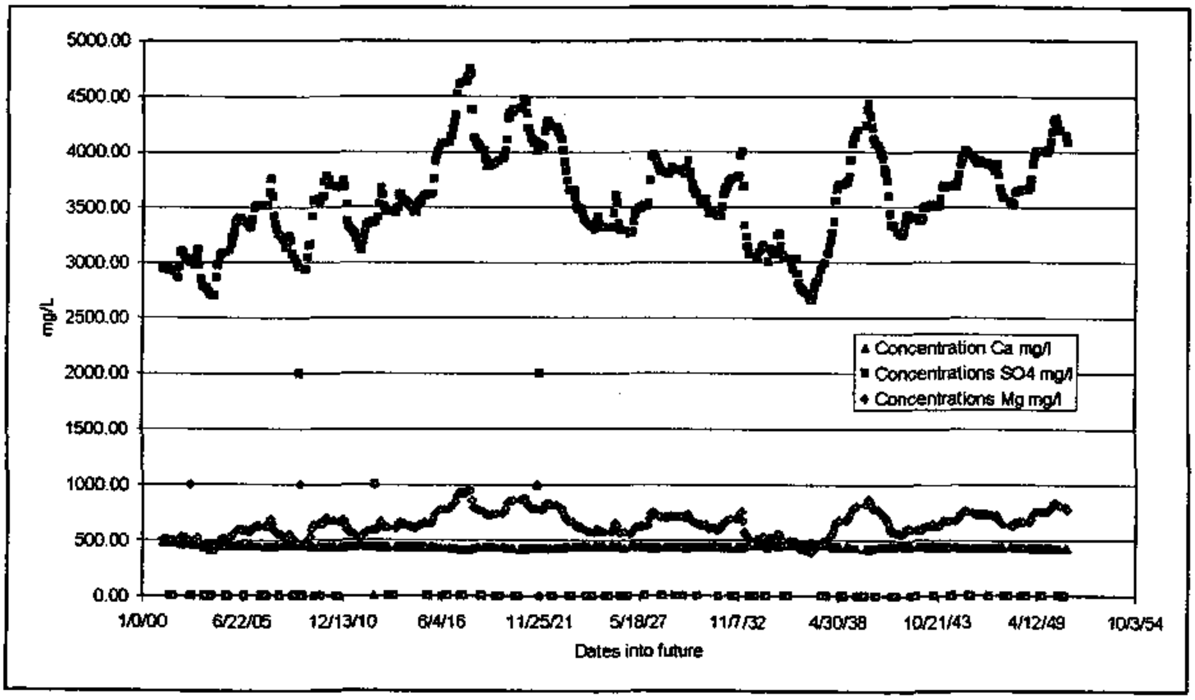


Figure 5.2. Predicted concentrations at which specific constituents will leach into the groundwater underneath the irrigation site.

- Up to now, no significant pollution has been detected in the monitoring boreholes. It will take significantly longer than three years for the pollution plume to migrate through the soil and into the aquifer, despite the water table being within 5 m of the surface. It is also suggested that the attenuation properties of the soil be investigated.

- For modelling purposes, chemical constituents in the environment are grouped in different categories, depending on their reactivity, attenuation characteristics and decay properties. Monovalent constituents such as chloride and nitrate are, for instance, very mobile whereas bivalent constituents such as calcium, magnesium and sulphate are slow movers in aquifers. In the simulations that follow, no retardation is assumed. If retardation takes place, the time of the output must be multiplied by the retardation factor.

- Heavy metals should not mobilise from the irrigation site because of the near neutral pH of the irrigation water and the precipitation of iron and manganese at source.

5.3. Hydraulic variables and constraints

Variables and constraints that act upon the movement of pollutants 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 occur where groundwater is abstracted or naturally emanates on the surface in the form of fountains.

5.3.1. Transmissivity and hydraulic conductivity

Transmissivity values for the irrigation site range between 0.25 – 0.83 $m^2 d^{-1}$ with an average of 0.46 $m^2 d^{-1}$. For the purposes of modelling a transmissivity of 0.5 $m^2 d^{-1}$, longitudinal dispersion of 0.06 $m d^{-1}$ and transverse dispersion of 0.008 $m d^{-1}$ is used.

5.3.2. Storativity and effective porosity

The storage coefficient and effective porosity of the weathered aquifer is assumed to be 0.06. This could not be tested through pumping test methods because of the low yield of the aquifer. This value is nevertheless acceptable, considering the highly weathered condition of the sandstone.

5.3.3. Regional water table gradient, dispersion and convection

The regional water table gradient within the irrigation area is controlled by the surface topography. The latter may therefore be used as a controlling factor in a Bayesian estimation model to interpolate groundwater levels in areas where monitoring boreholes are not available. This provides a well-defined distribution of water tables, which, in turn, is essential for calculating groundwater flow directions and velocities.

To illustrate the sensitivity of the system to a change in the regional groundwater gradient, scenario simulations have been done. Three outputs from these simulations are included in Figure 5.3. This demonstrates the incredible variation that is possible, by just changing one parameter. Changes in the hydraulic conductivity and effective porosity would result in similar order of magnitude changes.

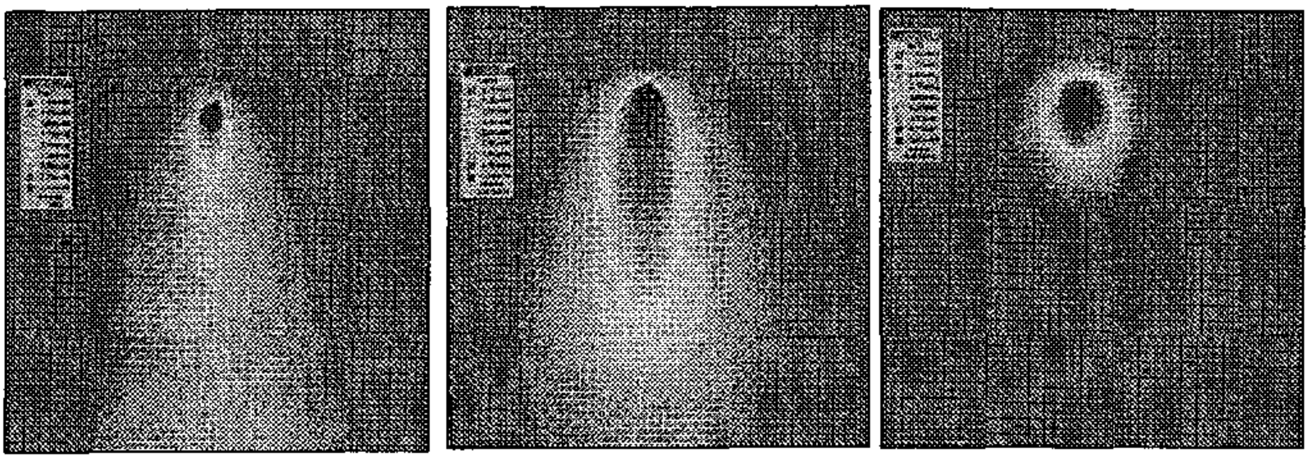


Figure 5.3. Pollution plumes for hydraulic gradients 1:10, 1:100 and 1:1000 from North to South through a pollution source over a period of 3 years. The scale for each diagram is 1000 m from left to right.

5.3.4. Boundaries

In nature groundwater boundaries exist in various forms and have been accounted for in the model. Typical boundaries are topographic 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, have also been considered. Constant concentration boundaries have been specified for the pivot and dam area. Other than these, no other boundary conditions have been considered.

To illustrate the dramatic impact that a stream and a borehole could have on groundwater pollution migration, Figure 5.4 has been compiled.

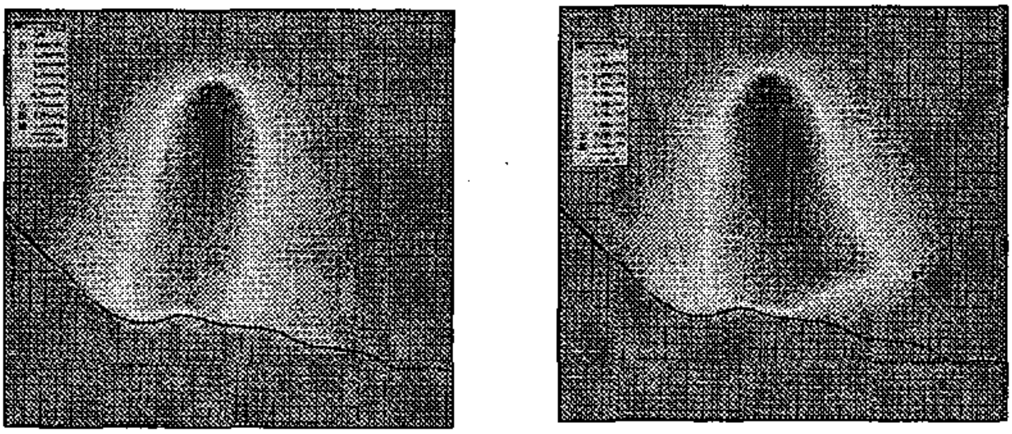


Figure 5.4. Stream intersecting a pollution plume (left). Stream and borehole which abstract water, intersect the same pollution plume (right).

The conclusion is that pollution plumes can be intercepted and managed on condition that the flow dynamics is understood. Furthermore, the shape of a pollution plume is dependent on site-specific issues and it is senseless to simulate hypothetical scenarios to demonstrate the variability in possible outcomes. Therefore, the simulations that follow will be based on actual data from the irrigation site.

5.3.5. Sources of water

Sources of water are incorporated in the groundwater model as constant or specified flux sources. Examples of such sources are the constant water infiltration from the mine water dam and specified flux from the irrigation pivot area. Another source of water is the rainfall that recharges the aquifer. Simulations for the water that flows through the soil, done with the SWB model, suggest that some 20 $m^3\ d^{-1}$ passes through the soil and into the aquifer below. This is slightly less, but of the same order, as the recharge estimated from the annual fluctuation of water levels in the area, which amounts to 80 $m^3\ d^{-1}$.

5.3.6. Sinks

Points where water is taken from the system, such as boreholes, drains or fountains, are referred to as sinks. Currently, there are no users of groundwater in the area who could impact on the movement of pollutants through the aquifer.

5.4. Links between the irrigation and the groundwater model

Flow of irrigation water through the soil has been researched in detail during this project. Below the soil zone lies weathered sandstone. The degree of weathering varies from one locality to the next in the irrigation area. The conclusion is that a continuum exists in the weathered sandstone, from highly weathered to almost unweathered. In the highly weathered sandstone, porous flow will be the dominating flow mechanism. Fracture flow will be the dominant mechanism in the unweathered strata. It should therefore, in theory, take longer for the irrigation water to pass through the highly weathered sediments than through the fractured sediments.

In reality, this does not matter. The vertical distance to the aquifer is less than 4 m. The horizontal scale of the pivot is 640 m in diameter. The time that it will take for water to move under unity gradient through the 4 m unsaturated zoned would be negligibly small compared to the time that it would take for the water to flow laterally underneath the pivot. The vertical seepage time can therefore be ignored in groundwater pollution plume modelling.

5.5. Discussion of modelling results

Two simulations have been done. The first simulation was that of potential pollution dispersion from the irrigation area. The second simulation included the dirty water dam. The results from these simulations are included in Figures 5.5 to 5.7.

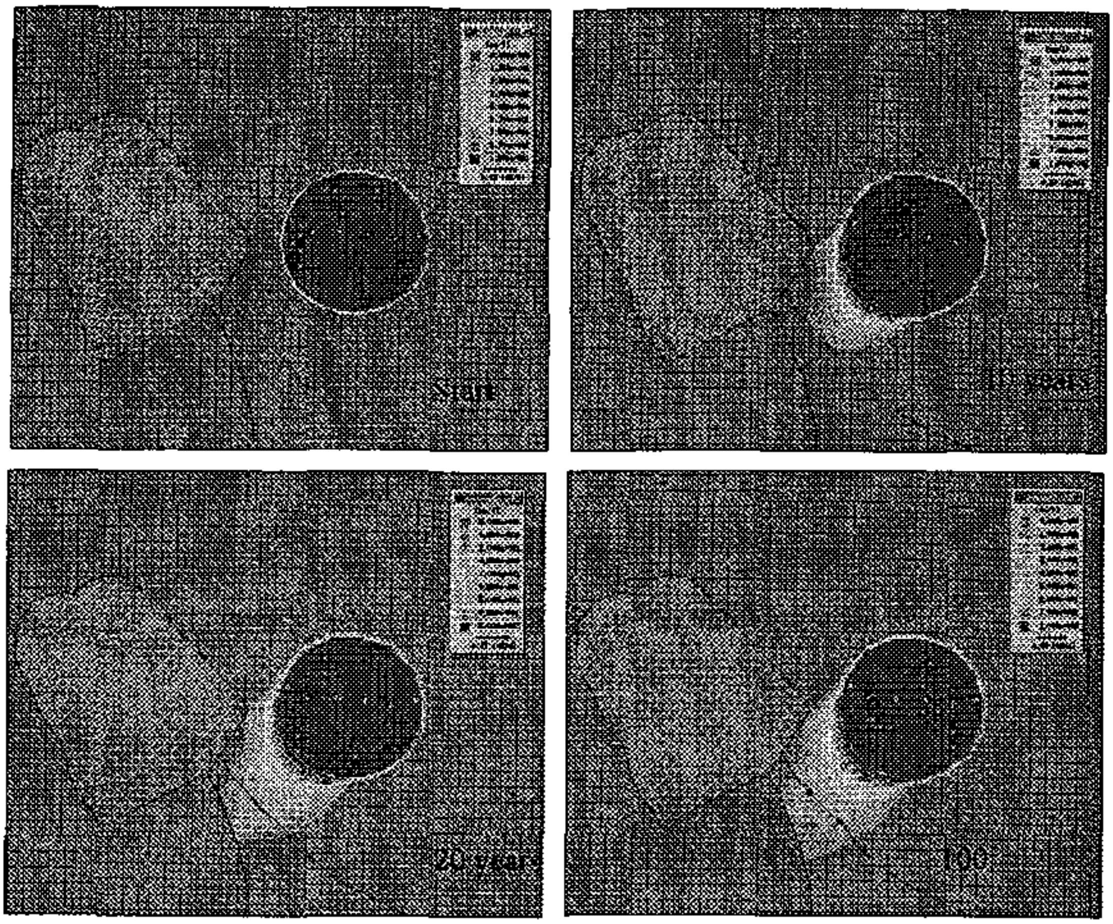


Figure 5.5. Development of the pollution plume with no retardation, on the assumption that pollution has moved vertically into the aquifer over the whole irrigation pivot.

The green dots show the positions of the current monitoring boreholes. In the fourth diagram, four positions are shown laterally away from the irrigation pivot. Breakthrough curves showing the simulated concentrations at these localities are indicated in Figure 5.6.

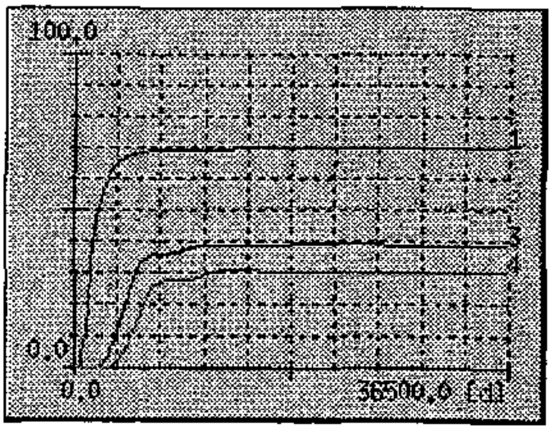


Figure 5.6. Breakthrough curves for positions indicated in Figure 5.5 (fourth diagram).

The conclusion is that the pollution plume will take about 25 years to develop fully, after which the system achieves steady state. Dilution from rainfall at 3% recharge, lateral dispersion of the pollution plume and seepage water emanating at the stream are the main reasons for achieving steady state.

Using the same finite element configuration, the holding dam that contains mine water was included in a follow-up simulation. The results are shown in Figure 5.7.

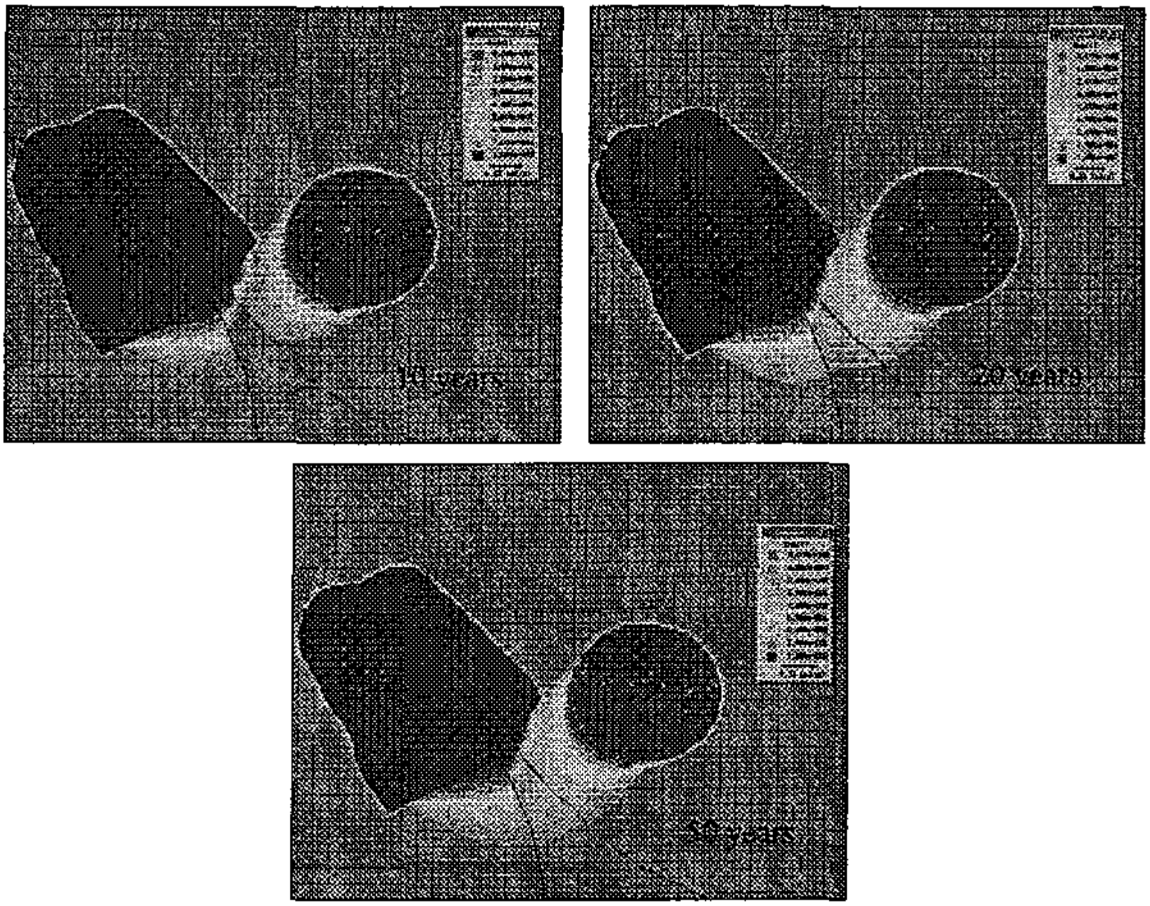


Figure 5.7. Potential development of the pollution plumes from the irrigation area and mine water dam.

The conclusion is that pollution from these two sources will surface in the stream and furrow. Interception facilities can be installed at these points, from where polluted water can be returned to the dam. There is no risk of regional pollution in the aquifer.

CHAPTER 6

6. CONCLUSIONS AND RECOMMENDATIONS

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

Objective 1

The feasibility of managing irrigation with gypsiferous 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. In the field trial carried out at Kleinkopje 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-term (three years).

Objective 2

The impact of irrigation with gypsiferous water was evaluated through field monitoring, laboratory experiments and modelling.

Objective 2.1

Yield and plant nutritional effects on a selection of crops that can be grown in the area were evaluated. Excellent yields were obtained for wheat on both virgin and rehabilitated land, and also short-season maize grown on virgin land. The yields of sugarbeans were reasonable, and definitely higher than those obtained under dry land cropping.

Based on chemical analyses carried out on soil samples collected in the field, exchangeable Ca^{2+} and Mg^{2+} increased with time, whilst K^+ decreased at all four pivot sites. This indicated that Ca^{2+} and, to a certain extent Mg^{2+}, replaced K^+ on the cation exchange complex. If loss of K^+ through leaching causes nutrient deficiencies to the crop, corrective fertilization should be applied as, or preferably before, symptoms appear. Field monitoring of crop nutrient status is therefore essential at this stage of the research and for long-term management with these water qualities.

In a glasshouse pot trial, calcium and magnesium sulphate salinity decreased the biomass production of wheat. This was mainly due to interactions of Mg with the uptake of essential nutrients. The application of NO_3, NH_4, and K at rates different from the level considered beneficial for non-saline conditions improved wheat growth under sulphate saline conditions. A beneficial effect of higher NH_4 supply was observed. This can be ascribed to the antagonistic effect that NH_4 exerted on Mg concentrations in plants and/or to a higher N-utilization efficiency where N was supplied as NH_4 compared to NO_3, which competes for uptake with SO_4. Differential application of P had no effect on the yield of wheat. Further experimentation is needed to verify these results under field conditions and determine the optimal rate, method and timing of especially NH_4 when irrigating crops with these calcium and magnesium sulphate enriched waste waters.

The results from the herbicide trial indicated that the Tweefontein and Jacuzzi water may exert an influence on the adsorption characteristics of atrazine and 2,4-D molecules. This is not completely unexpected, as one would expect dissolved salts to have an effect on the polarity of the compounds. This would mean that in the field, there is a possibility that soil retention would decrease and therefore leaching could increase, reducing the efficacy of the herbicides because the herbicide may not stay long enough in the topsoil layer to be absorbed by plants. Leaching would also lead to groundwater contamination. The increase in activity of atrazine found in bioassays probably does not hold any practical consequences in terms of herbicide efficacy, selectivity or persistence. In contrast, reduction of metolachlor activity in the presence of gypsum implies that weed control by the herbicide will be poor on soils irrigated with water containing high levels of calcium sulphate. In the case of metolachlor, the finding does not suggest that selectivity of the herbicide towards the crop would be a concern. The effect on herbicide selectivity is also not an issue in the case of the atrazine, because of the inherent high tolerance of the main crop in which it is used, namely maize.

In the study on characterization of soil materials, a database of bulk density, water retention properties, hydraulic conductivity and solute transport characteristics (dispersion, adsorption and rate dependant transfers) was generated. Based on these results, it was concluded that high bulk density due to soil compaction and the presence of the spoil layer with low hydraulic conductivity could be limiting factors for crop production under irrigation on rehabilitated land.

Proper preparation of rehabilitated land proved to be important. Settlement on rehabilitated land caused ponding and waterlogging that had to be overcome by contouring and installing surface drainage waterways. This problem is related to the physical nature of rehabilitated land, and not to the chemistry of the water used for irrigation. A spatial variability study and a two- or three-dimensional model are recommended to accurately predict crop growth and water use, as well as the water and salt balance under such conditions. In the rehabilitation process, if rehabilitated land is to be used for crop production under irrigation, the spoil material should be packed on a slight slope to prevent waterlogging.

Objective 2.2

Several methods for measurement of gypsum precipitated in the soil were considered at the Soil Science Laboratory (University of Pretoria). The Adapted Dilution Method was eventually selected and applied. At the Department of Geology (University of Cape Town), the gypsum saturation index (SI) of a saturated gypsum solution and that of solutions in equilibrium with soil samples to which known masses of gypsum had been added was calculated using PHREEQC (Parkhurst and Apello, 1999). An attempt to measure gypsum precipitated in the soil profile was done on deep soil samples collected in June 2000. It was, however, clear from the results obtained that a sufficiently accurate method to measure gypsum precipitation still needs to be developed.

Objective 2.3

The effects of gypsum precipitation and salt accumulation on soil characteristics were investigated in a laboratory trial. There was no evidence that precipitated gypsum affected the water retention capacity adversely. Further research is required to confirm these findings and determine changes in pore size distribution and water retention capacity for larger amounts of gypsum precipitated in the soil.

Objective 2.4

Depth of salinization of soil over time was investigated in the field trial for different irrigation management practices. Soil chemical analyses indicated that soil salinity increased compared to the initial conditions. The electrical conductivity of the saturated soil extract increased mainly due to an increase in concentrations of soluble Ca^{2+}, Mg^{2+} and SO_4^{2-}, which are the main ionic species in the irrigation water. The values of soil saturated EC were, however, still < 400 mS m^{-1} even after particularly dry seasons due to gypsum precipitation and leaching of soluble salts. The data generally indicated higher soil salinity in the topsoil layers compared to deeper layers.

Deep soil sampling was carried out in June 2000 in order to explore whether any salt breakthrough originating from irrigation could be identified deeper in the soil profile. The results indicated that, at pivot Major and Tweefontein, most soluble salts were confined to the upper 1 m, probably due to the presence of the plinthic layer and spoil layers limiting free drainage. At pivot Fourth, there was a more uniform distribution of salts in the soil profile, with a slight peak between 1.5 and 2 m down in the profile indicating leaching of salts below the root-zone.

The results of the spatial variability study indicated that there is a tendency for salinity levels to be higher in the central region of each pivot. This is believed to be due to the larger quantities of saline irrigation water that have been applied in these zones during the course of the experiment. The salinity levels measured at the end of the trial are unlikely to have an adverse effect on the growth of most crops.

Objective 2.5

The quality and quantity of drainage water was calculated using the SWB model. Runoff amount and quality data collected at the weirs, indicated that less than 2% of the salts added since the beginning of the trial were lost from the irrigated fields through surface and subsurface runoff from November 1999 to April 2000. More runoff was recorded at pivot Tweefontein compared to pivot Major, due to the restricted soil depth and steep slopes of the rehabilitated land.

Objective 2.6

Seasonal fluctuations of soil salinity and drainage water characteristics were observed in the field trial. The results of chemical analyses of soil samples and soil water extracted with ceramic cup soil water samplers, indicated that soil salinity is a very dynamic variable as it depends on many factors, mainly rainfall, irrigation amounts and evapotranspiration. Model predictions confirmed that seasonal fluctuations of drainage water characteristics can be expected. Data collected at the weirs indicated that runoff occurred during the summer rainy season.

Objective 2.7

The ameliorating effect of gypsiferous water on acidic soils was assessed using results of chemical analyses on soil samples collected in the field. Soil pH(H_2O) generally showed a slight tendency to increase during the course of the trial at all pivots.

Objective 3

The SWB model was developed for predictions of salt and water budgets under irrigation with gypsum rich mine water.

Objective 4

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. This indicated that SWB can be used to predict the water and salt balance in the long term (many decades or centuries). The present version of SWB includes a cascading water redistribution and assumes complete mixing of irrigation and rainfall with the soil solution.

The validation of the chemical equilibrium subroutine in SWB, done by comparing model output to direct measurements of gypsum precipitated in the soil, failed as the method used to measure precipitated gypsum was inaccurate. The chemical equilibrium model has been widely tested by other research groups and is likely to be quite reliable. A reliable gypsum analysis method is urgently required.

A comparison between SWB and FAO-SWS (Suarez et al., 2001), a modification to UNSATCHEM (Simunek et al., 2001), was run in order to test the chemical equilibrium subroutine. There was excellent agreement between SWB and FAO-SWS. This gave confidence that the cascading soil water balance and Robbins' (1991) chemical equilibrium used in the SWB model are accurate enough in gypsum-dominated systems. Caution should, however, be exercised in the simulation of chemical equilibrium in calcitic soils with Robbins' (1991) model (DL Suarez, Salinity Laboratory, Riverside, California, personal communication).

Objective 5

Scenario simulations were carried out with SWB in order to recommend the most profitable and environmentally sustainable cropping and irrigation water management system. From this study, it was clear that perennial pastures have the biggest year round green canopy, they will use the most water and precipitate the most salts of all other cropping systems evaluated. They also require the smallest irrigation area and therefore capital cost to utilize the water. These systems will require animal production systems to utilize the fodder produced, and although this might be a very attractive option economically, the company managing the irrigation must be geared to animal production systems. These systems tend to be more labour intensive and are therefore often not preferred. Cash crop systems lend themselves to mechanization and are therefore often preferred by bigger farming companies.

A balance between agriculture and environment must be found. It was clear from the scenario modelling study that large quantities of gypsum can be precipitated in the soil and therefore removed from the water system. However, careful management of this system is needed to precipitate a considerable fraction of the applied salts, minimize leaching and still achieve yields that are acceptable to the farming company. Simulated yields were the highest for the leaching fraction strategy. However, with this strategy more salts were leached (64% of the applied salts) compared to the room for rain strategy where only 53% of applied salts were leached.

In the scenario modelling study, several management options were proposed for utilization of gypsiferous mine waste water through irrigation. The acceptability of the proposed management strategies will depend on the standards for environmental protection, as well as social and economic issues. It is essential that strategic decisions are made on cropping systems, as many options are available, all with different implications for job creation, ease of management, profitability, capital equipment requirements, water use, irrigated area and salt precipitation. It is also essential that the necessary management capacity and infrastructure is available, as only healthy well-managed crops can use water and precipitate gypsum. Different cropping systems have different capital and running costs and this should be quantified. It is clear, therefore, that one is dealing with a very flexible system that can be managed in a certain way to achieve the desired result, be it maximum crop production, water use, job creation, economic return or maximum gypsum precipitation and minimum salt leaching.

Objective 6

The SWB model was linked to a groundwater model and provided inputs to associated groundwater studies.

Objective 7

The groundwater study consisted of monitoring groundwater level and quality from boreholes installed on virgin (unmined) land at pivot Major, as well as modelling.

Objective 7.1

Field monitoring indicated that salt migration through soil and aquifers is a slow process. After more than three years of irrigation, there was still no conclusive evidence that saline irrigation water had reached the aquifer below the irrigation site at pivot Major. This is in spite of the fact that groundwater levels are within 1 - 3 m from the surface.

A slight rise in nitrate concentrations was observed at two boreholes. This was derived from fertilizer application. At five of the boreholes, a small increase in calcium, magnesium and sulphate levels was observed. It is concluded that the system will have to be observed over many more years before a conclusive answer can be given in terms of the potential long-term impact of irrigation on the aquifer.

Objective 7.2

Output of the SWB model was used as input into the groundwater model in order to predict the long-term effects of irrigation with gypsiferous mine water on groundwater for a case study at pivot Major. Two simulations were done with the groundwater model. The first simulation was that of potential pollution dispersion from the irrigation area. The second simulation included the dirty water controlled release dam. Modelling of potential pollution migration through the aquifer suggested migration to the South-West, eventually to emanate in the stream at a concentration of about 30% of that reaching the aquifer below the irrigated site. This drop in salt levels was ascribed to dilution by rainwater infiltration and the dispersive characteristics of the aquifer. The conclusion is that pollution from these two sources (irrigation site and dam) will surface in the stream and furrow. Interception facilities can be installed at these points, from where polluted water can be returned to the dam. There is no risk of regional pollution of the aquifer.

The following recommendations for groundwater modelling are made:

- Groundwater quality monitoring should continue for as long as irrigation with mine water continues.
- The monitoring boreholes should be measured with a multi-parameter probe on a bi-annual basis to ensure that sampling is done using the correct method. Sampling should be done using either stratified or pumping methods, depending on the circumstances.
- In the event that the monitoring holes are polluted by the bentonite plugs, the holes should be purged to remove all pollution derived from piezometer installations.
- Parameters that should be analysed for are pH, EC, Ca, Mg, Na, K, Cl, SO_4, TAlk, NO_3, Fe, Mn and F. In addition, heavy metals should be analysed for, if pH-values drop below 5.0. The samples should be preserved in the field.
- Water levels should be measured in the boreholes before each sampling exercise.
- The data should be added to that generated during this exercise and processed as it becomes available.
- Anomalies should be identified and followed up.

- Reports should be issued on an annual basis.

Recommendations for further research

It is recommended to continue the field trial at Kleinkopje in order to collect more years of data on the impact of irrigation with gypsiferous mine water on soil and groundwater resources, as an extremely valuable research site with a well monitored history of irrigation with such water has been established. Extrapolation to other climatic conditions, soils and waters is also essential in order to get experience with other conditions. This could be achieved by *testing the SWB model for different environmental conditions* (water qualities, soils, climates, cropping systems) to extend the scope of the long-term predictive mode of the model.

Attention should be paid to groundwater quality, as it will take significantly longer than three years for the pollution plume to migrate through the soil and into the aquifer. The link between SWB and the groundwater model gives the opportunity to predict the extent of groundwater contamination at specific mines. Groundwater contamination on a regional scale will depend on the geometry and geological properties of specific sites. It is also suggested that the adsorption capacity of the vadose zone be investigated.

The fact that only gypsum can be held up in the soil to some extent, and all other more soluble salts must be leached for successful crop production, suggests that although this technology can make an enormous contribution to water management in the mining industry, it will not be able to completely solve all their problems. Some mines also generate significant volumes of saline waters that are not particularly gypsiferous. In order to deal with such waters and the concentrated leachate from gypsiferous mine water irrigation, other agricultural technologies should be considered. The most promising technology is serial biological concentration, where increasingly concentrated leachate is applied to increasingly salt tolerant crops to reduce the volumes of water and to allow minimal salt export from the mines.

Soil physical analyses of rehabilitated profiles indicated that high bulk density due to soil compaction and the presence of the spoil layer with low hydraulic conductivity could be limiting factors for crop production under irrigation. It is recommended to investigate measures for reducing soil compaction on rehabilitated soil profiles in order to improve land capability, or make use of this opportunity to create a "duplex" soil from which drainage water can be retrieved for use in serial biological concentration.

There is opportunity for further improvement to SWB. The simulations with the finite-difference water balance model were carried out without simulating salt redistribution, as the convection/dispersion subroutine is currently being debugged. The finite-difference model has the potential to predict the soil water and salt balance more accurately than the cascading model, once the salt redistribution subroutine becomes operational.

CHAPTER 7

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CHAPTER 8

CAPACITY BUILDING

The capacity building actions carried out during the course of this project were mainly oriented towards student training.

A large number of students, both from the University of Pretoria and other institutions, have been trained on several topics during the course of the project. The students that were registered for postgraduate degrees were:

Student	Degree registered	Topic	Status
JJB Pretorius	BSc Agric (Hons)	Economics of cropping systems	Completed in February 2000
AM van der Westhuizen	PhD	Serial biological concentration	To be completed
MS Mpandeli	M Inst Agr	Measuring and modelling soil evaporation	To be completed
I van der Stoep	MSc	TDR system	To be completed
MP Nepfumbada	PhD	Soil physics	To be completed
PHE Strohmenger	MSc	Plant nutrition	Completed in March 2001
L Grobler	MSc	Soil chemistry	To be completed
C de Jager	MSc	Plant nutrition	To be completed
R Campbell	MSc	Soil chemistry	To be completed
G Narciso	MSc	Remote sensing	To be completed

Other students were also engaged in the field work during field visits.

The students were trained in the following activities:

- They attended several undergraduate and postgraduate courses at the University of Pretoria.
- They were presented with practical work and problems facing two important branches of the country's economy (mining and agriculture).
- They were trained to use instrumentation for field research: principles, installation, management and data manipulation.
- They were trained in preparing presentations, publications and thesis.

CHAPTER 9

TECHNOLOGY TRANSFER

Irrigation with gypsiferous mine water could bring benefits to both the mining industry through utilization of polluted water, and to farming communities as an additional water source for irrigation. This technology could be applied to other mines with similar water qualities. Due to the encouraging results of this project, the following mines have shown interest in using waste water for irrigation: Syferfontein (Sasol, Secunda), New Vaal (Anglo Coal, Sasolburg), Optimum (Ingwe, Hendrina), Kromdraai (Anglo Coal, Witbank), Mpunzi (Witbank) and BCL (Selebi Phikwe, Botswana).

Farmers would also benefit from this technology as all these mines are located in summer rainfall areas, where dry land winter cropping is not feasible.

The experiences gained with irrigation on rehabilitated land should provide general guidelines as to how the land rehabilitation process should be carried out, especially if rehabilitated land is to be used for cropping under irrigation.

The results of this project should also provide general guidelines on which cropping system to choose, and how to manage cropping systems and irrigation water. Cropping system, agronomic practices (fertilization, weed control etc.) and irrigation water management will depend on the particular environmental conditions (geology, topography, climate, type of soil etc.) and water quality.

The SWB model was improved during the course of this project and accurate predictions were obtained compared to measurements. Scenario simulations can be carried out to recommend the most suitable management practices depending on the specific requirements of a mine. As this model makes provision for different soils, climates and crops, it could be used under different environmental conditions. This should, however, be tested. SWB, in combination with a groundwater model, could also be used for predictions of environmental pollution for specific case studies.

User-friendly software makes transfer of technology developed in this project relatively simple. The following computer software was developed during this project:

i) Improved SWB crop growth, soil water and salt balance model.
ii) ETo calculator (software for calculation and error analysis of the FAO reference evapotranspiration).
iii) HDS calculator (software for calibration and temperature correction of heat dissipation soil matric potential sensors).
iv) ChemEq model (software for calculation of chemical equilibrium in waters and soils).
v) CLIMGEN (software for generation of weather data).

The following publications and presentations emanated from the research done during the course of this project:

Workshops

JOVANOVIC NZ, ANNANDALE JG and BENADÉ N (1997) Modelling the Long-Term Effect of Irrigation with Gypsiferous Water on Soil and Water Resources. Biological Simulation

Forum Workshop, 10 October 1997, SASEX Research Institute, Mount Edgecombe, South Africa.

Conference presentations

JOVANOVIC NZ, ANNANDALE JG and BENADÉ N (1997) A simple water balance-soil salinity model for irrigation with gypsiferous water. *First All Africa Crop Science Congress*, January 1997, Pretoria, South Africa.

ANNANDALE JG, BENADÉ N, JOVANOVIC NZ and VAN DER WESTHUIZEN AJ (1997) The soil water balance (SWB) irrigation scheduling model. *First All Africa Crop Science Congress*, January 1997, Pretoria, South Africa.

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RETHMAN NFG and JOVANOVIC NZ (1998) Potential forages for areas irrigated with gypsiferous water. *4th International Conference on Land Reclamation*, September 1998, Nottingham, United Kingdom.

JOVANOVIC NZ, ANNANDALE JG and PRETORIUS JJB (1999) Modelling and monitoring crop production, soil properties and drainage water under centre pivot irrigation with gypsiferous mine water. *Congress of the SA Society of Crop Production*, January 1999, Stellenbosch, South Africa.

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Proposal for archiving data

All data collected and generated in this project will be saved and stored on CD. Copies of the CD will be made available to Mr ME Aken (Anglo Coal Environmental Services, Witbank), Mr HC van Zyl (Chamber of Mines), Prof JG Annandale (University of Pretoria, Pretoria) and the Water Research Commission.

APPENDIX A

Tables

Table A1. Crops, cultivars, planting dates and agronomic techniques applied under irrigation with gypsiferous mine water at pivot Major.

Season	Crop	Cultivar	Planting date	Row spacing (m)	Planting density	Fertilization	Herbicide
1997/98	Sugarbeans	Pan 148 and Kranskop	From 27/11/1997 to 03/12/1997	0.9	70 kg seed ha^{-1}	5 Mg ha^{-1} Dolomitic lime and 300 kg ha^{-1} Superphosphate before planting (mixed into the soil to a depth of 0.2 m); 250 kg ha^{-1} 3:4:3 (20) liquid fertilizer at planting.	Preecede with active ingredient Metazachlor was sprayed to control broad leaf weeds and grasses.
1997/98	Maize*	Pannar 6146	26/11/1997	0.9	60,000 plants ha^{-1}	5 Mg ha^{-1} Dolomitic lime and 300 kg ha^{-1} Superphosphate before planting (mixed into the soil to a depth of 0.2 m); 250 kg ha^{-1} 3:4:3 (20) liquid fertilizer at planting.	Weeds were controlled manually.
1997/98	Babala*	Pan 911	26/11/1997	0.9	6 kg seed ha^{-1}	5 Mg ha^{-1} Dolomitic lime and 300 kg ha^{-1} Superphosphate before planting (mixed into the soil to a depth of 0.2 m); 250 kg ha^{-1} 3:4:3 (20) liquid fertilizer at planting.	Weeds were controlled manually.
1998	Wheat	SST 825 and Kariega 103	From 24/06/1998 to 26/06/1998	0.3	150 kg seed ha^{-1}	120 kg ha^{-1} urea and 200 kg ha^{-1} 3:4:3 (20) before planting; top dressing data are not available.	Buctril at 1 l ha^{-1} and MCPA at 0.5 l ha^{-1} 4 weeks after emergence.
1998	Ryegrass*	Dargle	21/04/1998	-	Broadcast	-	-
1998	Stooling rye*	Rydal	21/04/1998	-	Broadcast	-	-
1998	Lucerne and fescue**	Pannar 4821 and Cajun	24/04/1998	-	Broadcast	-	-

* Alternative annual cropping systems

** Mixed perennial pasture

Table A1 (continued). Crops, cultivars, planting dates and agronomic techniques applied under irrigation with gypsiferous mine water at pivot Major.

Season	Crop	Cultivar	Planting date	Row spacing (m)	Planting density	Fertilization	Herbicide
1998/99	Maize	Not available	29/12/1998	0.9	60,000 plants ha^{-1}	Not available	Not available
1999	Wheat	SST 825	01/07/1999	0.3	150 kg seed ha^{-1}	300 kg ha^{-1} 4:1:1 (22) before planting; 130 kg ha^{-1} 2:3:4 (20) at planting; 420 kg ha^{-1} 3:0:1 (16) on 19/08/1999; 420 kg ha^{-1} 3:0:1 (16) on 16/09/1999.	4 l ha^{-1} Kelp-P-Max, 500 *ml* ha^{-1} MCPA and 4 l ha^{-1} Broxonol.
1999/00	Maize	PHI 33408 (Bt gene)	From 13/12/1999 to 14/12/1999	0.8	67,500 plants ha^{-1}	380 kg ha^{-1} 5:3:6 (02) before planting; 220 kg ha^{-1} 1:0:1 (13) and 220 kg ha^{-1} UAN (32) as top dressing; 2 kg ha^{-1} Map, 1 kg ha^{-1} NGSO4 and 100 kg ha^{-1} Omnispoor for leaf nutrition.	*400 ml* ha^{-1} Galleon, 600 ml ha^{-1} Wenner and 40 ml ha^{-1} Karate at planting; 700 ml ha^{-1} Relay, 120 ml ha^{-1} Allbuff, 2 l ha^{-1} Bladex and 4 l ha^{-1} Bromox after emergence.
2000	Wheat	SST 825	26/06/2000	0.2	225 kg seed ha^{-1}	548 kg ha^{-1} 4:1:1 (22) before *planting;* 150 kg ha^{-1} 2:3:4 (30) 0.50 % Zn at planting; 417 kg ha^{-1} 3:0:1 (16) at 35 days after emergence; 417 kg ha^{-1} 3:0:1 (16) at 50 days after emergence; 100 kg ha^{-1} ANO (21) after flag *leaf for protein increase;* Omniboost for leaf nutrition.	150 kg ha^{-1} Bromox and 500 ml ha^{-1} MCPA on 01/09/2000.

Table A2. Crops, cultivars, planting dates and agronomic techniques applied under irrigation with gypsiferous mine water at pivot Tweefontein.

Season	Crop	Cultivar	Planting date	Row spacing (m)	Planting density	Fertilization	Herbicide
1997/98	Sugarbeans	Kranskop	09/01/1998	0.9	70 kg seed ha^{-1}	3 Mg ha^{-1} Calcitic lime before planting (mixed into the soil to a depth of 0.2 m); 250 kg ha^{-1} 3:4:3 (20) liquid fertilizer at planting.	Preecede with active ingredient Metazachlor was sprayed to control broad leaf weeds and grasses.
1998	Wheat	SST 825 and Kariega 103	30/06/1998	0.3	150 kg seed ha^{-1}	120 kg ha^{-1} urea and 200 kg ha^{-1} 3:4:3 (20) before planting; top dressing data are not available.	Buctril at 1 l ha^{-1} and MCPA at 0.5 l ha^{-1} 4 weeks after emergence.
1998/99	Sugarbeans	Kranskop	06/01/1999	0.9	70 kg seed ha^{-1}	250 kg ha^{-1} 3:4:3 (20) liquid fertilizer at planting.	Preecede at 1 l ha^{-1} at planting.
1999	Wheat	SST 825	03/07/1999	0.3	150 kg seed ha^{-1}	300 kg ha^{-1} 4:1:1 (22) before planting; 130 kg ha^{-1} 2:3:4 (20) at planting; 420 kg ha^{-1} 3:0:1 (16) on 19/08/1999; 420 kg ha^{-1} 3:0:1 (16) on 16/09/1999.	4 l ha^{-1} Kelp-P-Max, 500 ml ha^{-1} MCPA and 4 l ha^{-1} Broxonol.
1999/00	Maize	PHI 33408 (Bt gene)	From 15/12/1999 to 16/12/1999	0.8	67,500 plants ha^{-1}	380 kg ha^{-1} 5:3:6 (02) before planting; 220 kg ha^{-1} 1:0:1 (13) and 220 kg ha^{-1} UAN (32) as top dressing; 2 kg ha^{-1} Map, 1 kg ha^{-1} NGSO4 and 100 kg ha^{-1} Omnispoor for leaf nutrition.	400 ml ha^{-1} Galleon, 600 ml ha^{-1} Wenner and 40 ml ha^{-1} Karate at planting; 700 ml ha^{-1} Relay, 120 ml ha^{-1} Alibuff, 2 l ha^{-1} Bladex and 4 l ha^{-1} Bromox after emergence.

Table A2 (continued). Crops, cultivars, planting dates and agronomic techniques applied under irrigation with gypsiferous mine water at pivot Tweefontein.

Season	Crop	Cultivar	Planting date	Row spacing (m)	Planting density	Fertilization	Herbicide
2000	Wheat	SST 825	28/06/2000	0.2	Not available	548 kg ha^{-1} 4:1:1 (22) before planting; 150 kg ha^{-1} 2:3:4 (30) 0.50 % Zn at planting; 417 kg ha^{-1} 3:0:1 (16) on 35 days after emergence; 417 kg ha^{-1} 3:0:1 (16) on 50 days after emergence; 100 kg ha^{-1} ANO (21) after flag leaf for protein increase; Omniboost for leaf nutrition.	150 kg ha^{-1} Bromox and 500 ml ha^{-1} MCPA on 17/08/2000.

Table A3. Crops, cultivars, planting dates and agronomic techniques applied under irrigation with gypsiferous mine water at pivot Jacuzzi.

Season	Crop	Cultivar	Planting date	Row spacing (m)	Planting density	Fertilization	Herbicide
1997/98	Sugarbeans	Kranskop	06/01/1998	0.9	70 kg seed ha^{-1}	3 Mg ha^{-1} Calcitic lime before planting (mixed into the soil to a depth of 0.2 m); 250 kg ha^{-1} 3:4:3 (20) liquid fertilizer at planting.	Preecede with active ingredient Metazachlor was sprayed to control broad leaf weeds and grasses.
1998	Wheat	SST 825 and Kariega 103	30/06/1998	0.3	150 kg seed ha^{-1}	120 kg ha^{-1} urea and 200 kg ha^{-1} 3:4:3 (20) before planting.	Buctril at 1 l ha^{-1} and MCPA at 0.5 l ha^{-1} 4 weeks after emergence.
1998/99	Sugarbeans	Kranskop	04/01/1999	0.9	70 kg seed ha^{-1}	250 kg ha^{-1} 3:4:3 (20) liquid fertilizer at planting.	Preecede at 1 l ha^{-1} at planting.

Table A4. Crops, cultivars, planting dates and agronomic techniques applied under irrigation with gypsiferous mine water at pivot Fourth.

Season	Crop	Cultivar	Planting date	Row spacing (m)	Planting density	Fertilization	Herbicide
1999	Wheat	SST 825 and SST 876	07/07/1999	0.3	150 kg seed ha^{-1}	300 kg ha^{-1} 4:1:1 (22) before planting; 130 kg ha^{-1} 2:3:4 (20) at planting; 420 kg ha^{-1} 3:0:1 (16) on 19/08/1999; 420 kg ha^{-1} 3:0:1 (16) on 16/09/1999.	4 l ha^{-1} Kelp-P-Max, 500 ml ha^{-1} MCPA and 4 l ha^{-1} Broxonol.
1999/00	Maize	PHI 33408 (Bt gene)	17/12/1999	0.8	60,000 plants ha^{-1}	380 kg ha^{-1} 5:3:6 (02) before planting; 220 kg ha^{-1} 1:0:1 (13), 220 kg ha^{-1} UAN (32) and 380 kg ha^{-1} 3:0:1 (16) as top dressing; 2 kg ha^{-1} Map, 1 kg ha^{-1} NGSO4 and 100 kg ha^{-1} Omnispoor for leaf nutrition.	400 ml ha^{-1} Galleon, 600 ml ha^{-1} Wenner and 40 ml ha^{-1} Karate at planting; 700 ml ha^{-1} Relay, 120 ml ha^{-1} Allbuff, 2 l ha^{-1} Bladex and 4 l ha^{-1} Bromox after emergence.
2000	Wheat	SST 825	27/06/2000	0.2	225 kg seed ha^{-1}	548 kg ha^{-1} 4:1:1 (22) before planting; 150 kg ha^{-1} 2:3:4 (30) 0.50 % Zn at planting; 417 kg ha^{-1} 3:0:1 (16) on 35 days after emergence; 417 kg ha^{-1} 3:0:1 (16) on 50 days after emergence; 100 kg ha^{-1} ANO (21) after flag leaf for protein increase; Omniboost for leaf nutrition.	150 kg ha^{-1} Bromox and 500 ml ha^{-1} MCPA on 18/08/2000.

Table A5. Instrumentation installed in the intensive monitoring stations of pivot Major and soil profile description for each season and treatment.

Season and crop	Treatment	Tipping bucket rain gauges	Heat dissipation sensors	Tensiometers	CS-615 soil reflectometers	Neutron probe access tubes	TDR probes	Ceramic cup soil water samplers	Soil profile description
Summer 1997/98, sugar-beans	Leaching fraction strategy	2	6 (depths: 1, 11, 21, 41, 61 and 81 cm)	4	4 (depths: 11, 21, 41 and 61 cm)	2	-	3 (depths: 40, 100 and 140 cm)	0-20 cm Orthic A horizon; 20-50 cm Apedal B horizon; 50-85 cm hard Plinthite; +85 cm weathered sandstone; water table at 93 cm.
	Field capacity strategy	2	6 (depths: 5, 15, 35, 55, 75 and 95 cm)	4	4 (depths: 5, 15, 55 and 95 cm)	2	-	3 (depths: 40, 100 and 140 cm)	0-25 cm Orthic A horizon;25-70 cm Apedal B horizon; 70-90 cm hard Plinthite; +90 cm weathered sandstone.
	Deficit strategy	2	6 (depths: 5, 15, 35, 55, 85 and 125 cm)	4	4 (depths: 15, 35, 55, 105 cm)	2	-	3 (depths: 40, 100 and 140 cm)	0-35 cm Orthic A horizon; 35-60 cm Apedal B horizon; 60-105 cm weathered sandstone; +105 cm wet clay layer.
	Dry land*	1	6 (depths: 10, 20, 30, 40, 60 and 80 cm)	4	4 (depths: 10, 20, 45 and 75 cm)	2	-	-	0-30 cm Orthic A horizon; 30-75 cm Apedal B horizon; 75-110 cm hard Plinthite; +110 cm weathered sandstone.
Summer 1997/98, babala and maize (alternative cropping systems)	Leaching fraction strategy	1 (manual)	-	-	-	2	-	-	-
	Field capacity strategy	1 (manual)	-	-	-	2	-	-	-
	Deficit strategy	1 (manual)	-	-	-	2	-	-	-
	Dry land*	1 (manual)	-	-	-	2	-	-	-

* Monitoring in the dry land area outside the pivot circle, as control.

Table A5 (continued). Instrumentation installed in the intensive monitoring stations of pivot Major and soil profile description for each season and treatment.

Season and crop	Treatment	Tipping bucket rain gauges	Heat dissipation sensors	Tensiometers	CS-615 soil reflectometers	Neutron probe access tubes	TDR probes	Ceramic cup soil water samplers	Soil profile description
From winter 1998 until the end of the trial, lucerne-fescue perennial pasture (alternative cropping system)	Leaching fraction strategy	2	6 (depths: 10, 20, 30, 40, 60 and 80 cm)	3	-	2	8 (depths: 10, 15, 20, 30, 40, 50, 60 and 80 cm)	3 (depths: 40, 100 and 140 cm)	0-20 cm Orthic A horizon; 20-80 cm Apedal B horizon; +80 cm hard Plinthite.
	Field capacity strategy	2	6 (depths: 12, 22, 32, 52, 72 and 92 cm)	3	-	2	8 (depths: 6, 12, 22, 32, 42, 52, 72 and 88 cm)	3 (depths: 40, 100 and 140 cm)	0-20 cm Orthic A horizon; 20-90 cm Apedal B horizon; +90 cm hard Plinthite.
	Deficit strategy	2	6 (depths: 13, 23, 33, 43, 53 and 73 cm)	3	-	2	8 (depths: 7, 13, 23, 33, 43, 53, 62 and 73 cm)	3 (depths: 40, 100 and 140 cm)	0-30 cm Orthic A horizon; 30-40 cm Apedal B horizon; 40-50 cm hard Plinthite; +50 cm weathered sandstone.
Winter 1998, wheat	Leaching fraction strategy	-	-	-	-	2	-	-	-
	Field capacity strategy	-	-	-	-	2	-	-	-
	Deficit strategy	-	-	-	-	2	-	-	-
Winter 1998, ryegrass and stooling rye (alternative cropping systems)	Leaching fraction strategy	1 (manual)	-	-	-	2	-	-	-
	Field capacity strategy	1 (manual)	-	-	-	2	-	-	-
	Deficit strategy	1 (manual)	-	-	-	2	-	-	-

Table A5 (continued). Instrumentation installed in the intensive monitoring stations of pivot Major and soil profile description for each season and treatment.

Season and crop	Treatment	Tipping bucket rain gauges	Heat dissipation sensors	Tensiometers	CS-615 soil reflectometers	Neutron probe access tubes	TDR probes	Ceramic cup soil water samplers	Soil profile description
Summer 1998/99, maize	Leaching fraction strategy	2	4 (depths: 15, 25, 35 and 55 cm)	3	-	2	-	3 (depths: 40, 100 and 140 cm)	0-30 cm Orthic A horizon;30-60 cm Apedal B horizon;60-90 cm hard Plinthite;+90 cm weathered sandstone.
	Field capacity strategy	2	5 (depths: 15, 35, 55, 75 and 105 cm)	3	-	2	-	3 (depths: 40, 100 and 140 cm)	0-30 cm Orthic A horizon; 30-110 cm Apedal B horizon; +110 cm hard Plinthite.
	Deficit strategy	2	4 (depths: 15, 25, 35 and 55 cm)	3	-	2	-	3 (depths: 40, 100 and 140 cm)	0-30 cm Orthic A horizon; 30-60 cm Apedal B horizon; +60 cm hard Plinthite.
Winter 1999, wheat	Leaching fraction strategy	-	-	-	-	2	-	-	-
	Field capacity strategy	-	-	-	-	2	-	-	-
	Deficit strategy	-	-	-	-	2	-	-	-
Summer 1999/00, Maize	Leaching fraction strategy	-	-	-	-	2	-	-	-
	Field capacity strategy	-	-	-	-	2	-	-	-
	Deficit strategy	-	-	-	-	2	-	-	-
Winter 2000, wheat	Leaching fraction strategy	-	-	-	-	2	-	-	-
	Field capacity strategy	-	-	-	-	2	-	-	-
	Deficit strategy	-	-	-	-	2	-	-	-

Table A6. Instrumentation installed in the intensive monitoring stations of pivot Tweefontein and soil profile description for each season and treatment.

Season and crop	Treatment	Tipping bucket rain gauges	Heat dissipation sensors	Tensiometers	CS-615 soil reflectometers	Neutron probe access tubes	TDR probes	Ceramic cup soil water samplers	Soil profile description
Summer 1997/98, sugar-beans	Leaching fraction strategy	2	6 (depths: 10, 20, 40, 60, 80 and 100 cm)	3	-	2	-	3 (depths: 40, 100 and 140 cm)	0-90 cm red Apedal; +90 cm spoil; water table at 85 cm.
	Field capacity strategy	1	6 (depths: 5, 15, 35, 55, 75 and 95 cm)	3	-	2	-	3 (depths: 40, 100 and 140 cm)	0-90 cm red Apedal; +90 cm spoil.
	Deficit strategy	2	6 (depths: 10, 20, 40, 70, 80 and 100 cm)	3	-	2	-	3 (depths: 40, 100 and 140 cm)	0-90 cm red Apedal; +90 cm spoil.
Winter 1998, wheat	Leaching fraction strategy	2	6 (depths: 5, 15, 35, 55, 75 and 95 cm)	3	5 (depths: 5, 15, 35, 55 and 75 cm)	2	-	3 (depths: 40, 100 and 140 cm)	0-110 cm red Apedal; +110 cm spoil.
	Field capacity strategy	1	6 (depths: 12, 22, 32, 52, 72 and 92 cm)	3	5 (depths: 12, 22, 32, 52 and 72 cm)	2	-	3 (depths: 40, 100 and 140 cm)	0-110 cm red Apedal; +110 cm spoil.
	Deficit strategy	2	6 (depths: 12, 22, 32, 42, 62 and 82 cm)	3	5 (depths: 12, 22, 32, 42 and 62 cm)	2	-	3 (depths: 40, 100 and 140 cm)	0-110 cm red Apedal; +110 cm spoil.
Summer 1998/99, sugar-beans	Leaching fraction strategy	2	4 (depths: 16, 36, 56 and 86 cm)	3	5 (depths: 16, 21, 36, 56 and 86 cm)	2	-	3 (depths: 40, 100 and 140 cm)	0-125 cm red Apedal; +125 cm spoil.
	Field capacity strategy	2	4 (depths: 15, 35, 50 and 65 cm)	3	5 (depths: 15, 25, 35, 50 and 65 cm)	2	-	3 (depths: 40, 100 and 140 cm)	0-95 cm red Apedal; +95 cm spoil.
	Deficit strategy	2	4 (depths: 10, 30, 50 and 80 and cm)	3	5 (depths: 10, 20, 30, 50 and 80 cm)	2	-	3 (depths: 40, 100 and 140 cm)	0-120 cm red Apedal; +120 cm spoil.
Winter 1999, wheat	Field capacity strategy	1	-	-	-	2	-	-	-
Summer 1999/00, wheat	Field capacity strategy	1	-	-	-	2	-	-	-
Winter 2000, wheat	Field capacity strategy	2	-	-	-	2	-	-	-

Table A7. Instrumentation installed in the intensive monitoring stations of pivot Jacuzzi and soil profile description for each season and treatment.

Season and crop	Treatment	Tipping bucket rain gauges	Heat dissipation sensors	Tensiometers	CS-615 soil reflectometers	Neutron probe access tubes	TDR probes	Ceramic cup soil water samplers	Soil profile description
Summer 1997/98, sugar-beans	Leaching fraction strategy	2	6 (depths: 1, 11, 31, 51, 71 and 101 cm)	3	-	2	-	3 (depths: 40, 100 and 140 cm)	0-90 cm red Apedal; +90 cm spoil.
	Field capacity strategy	2	7 (depths: 15, 35, 65, 95, 125, 165 and 195 cm)	3	-	2	-	3 (depths: 40, 100 and 140 cm)	0-195 cm red Apedal; +195 cm spoil; water table at 190 cm.
	Deficit strategy	2	8 (depths: 10, 20, 40, 60, 80, 100, 130 and 180 cm)	3	-	2	-	3 (depths: 40, 100 and 140 cm)	0-170 cm red Apedal; +170 cm spoil; water table at 155 cm.
Winter 1998, wheat	Leaching fraction strategy	2	4 (depths: 10, 26, 42 and 65 cm)	3	-	2	-	2 (depths: 40 and 75 cm)	0-75 cm red Apedal; +75 cm spoil.
	Field capacity strategy	2	5 (depths: 15, 25, 45, 65 and 85 cm)	3	-	2	-	-	0-250 cm red Apedal; +250 cm spoil.
	Deficit strategy	2	5 (depths: 7, 17, 27, 47 and 70 cm)	3	-	2	-	2 (depths: 40 and 80 cm)	0-80 cm red Apedal; +80 cm spoil.
Summer 1998/99, sugar-beans	Leaching fraction strategy	1	-	-	-	2	-	-	-
	Field capacity strategy	1	-	-	-	2	-	-	-
	Deficit strategy	1	-	-	-	2	-	-	-

Table A8. Instrumentation installed in the intensive monitoring stations of pivot Fourth and soil profile description for each season and treatment.

Season and crop	Treatment	Tipping bucket rain gauges	Heat dissipation sensors	Tensiometers	CS-615 soil reflectometers	Neutron probe access tubes	TDR probes	Ceramic cup soil water samplers	Soil profile description
Winter 1999, wheat	Leaching fraction strategy (repl.1)	2	5 (depths: 6, 16, 26, 46 and 84 cm)	-	-	1	(depths: 6, 16, 26, 36, 46, 60, 72 and 84 cm)	3 (depths: 40, 100 and 140 cm)	0-20 cm Orthic A horizon; +20 cm red Apedal B horizon.
	Leaching fraction strategy (repl. 2)	2	5 (depths: 6, 16, 26, 46 and 84 cm)	-	-	1	(depths: 6, 16, 26, 36, 46, 60, 72 and 84 cm)	3 (depths: 40, 100 and 140 cm)	0-20 cm Orthic A horizon; +20 cm red Apedal B horizon.
	Field capacity strategy (repl. 1)	2	5 (depths: 6, 16, 26, 46 and 84 cm)	-	-	1	(depths: 6, 16, 26, 36, 46, 60, 72 and 84 cm)	3 (depths: 40, 100 and 140 cm)	0-20 cm Orthic A horizon; +20 cm red Apedal B horizon.
	Field capacity strategy (repl. 2)	2	5 (depths: 6, 16, 26, 46 and 84 cm)	-	-	1	(depths: 6, 16, 26, 36, 46, 60, 72 and 84 cm)	3 (depths: 40, 100 and 140 cm)	0-20 cm Orthic A horizon; +20 cm red Apedal B horizon.
	Deficit strategy (repl. 1)	2	5 (depths: 6, 16, 26, 46 and 84 cm)	-	-	1	(depths: 6, 16, 26, 36, 46, 60, 72 and 84 cm)	3 (depths: 40, 100 and 140 cm)	0-20 cm Orthic A horizon; +20 cm red Apedal B horizon.
	Deficit strategy (repl. 2)	2	5 (depths: 6, 16, 26, 46 and 84 cm)	-	-	1	(depths: 6, 16, 26, 36, 46, 60, 72 and 84 cm)	3 (depths: 40, 100 and 140 cm)	0-20 cm Orthic A horizon; +20 cm red Apedal B horizon.

Table A8 (continued). Instrumentation installed in the intensive monitoring stations of pivot Fourth and soil profile description for each season and treatment.

Season and crop	Treatment	Tipping bucket rain gauges	Heat dissipation sensors	Tensiometers	CS-615 soil reflectometers	Neutron probe access tubes	TDR probes	Ceramic cup soil water samplers	Soil profile description
Summer 1999/00, maize	Leaching fraction strategy (repl. 1)	2	5 (depths: 10, 20, 40, 70 and 100 cm)	-	-	2	8 (depths: 10, 20, 30, 40, 50, 60, 80 and 100 cm)	3 (depths: 40, 100 and 140 cm)	0-20 cm Orthic A horizon; +20 cm red Apedal B horizon.
	Leaching fraction strategy (repl. 2)	2	5 (depths: 10, 20, 40, 70 and 100 cm)	-	-	2	8 (depths: 10, 20, 30, 40, 50, 60, 80 and 100 cm)	3 (depths: 40, 100 and 140 cm)	0-20 cm Orthic A horizon; +20 cm red Apedal B horizon.
	Field capacity strategy (repl. 1)	2	5 (depths: 10, 20, 40, 70 and 100 cm)	-	-	2	8 (depths: 10, 20, 30, 40, 50, 60, 80 and 100 cm)	3 (depths: 40, 100 and 140 cm)	0-20 cm Orthic A horizon; +20 cm red Apedal B horizon.
	Field capacity strategy (repl. 2)	2	5 (depths: 10, 20, 40, 70 and 100 cm)	-	-	2	8 (depths: 10, 20, 30, 40, 50, 60, 80 and 100 cm)	3 (depths: 40, 100 and 140 cm)	0-20 cm Orthic A horizon; +20 cm red Apedal B horizon.
	Deficit strategy (repl. 1)	2	5 (depths: 10, 20, 40, 70 and 100 cm)	-	-	2	8 (depths: 10, 20, 30, 40, 50, 60, 80 and 100 cm)	3 (depths: 40, 100 and 140 cm)	0-20 cm Orthic A horizon; +20 cm red Apedal B horizon.
	Deficit strategy (repl. 2)	2	4 (depths: 10, 40, 70 and 100 cm)	-	-	2	8 (depths: 10, 20, 30, 40, 50, 60, 80 and 100 cm)	3 (depths: 40, 100 and 140 cm)	0-20 cm Orthic A horizon; +20 cm red Apedal B horizon.

Table A8 (continued). Instrumentation installed in the intensive monitoring stations of pivot Fourth and soil profile description for each season and treatment.

Season and crop	Treatment	Tipping bucket rain gauges	Heat dissipation sensors	Tensiometers	CS-615 soil reflectometers	Neutron probe access tubes	TDR probes	Ceramic cup soil water samplers	Soil profile description
Winter 2000, wheat	Leaching fraction strategy (repl. 1)	2	4 (depths: 10, 30, 50 and 100 cm)	-	-	2	7 (depths: 10, 20, 30, 40, 50, 70 and 100 cm)	3 (depths: 40, 100 and 140 cm)	0-20 cm Orthic A horizon; +20 cm red Apedal B horizon.
	Leaching fraction strategy (repl. 2)	2	4 (depths: 10, 30, 50 and 100 cm)	-	-	2	7 (depths: 10, 20, 30, 40, 50, 70 and 100 cm)	3 (depths: 40, 100 and 140 cm)	0-20 cm Orthic A horizon; +20 cm red Apedal B horizon.
	Field capacity strategy (repl. 1)	2	4 (depths: 10, 30, 50 and 100 cm)	-	-	2	7 (depths: 10, 20, 30, 40, 50, 70 and 100 cm)	3 (depths: 40, 100 and 140 cm)	0-20 cm Orthic A horizon; +20 cm red Apedal B horizon.
	Field capacity strategy (repl. 2)	2	4 (depths: 10, 30, 50 and 100 cm)	-	-	2	7 (depths: 10, 20, 30, 40, 50, 70 and 100 cm)	3 (depths: 40, 100 and 140 cm)	0-20 cm Orthic A horizon; +20 cm red Apedal B horizon.
	Deficit strategy (repl. 1)	2	4 (depths: 10, 30, 50 and 100 cm)	-	-	2	7 (depths: 10, 20, 30, 40, 50, 70 and 100 cm)	3 (depths: 40, 100 and 140 cm)	0-20 cm Orthic A horizon; +20 cm red Apedal B horizon.
	Deficit strategy (repl. 2)	2	4 (depths: 10, 30, 50 and 100 cm)	-	-	2	7 (depths: 10, 20, 30, 40, 50, 70 and 100 cm)	2 (depths: 100 and 140 cm)	0-20 cm Orthic A horizon; +20 cm red Apedal B horizon.

Table A9. Plant analysis data of wheat sampled on 27 August 1998.

Pivot	Treatment	CV	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	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal
T	DE	K	58 DAP	WS	3.5-4.5	**5.15**	0.2 – 0.4	**0.46**	2-3.5	**3.81**	0.2-0.5	0.33	0.15-0.5	0.34	-	0.03	0.51–1.6	1.42	5 -25	15	25-100	**155**	35-475	111	15-70	53
T	DE	K	58 DAP	WS	3.5-4.5	3.65	0.2-0.4	0.3	2-3.5	**3.6**	0.2-0.5	0.28	0.15-0.5	0.29	-	0.04	0.51–1.6	1.33	5 -25	12	25-100	44	35-475	81	15-70	38
T	FC	K	58 DAP	WS	3.5-4.5	3.95	0.2-0.4	0.38	2-3.5	**4.06**	0.2-0.5	0.17	0.15-0.5	0.26	-	0.03	0.51–1.6	1.02	5 -25	12	25-100	20	35-475	69	15-70	57
T	LF	K	58 DAP	WS	3.5-4.5	3.83	0.2-0.4	0.34	2-3.5	3.44	0.2-0.5	0.27	0.15-0.5	0.21	-	0.03	0.51–1.6	1.22	5 -25	11	25-100	27	35-475	54	15-70	20
J	DE	SST	56 DAP	WS	3.5-4.5	4.4	0.2-0.4	0.34	2-3.5	3.24	0.2-0.5	0.31	0.15-0.5	0.26	-	0.02	0.51–1.6	1.65	5 -25	8	25-100	**107**	35-475	137	15-70	38
J	FC	SST	56 DAP	WS	3.5-4.5	**4.66**	0.2-0.4	0.37	2-3.5	2.71	0.2-0.5	0.29	0.15-0.5	0.31	-	0.02	0.51–1.6	1.97	5 -25	9	25-100	**299**	35-475	126	15-70	26
J	LF	SST	56 DAP	WS	3.5-4.5	**4.96**	0.2-0.4	**0.43**	2-3.5	2.65	0.2-0.5	0.26	0.15-0.5	0.29	-	0.02	0.51–1.6	1.52	5 -25	14	25-100	**134**	35-475	84	15-70	47
M	DE	K	62 DAP	WS	3.5-4.5	4.35	0.2-0.4	0.27	2-3.5	3.19	0.2-0.5	0.2	0.15-0.5	0.24	-	0.02	0.51–1.6	1.35	5 -25	24	25-100	75	35-475	144	15-70	56
M	FC	K	62 DAP	WS	3.5-4.5	4.05	0.2-0.4	0.31	2-3.5	**3.76**	0.2-0.5	0.24	0.15-0.5	0.23	-	0.02	0.51–1.6	1.46	5 -25	6	25-100	54	35-475	113	15-70	23
M	LF	K	62 DAP	WS	3.5-4.5	3.45	0.2-0.4	0.21	2-3.5	3.04	0.2-0.5	0.24	0.15-0.5	0.24	-	0.03	0.51–1.6	1.33	5 -25	5	25-100	**111**	35-475	108	15-70	23

CV - Cultivar	M - Major	LF - Leaching fraction strategy
K- Kariega 103	J - Jacuzzi	FC - Field capacity strategy
SST - SST 825	T - Tweefontein	DE - Deficit irrigation strategy
DAP - Days after planting	Norm - Normal	
WS - Whole shoot	Anal - Analysis	
Highlighted values higher than the respective norm		

Table A10. Plant analysis data of wheat sampled on 10 September 1998.

Pivot	Treatment	CV	Growth stage	Plant part sampled	N (%)		P (%)		K (%)		Ca (%)		Mg (%)		Na (%)		SO₄ (%)		Cu (mgkg⁻¹)		Fe (mgkg⁻¹)		Mn (mgkg⁻¹)		Zn (mgkg⁻¹)		B (mgkg⁻¹)		Mo (mgkg⁻¹)	
					Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal
M	LF	K	76 DAP	YMB	3.5-4.5	4.1	0.2-0.4	0.32	2-3.5	2.82	0.2-0.5	0.08	0.15-0.5	0.15	-	0.02	0.51-1.6	1.06	5 -25	18	25-100	**203**	35-475	66	15-70	47	3–20	0.34	-	0.26
M	FC	K	76 DAP	YMB	3.5-4.5	4.25	0.2-0.4	0.26	2-3.5	**3.66**	0.2-0.5	0.28	0.15-0.5	0.18	-	0.02	0.51-1.6	1.02	5 -25	15	25-100	**149**	35-475	129	15-70	48	3–20	1.11	-	0
M	LF	SST	76 DAP	YMB	3.5-4.5	4.2	0.2-0.4	**0.44**	2-3.5	2.41	0.2-0.5	0.16	0.15-0.5	0.18	-	0.02	0.51-1.6	1.25	5 -25	17	25-100	**126**	35-475	48	15-70	74	3–20	0.26	-	0.05
M	DE	K	76 DAP	YMB + 2ndMB	3.5-4.5	**6**	0.2-0.4	**0.44**	2-3.5	**4.48**	0.2-0.5	0.14	0.15-0.5	0.25	-	0.02	0.51-1.6	1.11	5 -25	15	25-100	**159**	35-475	156	15-70	54	3–20	1.59	-	0
M	DE	K	76 DAP	YMB	3.5-4.5	**4.9**	0.2-0.4	0.24	2-3.5	**3.82**	0.2-0.5	0.16	0.15-0.5	0.26	-	0.02	0.51-1.6	1.26	5 -25	15	25-100	**168**	35-475	183	15-70	48	3–20	1.18	-	0
J	LF	SST	70 DAP	YMB	3.5-4.5	**4.6**	0.2-0.4	0.24	2-3.5	1.76	0.2-0.5	0.28	0.15-0.5	0.27	-	0.03	0.51-1.6	1.47	5 -25	20	25-100	**173**	35-475	110	15-70	56	3–20	0.65	-	0
J	FC	SST	70 DAP	YMB	3.5-4.5	4.2	0.2-0.4	0.2	2-3.5	2.39	0.2-0.5	0.18	0.15-0.5	0.22	-	0.02	0.51-1.6	1.28	5 -25	12	25-100	**135**	35-475	113	15-70	30	3–20	0.69	-	0
J	DE	SST	70 DAP	YMB	3.5-4.5	**5.2**	0.2-0.4	0.3	2-3.5	2.25	0.2-0.5	**0.53**	0.15-0.5	0.24	-	0.02	0.51-1.6	1.14	5 -25	**76**	25-100	**414**	35-475	123	15-70	**41**	3–20	0	-	*0*
T	LF	K	72 DAP	YMB	3.5-4.5	**4.6**	0.2-0.4	0.34	2-3.5	2.23	0.2-0.5	0.11	0.15-0.5	0.15	-	0.02	0.51-1.6	1.37	5 -25	12	25-100	**102**	35-475	29	15-70	29	3–20	0	-	0.21
T	FC	K	72 DAP	YMB	3.5-4.5	4.5	0.2-0.4	0.3	2-3.5	2.69	0.2-0.5	0.16	0.15-0.5	0.18	-	0.03	0.51-1.6	1.11	5 -25	11	25-100	95	35-475	80	15-70	32	3–20	0.37	-	0.25
T	DE	K	72 DAP	YMB	3.5-4.5	4.2	0.2-0.4	0.29	2-3.5	3.17	0.2-0.5	0.11	0.15-0.5	0.2	-	0.02	0.51-1.6	1.15	5 -25	18	25-100	92	35-475	105	15-70	39	3–20	0.99	-	0.1

CV - Cultivar	M - Major	LF - Leaching fraction strategy
K - Kariega 103	J - Jacuzzi	FC - Field capacity strategy
SST - SST 825	T - Tweefontein	*DE - Deficit irrigation strategy*
DAP - Days after planting	Norm - Normal	
YMB - Youngest mature leaf blade	Anal - Analysis	
YMB+2ndMB - Youngest and second youngest mature leaf blades	**Highlighted values higher than the respective norm**	

Table A11. Plant analysis data of wheat and lucerne sampled on 29 September 1998.

Pivot	Treatment	CV	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})		B (mg kg^{-1})		Mo (mg kg^{-1})	
					Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal
M	FC	K	95 DAP	FL	3.5-4.5	4	0.3-0.5	0.23	2-3	2.07	0.3-5	0.23	0.2-0.6	0.3	-	0.01	0.57-1.65	1.16	5-25	14	25-100	57	35-475	117	15-70	33	3-20	5.7	-	0
M	DE	K	95 DAP	FL	3.5-4.5	3.75	0.3-0.5	0.21	2-3	2.04	0.3-5	0.33	0.2-0.6	0.39	-	0.01	0.57-1.65	1.28	5-25	11	25-100	59	35-475	185	15-70	36	3-20	5.7	-	0
M	LF	K	95 DAP	FL	3.5-4.5	3.49	0.3-0.5	0.2	2-3	2.02	0.3-5	0.25	0.2-0.6	0.31	-	0.01	0.57-1.65	1.28	5-25	8	25-100	**131**	35-475	93	15-70	26	3-20	5.2	-	1.24
T	LF	K	91 DAP	FL	3.5-4.5	3.17	0.3-0.5	0.22	2-3	2.59	0.3-5	0.32	0.2-0.6	0.33	-	0.02	0.57-1.65	0.95	5-25	8	25-100	0	35-475	57	15-70	23	3-20	5.2	-	4.43
T	DE	K	91 DAP	FL	3.5-4.5	4	0.3-0.5	0.21	2-3	1.17	0.3-5	2.23	0.2-0.6	0.63	-	0.03	0.57-1.65	1.09	5-25	2	25-100	75	35-475	78	15-70	29	3-20	5.5	-	1.09
M	LF	L	95 DAP	T15	3-5	1.1	0.25-0.7	0.15	2-3	2.02	0.8-3	1.56	0.25-1	0.63	-	0.06	0.75-1.5	**1.83**	5-30	3	30-254	171	25-100	**113**	20-70	**80**	20-80	55.6	1-5	5.9
M	DE	L	95 DAP	T15	3-5	3.78	0.25-0.7	0.23	2-3	1.67	0.8-3	1.88	0.25-1	0.48	-	0.04	0.75-1.5	1.37	5-30	3	30-254	189	25-100	75	20-70	48	20-80	31.5	1-5	3.99
M	FC	L	95 DAP	T15	3-5	2.51	0.25-0.7	0.19	2-3	1.48	0.8-3	1.86	0.25-1	0.91	-	0.08	0.75-1.5	**1.68**	5-30	9	30-254	102	25-100	**101**	20-70	60	20-80	42.5	1-5	4.02
M	DE	L	95 DAP	T15	3-5	4.05	0.25-0.7	0.17	2-3	1.95	0.8-3	0.41	0.25-1	0.37	-	0.02	0.75-1.5	**1.91**	5-30	8	30-254	98	25-100	**120**	20-70	63	20-80	21.1	1-5	4.39
J	DE	K	89 DAP	FL	3.5-4.5	4	0.3-0.5	0.23	2-3	1.3	0.3-5	0.64	0.2-0.6	0.67	-	0.05	0.57-1.65	1.43	5-25	15	25-100	**173**	35-475	111	15-70	42	3-20	6.4	-	3.29
J	LF	SST	89 DAP	FL	3.5-4.5	3.74	0.3-0.5	0.19	2-3	2.44	0.3-5	0.27	0.2-0.6	0.3	-	0.02	0.57-1.65	2.86	5-25	8	25-100	**128**	35-475	224	15-70	45	3-20	6.9	-	4.38
M	DE	K	95 DAP	FL + 2nd MB	3.5-4.5	4.4	0.3-0.5	0.27	2-3	0.84	0.3-5	0.34	0.2-0.6	0.24	-	0.02	0.57-1.65	1.36	5-25	14	25-100	**230**	35-475	209	15-70	45	3-20	5.2	-	3.22

CV - Cultivar	FL + 2nd MB - Flag leaf + 2nd mature blade	LF - Leaching fraction strategy
K - Kariega 103	M - Major	FC - Field capacity strategy
L - Lucerne	J - Jacuzzi	DE - Deficit irrigation strategy
SST - SST 825	T - Tweefontein	
DAP - Days after planting	Norm - Normal	
FL - Flag leaf	Anal - Analysis	
Highlighted values higher than the respective norm		

Table A12. Plant analysis data of *maize and sugar* beans sampled on 15 February 1999.

Pivot	Treatment	Species	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	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal
M	LF	MZ	1.6m+	LBBW	2.75-3.5	2.45	0.25-0.45	0.22	1.75-2.25	2.08	.25-0.5	0.33	0.13-0.3	0.16	-	0.01	0.5-1.5	0.75	3-15	8	30-200	149	15-300	56	15-60	39
M	LF	MZ	0.5m	LBBW	3-3.5	2.99	0.25-0.45	0.30	2-2.5	2.65	.25-0.5	0.29	0.13-0.3	0.22	-	0.01	0.5-1.5	1.20	3-15	5	30-200	**227**	15-300	30	15-60	54
M	FC	MZ	1.6m+	LBBW	2.75-3.5	2.52	0.25-0.45	0.20	1.75-2.25	2.09	.25-0.5	0.32	0.13-0.3	0.20	-	0.01	0.5-1.5	0.92	3-15	6	30-200	200	15-300	77	15-60	42
M	DE	MZ	1.6m+	LBBW	2.75-3.5	2.14	0.25-0.45	0.25	1.75-2.25	1.97	.25-0.5	0.33	0.13-0.3	0.22	-	0.00	0.5-1.5	0.86	3-15	6	30-200	173	15-300	59	15-60	38
M	DE	MZ	0.5m	LBBW	3-3.5	3.10	0.25-0.45	0.47	2-2.5	2.89	.25-0.5	0.28	0.13-0.3	0.21	-	0.02	0.5-1.5	1.49	3-15	5	30-200	125	15-300	38	15-60	78
T	LF	SB	43 DAP	WS	-	3.76	-	0.36	-	3.33	-	1.78	-	0.54	-	0.03	-	1.89	-	9	-	266	-	50	-	45
T	FC	SB	43 DAP	WS	-	3.55	-	0.30	-	2.91	-	2.08	-	0.74	-	0.03	-	1.98	-	9	-	414	-	63	-	39
T	DE	SB	43 DAP	WS	-	3.75	-	0.32	-	2.71	-	2.07	-	0.79	-	0.03	-	1.77	-	6	-	443	-	81	-	48
T	LF	SB	43 DAP	YMB	-	5.35	-	0.31	-	2.49	-	2.46	-	0.69	-	0.30	-	2.79	-	8	-	357	-	75	-	153
T	FC	SB	43 DAP	YMB	-	4.70	-	0.24	-	1.78	-	3.09	-	1.06	-	0.01	-	2.41	-	15	-	471	-	93	-	48
T	DE	SB	43 DAP	YMB	-	5.00	-	0.23	-	1.82	-	2.95	-	1.21	-	0.01	-	1.34	-	9	-	776	-	104	-	89
J	FC	SB	41 DAP	WS	-	3.68	-	0.18	-	2.49	-	2.46	-	0.72	-	0.01	-	2.04	-	12	-	902	-	221	-	98
J	DE	SB	41 DAP	YL	-	2.83	-	0.31	-	1.72	-	2.21	-	0.76	-	0.02	-	2.03	-	72	-	479	-	495	-	60
J	LF	SB	41 DAP	YMB	-	5.60	-	0.34	-	3.10	-	2.31	-	0.55	-	0.01	-	1.49	-	8	-	341	-	87	-	42
J	FC	SB	41 DAP	YMB	-	6.00	-	0.30	-	2.43	-	1.98	-	0.96	-	0.01	-	1.61	-	11	-	581	-	228	-	56
J	DE	SB	41 DAP	YMB	-	5.80	-	0.23	-	1.98	-	2.46	-	1.11	-	0.01	-	1.22	-	9	-	350	-	320	-	42

MZ - Maize	LBBW -	LF - Leaching fraction strategy
SB - Sugar Bean	M - Major	FC - Field capacity strategy
DAP - Days after planting	J - Jacuzzi	DE - Deficit irrigation strategy
YMB - Youngest mature leaf blade	T - Tweefontein	
WS - Whole shoot	Norm - Normal	
YL - Youngest leaves	*Anal - Analysis*	
Highlighted values higher than the respective norm		

Table A13. Plant analysis data of wheat from pivot Major sampled in winter 2000.

Treatment	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	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal
DE	Tiller	WT	4.0 - 5.0	2.97	0.4 - 0.7	0.35	3.2 - 4.0	**4.39**	0.2 - 0.5	0.42	0.15 - 0.5	0.16	-	0.02	0.66 – 1.65	1.65	5 -25.	3	25 - 100	**149**	11 - 13.	**76.**	15 - 70	37
FC	Tiller	WT	4.0 - 5.0	2.90	0.4 - 0.7	0.31	3.2 - 4.0	**4.16**	0.2 - 0.5	0.42	0.15 - 0.5	0.17	-	0.02	0.66 – 1.65	1.50	5 -25.	3	25 - 100	**146**	11 - 13.	**69**	15 - 70	30
LF	Tiller	WT	4.0 - 5.0	2.83	0.4 - 0.7	0.37	3.2 - 4.0	3.92	0.2 - 0.5	0.39	0.15 - 0.5	0.16	-	0.02	0.66 – 1.65	1.44	5 -25.	2	25 - 100	**140**	11 - 13.	**62**	15 - 70	28
DE	Till-SE	WT	3.5 - 4.5	3.64	0.2 - 0.4	0.38	2.0 - 3.5	**3.61**	0.2 - 0.5	0.38	0.15 - 0.5	0.21	-	0.02	0.57 – 1.65	**2.53**	5 -25.	**11**	25 - 100	**168**	11 - 13.	**105**	15 - 70	43.
FC	Till-SE	WT	3.5 - 4.5	3.64	0.2 - 0.4	0.37	2.0 - 3.5	**3.59**	0.2 - 0.5	0.37	0.15 - 0.5	0.24	-	0.03	0.57 – 1.65	**2.35**	5 -25.	10	25 - 100	**141**	11 - 13.	**91**	15 - 70	40
LF	Till-SE	WT	3.5 - 4.5	3.32	0.2 - 0.4	0.31	2.0 - 3.5	**3.48**	0.2 - 0.5	0.40	0.15 - 0.5	0.20	-	0.03	0.57 – 1.65	**2.33**	5 -25.	8	25 - 100	**122**	11 - 13.	**93**	15 - 70	41
DE	SE_a	WT	3.0 - 4.0	2.77	0.2 - 0.4	0.25	1.8 - 3.0	**3.74**	0.2 - 0.5	0.37	0.15 - 0.5	0.24	-	0.03	0.51 - 1.65	**2.42**	5 -25.	5	25 - 100	**178**	11 - 13.	**116**	15 - 70	40
FC	SE_a	WT	3.0 - 4.0	2.78	0.2 - 0.4	0.29	1.8 - 3.0	**4.74**	0.2 - 0.5	0.41	0.15 - 0.5	0.29	-	0.04	0.51 – 1.65	**3.39**	5 -25.	7	25 - 100	**164**	11 - 13.	**96**	15 - 70	**44**
LF	SE_a	WT	3.0 - 4.0	3.00	0.2 - 0.4	0.32	1.8 - 3.0	**4.95**	0.2 - 0.5	0.43	0.15 - 0.5	0.32	-	0.04	0.51 – 1.65	**3.36**	5 -25.	11	25 - 100	**185**	11 - 13.	**60**	15 - 70	40
DE	SE_b	WT	3.0 - 4.0	1.92	0.2 - 0.4	0.23	1.8 - 3.0	**5.02**	0.2 - 0.5	0.33	0.15 - 0.5	0.24	-	0.03	0.51- 1.65	1.47	5 -25.	10	25 - 100	**148**	11 - 13.	**127**	15 - 70	37
FC	SE_b	WT	3.0 - 4.0	2.15	0.2 - 0.4	0.26	1.8 - 3.0	**6.24**	0.2 - 0.5	0.36	0.15 - 0.5	0.29	-	0.04	0.51 – 1.65	1.86	5 -25.	12	25 - 100	**128**	11 - 13.	**145**	15 - 70	45
LF	SE_b	WT	3.0 - 4.0	2.19	0.2 - 0.4	0.24	1.8 - 3.0	**5.8**	0.2 - 0.5	0.39	0.15 - 0.5	0.28	-	0.04	0.51 – 1.65	1.65	5 -25.	10	25 - 100	**152**	11 - 13.	**70**	15 - 70	41
DE	Heading	WT	2.1 - 3.0	2.83	0.21 - 0.5	-	1.5 - 3.0	-	0.2 - 0.5	-	0.15 - 0.5	-	-	-	0.44 – 1.2	-	5 -25.	-	25 - 100	-	11 - 13.	-	15 - 70	-
FC	Heading	WT	2.1 - 3.0	5.60	0.21 - 0.5	-	1.5 - 3.0	-	0.2 - 0.5	-	0.15 - 0.5	-	-	-	0.44 – 1.2	-	5 -25.	-	25 - 100	-	11 - 13.	-	15 - 70	-
LF	Heading	WT	2.1 - 3.0	6.00	0.21 - 0.5	-	1.5 - 3.0	-	0.2 - 0.5	-	0.15 - 0.5	-	-	-	0.44 – 1.2	-	5 -25.	-	25 - 100	-	11 - 13.	-	15 - 70	-

SE - Stem extension	Norm - Normal	LF - Leaching fraction strategy
Till - SE -Stage from leaf sheaths lengthen to first node of stem visible	Anal - Analysis	FC - Field capacity strategy
SE_a - Stage from second node visible to last leaf just visible	**Highlighted values higher than the respective norm**	DE - Deficit irrigation strategy
SE_b - Ligule of last leaf just visible to in "boot"		
WT - Whole tops		

Table A14. Plant analysis data of wheat from pivot Fourth sampled in winter 2000.

Treatment	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	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal
DE	Tiller	WT	4.0 - 5.0	2.92	0.4 - 0.7	0.43	3.2 - 4.0	**4.64**	0.2 -0.5	0.38	0.15 - 0.5	0.22	-	0.03	0.66 – 1.65	1.62	5 -25.	4	25 - 100	**132**	11 - 13.	**47**	15 - 70	50
FC	Tiller	WT	4.0 - 5.0	2.95	0.4 - 0.7	0.42	3.2 - 4.0	**4.90**	0.2 -0.5	0.42	0.15 - 0.5	0.21	-	0.03	0.66 – 1.65	1.65	5 -25.	4	25 - 100	100	11 - 13.	**45**	15 - 70	48
LF	Tiller	WT	4.0 - 5.0	2.95	0.4 - 0.7	0.44	3.2 - 4.0	**4.75**	0.2 -0.5	0.43	0.15 - 0.5	0.22	-	0.03	0.66 – 1.65	1.59	5 -25.	4	25 - 100	**116**	11 - 13.	**34**	15 - 70	41
DE	Till-SE	WT	3.5 - 4.5	3.46	0.2 - 0.4	0.29	2.0 - 3.5	**4.49**	0.2 -0.5	0.36	0.15 - 0.5	0.03	-	0.03	0.57 – 1.65	**2.40**	5 -25.	7	25 - 100	66	11 - 13.	**84**	15 - 70	56
FC	Till-SE	WT	3.5 - 4.5	3.61	0.2 - 0.4	0.30	2.0 - 3.5	**4.48**	0.2 -0.5	0.39	0.15 - 0.5	0.03	-	0.04	0.57 – 1.65	**2.63**	5 -25.	7	25 - 100	64	11 - 13.	**77**	15 - 70	58
LF	Till-SE	WT	3.5 - 4.5	3.19	0.2 - 0.4	0.25	2.0 - 3.5	**3.69**	0.2 -0.5	0.38	0.15 - 0.5	0.03	-	0.04	0.57 – 1.65	**2.37**	5 -25.	5	25 - 100	68	11 - 13.	**83**	15 - 70	49
DE	SE_a	WT	3.0 - 4.0	2.53	0.2 - 0.4	0.27	1.8 - 3.0	**3.94**	0.2 -0.5	0.38	0.15 - 0.5	0.03	-	0.03	0.51 - 1.65	**2.36**	5 -25.	3	25 - 100	90	11 - 13.	**99**	15 - 70	49
FC	SE_a	WT	3.0 - 4.0	2.78	0.2 - 0.4	0.31	1.8 - 3.0	**4.33**	0.2 -0.5	0.46	0.15 - 0.5	0.03	-	0.04	0.51 – 1.65	**2.98**	5 -25.	8	25 - 100	**114**	11 - 13.	**94**	15 - 70	57
LF	SE_a	WT	3.0 - 4.0	3.19	0.2 - 0.4	0.32	1.8 - 3.0	**4.40**	0.2 -0.5	0.38	0.15 - 0.5	0.03	-	0.04	0.51 – 1.65	**2.65**	5 -25.	7	25 - 100	**101**	11 - 13.	**105**	15 - 70	57
DE	SE_b	WT	2.5 - 3.5	2.26	0.2 - 0.4	0.25	1.8 - 3.0	**5.56**	0.2 -0.5	0.35	0.15 - 0.5	0.27	-	0.03	0.51- 1.65	1.12	5 -25.	11	25 - 100	75	11 - 13.	**75**	15 - 70	57
FC	SE_b	WT	2.5 - 3.5	2.57	0.2 - 0.4	0.29	1.8 - 3.0	**5.84**	0.2 -0.5	0.39	0.15 - 0.5	0.31	-	0.04	0.51 – 1.65	1.51	5 -25.	12	25 - 100	**103**	11 - 13.	**77**	15 - 70	56
LF	SE_b	WT	2.5 - 3.5	2.06	0.2 - 0.4	0.27	1.8 - 3.0	**5.62**	0.2 -0.5	0.47	0.15 - 0.5	0.32	-	0.05	0.51 – 1.65	**1.66**	5 -25.	12	25 - 100	**154**	11 - 13.	**76**	15 - 70	53
DE	Heading	WT	2.1 - 3.0	-	0.21 - 0.5	-	1.5 - 3.0	-	0.2 -0.5	-	0.15 - 0.5	-	-	-	0.44 – 1.2	-	5 -25.	-	25 - 100	-	11 - 13.	-	15 - 70	-
FC	Heading	WT	2.1 - 3.0	-	0.21 - 0.5	-	1.5 - 3.0	-	0.2 -0.5	-	0.15 - 0.5	-	-	-	0.44 – 1.2	-	5 -25.	-	25 - 100	-	11 - 13.	-	15 - 70	-
LF	Heading	WT	2.1 - 3.0	-	0.21 - 0.5	-	1.5 - 3.0	-	0.2 -0.5	-	0.15 - 0.5	-	-	-	0.44 – 1.2	-	5 -25.	-	25 - 100	-	11 - 13.	-	15 - 70	-

SE- Stem extension	Norm - Normal	LF - Leaching fraction strategy
Till - SE -Stage from leaf sheaths lengthen to first node of stem visible	Anal - Analysis	FC - Field capacity strategy
SE_a - Stage from second node visible to last leaf just visible	**Highlighted values higher than the respective norm**	DE - Deficit irrigation strategy
SE_b - Ligule of last leaf just visible to in "boot"		
WT - Whole tops		

Table A15. Plant analysis data of wheat from pivot Tweefontein sampled in winter 2000.

Treatment	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	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal	Norm	Anal
FC	Tiller	WT	4.0 - 5.0	2.92	0.4 - 0.7	0.35	3.2 - 4.0	**4.36**	0.2 - 0.5	0.43	0.15 - 0.5	0.19	-	0.02	0.66 – 1.65	1.50	5 -25.	4	25 - 100	**142**	11 - 13	**52**	15 - 70	35
FC	Til-SE	WT	3.5 - 4.5	2.34	0.2 - 0.4	0.32	2.0 - 3.5	3.39	0.2 - 0.5	0.32	0.15 - 0.5	0.30	-	0.20	0.57 – 1.65	**2.66**	5 -25.	3	25 - 100	**102**	11 - 13	**14**	15 - 70	24
FC	Til-SE	WT	3.5 - 4.5	2.99	0.2 - 0.4	0.28	2.0 - 3.5	**3.64**	0.2 - 0.5	0.29	0.15 - 0.5	0.3	-	0.07	0.57 – 1.65	**2.83**	5 -25.	3	25 - 100	**125**	11 - 13	**48**	15 - 70	27
FC	Til-SE	WT	3.5 - 4.5	2.69	0.2 - 0.4	0.31	2.0 - 3.5	3.3	0.2 - 0.5	0.33	0.15 - 0.5	0.27	-	0.06	0.57 – 1.65	**2.43**	5 -25.	3	25 - 100	86	11 - 13	**20**	15 - 70	32
FC	SE_a	WT	3.5 - 4.5	4.44	0.2 - 0.4	0.42	1.8 - 3.0	**4.19**	0.2 - 0.5	0.44	0.15 - 0.5	0.32	-	0.06	0.51 - 1.65	**2.81**	5 -25.	9	25 - 100	**114**	11 - 13	**23**	15 - 70	44
FC	SE_a	WT	3.5 - 4.5	4.37	0.2 - 0.4	0.31	1.8 - 3.0	**4.44**	0.2 - 0.5	0.33	0.15 - 0.5	0.35	-	0.05	0.51 – 1.65	**2.89**	5 -25.	8	25 - 100	**137**	11 - 13	**42**	15 - 70	39
FC	SE_a	WT	2.5 - 3.5	3.92	0.2 - 0.4	0.26	1.8 - 3.0	**4.4**	0.2 - 0.5	0.39	0.15 - 0.5	0.25	-	0.05	0.51 – 1.65	**2.89**	5 -25.	4	25 - 100	**164**	11 - 13	**40**	15 - 70	32
FC	SE_b	WT	3.5 - 4.5	-	0.2 - 0.4	-	2.0 - 3.5	-	0.2 - 0.5	-	0.15 - 0.5	0.32	-	0.06	0.51- 1.65	**2.81**	5 -25.	9	25 - 100	**114**	11 - 13	**23**	15 - 70	44
FC	SE_b	WT	3.5 - 4.5	-	0.2 - 0.4	-	2.0 - 3.5	-	0.2 - 0.5	-	0.15 - 0.5	0.35	-	0.05	0.51 – 1.65	**2.89**	5 -25.	8	25 - 100	**137**	11 - 13	**42**	15 - 70	39
FC	SE_b	WT	2.5 - 3.5	-	0.2 - 0.4	-	1.8 - 3.0	-	0.2 - 0.5	-	0.15 - 0.5	0.25	-	0.05	0.51 – 1.65	**2.89**	5 -25.	4	25 - 100	**164**	11 - 13	**40**	15 - 70	32
FC	Heading	WT	2.1 - 3.0	-	0.21 - 0.5	-	1.5 - 3.0	-	0.2 - 0.5	-	0.15 - 0.5	-	-	-	0.15 - 0.4	-	5 -25.	-	25 - 100	-	11 - 13	-	15 - 70	-

SE- Stem extension	Norm - Normal	LF - Leaching fraction strategy
Till – SE -Stage from leaf sheaths lengthen to first node of stem visible	Anal - Analysis	FC - Field capacity strategy
SE_a - Stage from second node visible to last leaf just visible	**Highlighted values higher than the respective norm**	DE - Deficit irrigation strategy
SE_b - Ligule of last leaf just visible to in "boot"		
WT - Whole tops		

Table A16. Soil chemical analysis for four intensive monitoring sites at pivot Major (sugarbeans crop, *beginning* of 1997/98 summer season, Soil Science Laboratory, University of Pretoria).

Strategy	Depth (cm)	pH (H_2O)	Bray I P (mg kg^{-1})	Soluble cations (cmol$_c$ kg^{-1})				Exchangeable cations (cmol$_c$ kg^{-1})				Σ echangeable bases (cmol$_c$ kg^{-1})	SO_4^{2-} (ppm)	NH_4^+ (ppm)	NO_3^- (ppm)	Cl^- (ppm)	HCO_3^- (ppm)	CO_3^{2-} (ppm)	EC (*m*S *m*$^{-1}$)	Charge balance (cmol$_c$ kg^{-1})
				Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+									
Leaching fraction	0-20	5.86	16.21	0.152	0.029	0.010	0.004	1.07	0.115	0.082	0.02	1.287	0.030	4.06	82.2	-	-	-	-	0.085
	20-40	5.3	2.99	0.022	0.013	0.004	0.007	1.181	0.168	0.06	0	1.409	0.020	-	-	-	-	-	-	0.046
	40-60	4.94	1.48	0.006	0.011	0.004	0.009	0.823	0.261	0.078	0.015	1.177	0.0004	-	-	-	-	-	-	0.030
	60-80	4.57	0.29	0.004	0.004	0.002	0.010	0.133	0.172	0.093	0.032	0.43	0.001	-	-	-	-	-	-	0.020
	80-100	4.48	0.38	0.004	0.005	0.004	0.010	0.05	0.307	0.058	0.014	0.429	0.001	5.15	104.3	3.01	-	-	-	-0.125
Field capacity	0-20	4.54	46.33	0.069	0.087	0.024	0.008	0.503	0.377	0.116	0.006	1.002	0.031	3.32	103.1	4.73	0	0.57	-	0.025
	20-40	4.62	2.04	0.017	0.039	0.006	0.007	0.16	0.221	0.085	0.013	0.479	0.030	4.33	46.7	5.37	-	-	-	0.002
	40-60	4.05	1.5	0.027	0.03	0.006	0.009	0.284	0.192	0.083	0.009	0.568	0.010	3.81	52.7	4.20	-	-	-	-0.004
	60-80	4.03	0.96	0.032	0.031	0.003	0.008	0.667	0.391	0.07	0.011	1.139	0.020	3.51	72.7	5.33	-	-	-	-0.039
	80-100	4.65	2.05	0.009	0.011	0.003	0.006	2	0.373	0.098	0.034	2.505	0.0004	-	-	-	-	-	-	0.029
	100-120	4.53	1.51	0.005	0.014	0.004	0.008	0.442	0.508	0.09	0.01	1.05	0.0004	6.34	60.1	4.15	0	0.35	-	-0.044
Deficit	0-20	5.13	29.57	0.046	0.068	0.009	0.006	0.758	0.578	0.126	0.008	1.47	0.028	3.88	68.5	2.80	-	-	-	0.032
	20-40	4.17	1.8	0.015	0.018	0.007	0.007	1.044	0.318	0.126	0.012	1.5	0.033	4.05	51.9	3.35	-	-	-	-0.024
	40-60	4.48	0.28	0.028	0.032	0.015	0.006	0.794	0.511	0.141	0.013	1.459	0.012	5.57	52.4	6.70	0	2.08	-	0.002
	60-80	4.71	0.06	0.010	0.018	0.005	0.008	0.459	0.548	0.067	0.01	1.084	0.002	5.49	45.4	4.23	0	0.56	-	-0.016
	80-100	4.68	0.15	0.006	0.014	0.003	0.007	0.177	0.314	0.023	0.013	0.527	0.001	6.21	44.6	2.85	0	0.68	-	-0.018
	100-120	4.83	0	0.009	0.011	0.003	0.009	0.172	0.446	0.055	0.008	0.681	0.001	5.48	31.5	4.70	-	-	-	-0.002
Dry land	0-20	6.57	10.29	0.036	0.063	0.006	0.007	1.662	0.772	0.114	0.01	2.558	0.039	6.76	68.1	6.01	0	3.81	-	0.010
	20-40	4.15	1.72	0.023	0.034	0.005	0.006	1.254	0.116	0.064	0.013	1.447	0.017	2.43	57.0	2.28	-	-	-	-0.017
	40-60	3.72	1.23	0.064	0.066	0.015	0.009	0.102	0.09	0.068	0.01	0.27	0.015	8.55	123.7	2.98	0	0	-	-0.007
	60-80	4.53	0.49	-	-	-	-	-	-	-	-	1.594	-	-	-	-	-	-	-	-
	80-100	4.46	0.19	0.007	0.011	0.003	-	1.405	0.286	0.065	-	1.79	0.001	-	-	11.11	-	-	-	-0.010
	100-120	4.38	0.48	0.010	0.012	0.005	0.013	1.01	0.142	0.047	0.011	1.21	0.0004	3.84	37.8	3.17	0	0.64	-	-0.011

Table A17. Soil chemical analysis for three intensive monitoring sites at pivot Jacuzzi (sugarbeans crop, beginning of 1997/98 summer season, *Soil Science Laboratory, University of Pretoria*).

Strategy	Depth (cm)	pH (H_2O)	Bray I P (mg kg^{-1})	Soluble cations (cmol$_c$ kg^{-1})				Exchangeable cations (cmol$_c$ kg^{-1})				Σ echangeable bases (cmol$_c$ kg^{-1})	SO_4^{2-} (ppm)	NH_4^+ (ppm)	NO_3^- (ppm)	Cl^- (ppm)	HCO_3^- (ppm)	CO_3^{2-} (ppm)	EC (mS m^{-1})	Charge balance (cmol$_c$ kg^{-1})
				Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+									
Leaching fraction	0-20	4.7	20.92	0.013	0.009	0.012	0.003	0.461	0.054	0.18	0	0.695	0.018	-	-	9.66	0	9.33	23	-0.021
	20-40	4.71	0.73	0.04	0.002	0.005	0.012	0.19	0.027	0.12	0	0.337	0.004	-	-	7.99	0	9.70	12	0.004
	40-60	4.56	2.17	0.016	0.004	0.002	0.002	0.339	0.035	0.154	0.018	0.546	0.005	-	-	10.60	0	3.49	17	-0.018
	60-80	4.72	4.58	0.027	0.002	0.004	0.005	0.326	0.05	0.16	0.023	0.559	0.014	-	-	5.58	0	9.15	26	-0.008
	80-100	5.07	0.36	0.018	0.004	0.001	0.001	0.411	0.07	0.653	0.055	1.189	0.003	-	-	7.77	0	4.90	12	-0.014
	100-120	5.15	0.07	0.010	0.004	0.009	0.011	0.556	0.065	1.197	0.027	0.845	0.002	-	-	3.39	0	3.74	6	0.012
Field capacity	0-20	4.43	1.25	0.031	0.008	0.013	0.003	0.21	0.044	0.125	0.031	0.41	0.015	-	-	7.96	0	4.86	29	0.016
	20-40	4.34	0.94	0.017	0.006	0.010	0.006	0.205	0.041	0.103	0.023	0.372	0.008	-	-	6.57	0	4.37	20	0.006
	40-60	4.33	1.79	0.014	0.007	0.009	0.002	0.131	0.039	0.036	0	0.206	0.010	-	-	8.11	0	5.87	21	-0.010
	60-80	4.38	1.16	0.013	0.008	0.010	0.011	0.13	0.035	0.044	0	0.209	0.015	-	-	7.67	0	2.10	25	0.013
	80-100	4.21	1.17	0.014	0.029	0.027	0.002	0.111	0	0	0	0.121	0.100	-	-	8.83	0	17.17	66	-0.010
	100-120	4.22	0.65	0.011	0.007	0.010	0.004	0.12	0.034	0.033	0	0.167	0.013	-	-	6.53	0	0.65	26	0.011
Deficit	0-20	4.43	1.11	0.008	0.009	0.011	0.001	0.237	0.045	0.094	0.015	0.391	0.011	-	-	5.58	0	2.39	20	0.005
	20-40	4.61	1.15	0.010	0.010	0.008	0.009	0.24	0.049	0.115	0.002	0.406	0.010	-	-	7.43	0	7.20	36	-0.008
	40-60	4.29	1.16	0.017	0.008	0.011	0.002	0.181	0.039	0.077	0.022	0.319	0.020	-	-	8.18	0	1.54	27	0.010
	60-80	5.38	38.92	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	80-100	4.73	21.77	0.010	0.008	0.008	0.001	0.586	0.055	0.241	0.022	0.914	0.060	-	-	11.22	0	6.98	33	-0.028
	100-120	4.53	2.21	0.009	0.006	0.006	0.002	0.429	0.047	0.206	0.015	0.697	0.030	-	-	10.64	0	8.19	29	-0.034

Table A18. Soil chemical analysis for three intensive monitoring sites at pivot Tweefontein (sugarbeans crop, beginning of 1997/98 summer season, Soil Science Laboratory, University of Pretoria).

Strategy	Depth (cm)	pH (H_2O)	Bray I P (mg kg^{-1})	Soluble cations (cmol$_c$ kg^{-1})				Exchangeable cations (cmol$_c$ kg^{-1})				Σ echangeable bases (cmol$_c$ kg^{-1})	SO_4^{2-} (ppm)	NH_4^+ (ppm)	NO_3^- (ppm)	Cl^- (ppm)	HCO_3^- (ppm)	CO_3^{2-} (ppm)	EC (mS m^{-1})	Charge balance (cmol$_c$ kg^{-1})
				Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+									
Leaching fraction	0-20	5.03	6.85	0.025	0.008	0.002	0.047	2.056	0.145	0.473	0.011	2.685	0.059	-	-	5.89	0	10.90	36	0.029
	20-40	5.06	5.02	0.007	0.002	0.005	0.019	0.412	0.063	0.251	0.031	0.757	0.020	-	-	2.57	0	5.34	29	0.008
	40-60	5.11	4.39	0.011	0.002	0.008	0.068	0.473	0.052	0.261	0	0.786	0.050	-	-	6.81	0	8.21	29	0.042
	60-80	5.03	3.06	0.014	0.003	0.012	0.053	0.414	0.038	0.223	0.003	0.678	0.025	-	-	9.68	0	10.05	27	0.021
	80-100	4.73	3.27	0.009	0.002	0.008	0.044	0.443	0.052	0.267	0	0.762	0.017	-	-	9.17	0	6.68	19	0.015
	100-120	6.84	2.24	0.001	0.002	0.002	0.010	0.278	0.01	1.132	0.034	1.454	0.005	-	-	3.92	0	1.34	8	-0.001
Field capacity	0-20	5.11	8.50	0.048	0.009	0.023	0.016	0.553	0.098	0.305	0	0.956	0.020	-	-	8.77	0	10.34	45	0.037
	20-40	4.92	2.20	0.006	0.002	0.008	0.010	0.428	0.044	0.356	0.006	0.834	0.007	-	-	5.29	0	2.81	14	0.002
	40-60	4.93	1.91	0.006	0.002	0.008	0.017	0.497	0.05	0.3	0	0.847	0.007	-	-	8.22	0	4.38	17	-0.005
	60-80	4.81	1.70	0.005	0.002	0.008	0.014	0.477	0.043	0.345	0.007	0.872	0.006	-	-	6.82	0	3.63	14	-0.002
	80-100	5.62	1.60	0.004	0.003	0.006	0.008	0.704	0.091	0.699	0.021	1.515	0.007	-	-	4.54	0	2.42	9	0.000
	100-120	5.09	2.39	0	0.003	0.001	0.006	1.635	0.129	1.274	0.051	3.089	0.008	-	-	2.95	0	1.57	5	-0.004
Deficit	0-20	4.78	8.83	0.033	0.008	0.018	0.011	0.995	0.102	0.302	0.019	1.418	0.025	-	-	5.32	0	2.83	30	0.046
	20-40	4.61	1.33	0.008	0.007	0.010	0.018	0.358	0.09	0.266	0.005	0.719	0.010	-	-	7.65	0	4.07	22	0.008
	40-60	4.59	2.64	0.017	0.005	0.021	0.011	0.428	0.074	0.35	0.01	0.862	0.010	-	-	7.10	0	3.78	27	0.021
	60-80	4.58	1.25	0.010	0.004	0.013	0.011	0.547	0.083	0.376	0.004	1.01	0.010	-	-	5.28	0	2.81	17	0.014
	80-100	4.95	0.56	0.053	0.005	0.008	0.013	0.351	0.096	0.757	0.037	1.241	0.050	-	-	5.55	0	2.95	10	0.053
	100-120	4.63	0.55	0.032	0.004	0.006	0.008	0.792	0.085	0.616	0.032	1.525	0.010	-	-	3.50	0	1.86	9	0.034

Table A19. Soil chemical analysis for three intensive monitoring sites at pivot Major (sugarbeans crop, end of 1997/98 summer season, Soil Science Laboratory, University of Pretoria).

Strategy	Depth (cm)	pH (H_2O)	EC (mS m^{-1})	Bray I P (mg kg^{-1})	Soluble cations (cmol$_c$ kg^{-1})				Exchangeable cations (cmol$_c$ kg^{-1})				Σ echangeable bases (cmol$_c$ kg^{-1})	Cl^- (ppm)	SO_4^{2-} (cmol$_c$ kg^{-1})	Charge balance (cmol$_c$ kg^{-1})
					Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+				
Leaching fraction	0-20	3.78	95.5	-	0.056	0.002	0.036	0.005	0.504	0.047	0.282	0	0.833	1.48	0.127	-0.032
	20-40	4.38	70.9	-	0.078	0.005	0.065	0.164	0.522	0.047	0.147	0	0.716	2.71	0.193	0.111
	40-60	4.88	31.0	-	0.014	0.002	0.032	0.022	1.074	0.089	0.363	0.025	1.551	2.27	0.026	0.038
	60-80	4.38	6.0	5.9	0.002	0.001	0.003	0.008	0.194	0.053	0.295	0.015	0.557	-	0.002	0.012
	80-100	4.43	7.8	4.3	0.001	0.001	0.002	0.016	0.116	0.044	0.068	0.033	0.261	0	0	0.020
	100-120	6.64	8.3	5.95	0.010	0.001	0.005	0.005	0.230	0.067	0.486	0.056	0.839	4.85	0.002	0.005
Field capacity	0-20	3.96	82.0	-	0.098	0.010	0.114	0.013	0.553	0.110	0.487	0.001	1.151	25.20	0.273	-0.109
	20-40	3.51	59.6	-	0.079	0.007	0.076	0.176	0.323	0.079	0.070	0.018	0.49	4.85	0.184	0.140
	40-60	3.79	37.8	-	0.029	0.006	0.036	0.016	0.428	0.027	0.196	0.007	0.658	1.44	0.101	-0.018
	60-80	4.09	9.9	5.8	0.006	0.002	0.009	0.002	0.824	0.070	0.489	0	1.383	0	0.001	0.018
	80-100	4.21	15.8	6.7	0.011	0.002	0.013	0.003	0.417	0.042	0.197	0	0.656	0	0.001	0.028
	100-120	3.66	10.8	6.3	0.007	0.002	0.008	0.003	0.222	0.044	0.289	0	0.555	0	0.001	0.019
Deficit	0-20	4.96	134.0	-	0.129	0.009	0.263	0.210	3.296	0.109	1.489	0	4.894	0	0.495	0.116
	20-40	3.27	49.6	-	0.030	0.010	0.069	0.006	0.250	0.030	0.196	0	0.476	0	0.165	-0.050
	40-60	4.64	20.7	-	0.015	0.002	0.016	0.003	0.495	0.054	0.409	0	0.958	0	0.020	0.016
	60-80	4.20	20.9	5.1	0.022	0.003	0.025	0.002	0.409	0.045	0.328	0	0.782	11.50	0.003	0.017
	80-100	4.01	20.2	-	0.020	0.003	0.024	0.003	0.119	0.029	0.209	0	0.357	0	0.027	0.023
	100-120	3.82	13.4	5.7	0.006	0.003	0.013	0.002	0.125	0.084	0.370	0	0.579	0	0.001	0.023

Table A20. Soil chemical analysis for three intensive monitoring sites at pivot Jacuzzi (sugarbeans crop, end of 1997/98 summer season, Soil Science Laboratory, University of Pretoria).

Strategy	Depth (cm)	pH (H_2O)	EC (mS m^{-1})	Bray I P (mg kg^{-1})	Soluble cations (cmol$_c$ kg^{-1})				Exchangeable cations (cmol$_c$ kg^{-1})				Σ echangeable bases (cmol$_c$ kg^{-1})	Cl^- (ppm)	SO_4^{2-} (cmol$_c$ kg^{-1})	Charge balance (cmol$_c$ kg^{-1})
					Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+				
Leaching fraction	0-20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	20-40	4.45	15.7	5.7	0.025	0.001	0.004	0.036	0.337	0.036	0.098	0.023	0.494	5.61	0.003	0.047
	40-60	4.44	-	2.8	0.002	0	0.003	0.003	0.315	0.031	0.211	0.007	0.564	-	0	0.008
	60-80	4.49	5.4	6.42	0.002	0.001	0.002	0.004	0.330	0.034	0.274	0	0.638	0	0.001	0.008
	80-100	5.26	8.2	4.37	0.018	0.001	0.004	0.003	2.748	0.085	1.387	0.060	4.28	0	0.001	0.025
Field capacity	0-20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	20-40	3.64	15.0	12.4	0.012	0.003	0.009	0.030	0.258	0.552	0.088	0	0.898	4.07	0.008	0.035
	40-60	4.25	19.5	19.6	0.025	0.003	0.007	0.041	0.276	0.044	0.109	0.004	0.433	2.26	0.013	0.057
	60-80	4.09	10.2	9.0	0.005	0.002	0.004	0.006	0.227	0.043	0.132	0	0.402	6.46	0.006	-0.007
	80-100	5.51	9.7	9.0	0.004	0.002	0.004	0.015	1.614	0.747	0.158	0.003	2.522	8.37	0.005	-0.004
Deficit	0-20	3.34	56.6	-	0.166	0.007	0.107	0.305	0.604	0.049	0.682	0.022	1.357	-	0.313	0.272
	20-40	3.56	21.8	11.3	0.020	0.003	0.011	0.040	0.180	0.039	0.132	0.013	0.364	4.81	0.006	0.054
	40-60	3.73	11.9	5.4	0.011	0.003	0.006	0.024	0.184	0.045	0.171	0	0.4	2.61	0.002	0.035
	60-80	4.23	18.6	-	0.014	0.004	0.009	0.007	0.636	0.073	0.233	0.018	0.96	3.88	0.025	-0.002
	80-100	4.17	16.2	5.3	0.018	0.002	0.010	0.013	0.512	0.044	0.642	0	1.198	13.39	0.002	0.003

Table A21. Soil chemical analysis for three intensive monitoring sites at pivot Tweefontein (sugarbeans crop, end of 1997/98 summer season, Soil Science Laboratory, University of Pretoria).

Strategy	Depth (cm)	pH (H_2O)	EC (mS m^{-1})	Bray I P (mg kg^{-1})	Soluble cations ($cmol_c$ kg^{-1})				Exchangeable cations ($cmol_c$ kg^{-1})				Σ echangeable bases ($cmol_c$ kg^{-1})	Cl^- (ppm)	SO_4^{2-} ($cmol_c$ kg^{-1})	Charge balance ($cmol_c$ kg^{-1})
					Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+				
Leaching fraction	0-20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	20-40	5.04	44.1	-	0.051	0.002	0.027	0.111	0.579	0.039	0.786	0.032	1.436	3.67	0.109	0.072
	40-60	8.47	18.4	50.0	0.009	0.001	0.005	0.043	0.731	0.030	0.123	0.081	0.965	8.58	0.035	-0.072
	60-80	4.71	23.4	86.5	0.014	0.001	0.008	0.060	1.385	0.030	0.139	0.090	1.644	3.70	0.066	0.007
	80-100	4.53	28.1	24.9	0.021	0.002	0.018	0.073	0.679	0.058	0.187	0.062	0.986	13.92	0.019	0.056
Field capacity	0-20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	20-40	4.54	28.5	48.4	0.050	0.001	0.019	0.088	1.099	0.033	0.480	0.022	1.634	8.95	0.037	0.096
	40-60	4.32	3.7	3.65	0.008	0.001	0.006	0.021	1.062	0.023	0.081	0.005	1.171	3.94	0	0.025
	60-80	4.96	15.8	4.1	0.007	0	0.006	0.017	0.663	0.031	0.076	0.009	0.779	3.39	0.012	0.008
	80-100	4.52	5.9	4.0	0.002	0.001	0.003	0.003	0.374	0.031	0.381	0.002	0.788	2.12	0	0.003
Deficit	0-20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	20-40	4.84	24.7	13.7	0.038	0.003	0.011	0.061	0.632	0.071	0.190	0	0.893	8.55	0.011	0.076
	40-60	4.10	15.6	4.3	0.034	0.001	0.002	0.011	0.587	0.064	0.350	0	1.001	4.64	0.001	0.034
	60-80	4.43	13.0	7.5	0.012	0.001	0.008	0.027	0.539	0.058	0.139	0.009	0.745	7.24	0.002	0.026
	80-100	4.73	10.8	6.7	0.008	0.001	0.008	0.025	0.622	0.064	0.112	0.027	0.825	5.66	0.004	0.022

Table A22. Soil chemical analysis for three intensive monitoring sites at pivot Major (wheat crop, beginning of 1998 winter season, Soil Science Laboratory, *University of Pretoria*).

Strategy	Depth (cm)	pH (H_2O)	EC (mS m^{-1})	Bray I P (mg kg^{-1})	Soluble cations (cmol$_c$ kg^{-1})				Exchangeable cations (cmol$_c$ kg^{-1})				Σ echangeable bases (cmol$_c$ kg^{-1})	SO_4^{2-} (cmol$_c$ kg^{-1})	Charge balance (cmol$_c$ kg^{-1})
					Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+			
Leaching fraction	0-20	5.85	390	9.3	0.798	0.028	0.639	0.111	4.250	0.157	1.355	0.115	5.877	1.723	-0.147
	20-40	4.89	200	2.0	0.369	0.011	0.226	0.027	0.807	0.079	0.429	0.036	1.351	0.691	-0.058
	40-60	2.92	180	1.7	0.247	0.020	0.194	0.026	0.250	0.097	0.353	0.037	0.737	0.560	-0.073
	60-80	3.18	100	1.6	0.096	0.027	0.093	0.025	0.331	0.154	0.360	0.044	0.889	0.157	0.084
	80-100	4.37	40	1.9	0.040	0.006	0.022	0.013	0.477	0.119	0.398	0.044	1.038	0.031	0.050
Field capacity	0-20	5.13	380	22.9	0.737	0.085	0.454	0.055	1.527	0.250	0.765	0.048	2.59	1.319	0.012
	20-40	4.12	190	0.9	0.362	0.008	0.218	0.030	1.074	0.102	0.738	0.043	1.957	0.618	0.000
	40-60	3.29	120	0.7	0.237	0.004	0.102	0.021	0.660	0.075	0.425	0.046	1.206	0.329	0.035
	60-80	3.42	120	1.9	0.350	0.006	0.130	0.004	0.736	0.097	0.450	0.082	1.365	0.470	0.020
	80-100	3.92	40	1.6	0.058	0.003	0.024	0.014	0.869	0.078	0.431	0.036	1.414	0.089	0.010
	100-120	3.87	30	1.2	0.040	0.001	0.021	0.002	0.976	0.063	0.578	0.020	1.637	0.015	0.049
Deficit	0-20	6.04	220	14.8	0.676	0.013	0.465	0.061	1.838	0.103	1.051	0.055	3.047	1.348	-0.133
	20-40	4.29	180	1.9	0.282	0.004	0.225	0.018	1.044	0.078	0.830	0.039	1.991	0.682	-0.153
	40-60	3.24	50	0.8	0.075	0.003	0.040	0.007	0.891	0.096	0.576	0.025	1.588	0.087	0.038
	60-80	3.66	30	1.0	0.030	0.003	0.019	0.001	0.338	0.046	0.244	0.027	0.655	0.014	0.039
	80-100	3.64	30	0.6	0.044	0.003	0.025	0.029	0.373	0.047	0.340	0.006	0.766	0.021	0.080

Table A23. Soil chemical analysis for three intensive monitoring sites at pivot Jacuzzi (wheat crop, beginning of 1998 winter season, Soil Science Laboratory, University of Pretoria).

Strategy	Depth (cm)	pH (H_2O)	EC (mS m^{-1})	Bray I P (mg kg^{-1})	Soluble cations (cmol$_c$ kg^{-1})				Exchangeable cations (cmol$_c$ kg^{-1})				Σ echangeable bases (cmol$_c$ kg^{-1})	SO_4^{2-} (cmol$_c$ kg^{-1})	Charge balance (cmol$_c$ kg^{-1})
					Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+			
Leaching fraction	0-20	5.34	290	20.6	0.746	0.021	0.251	0.046	2.196	0.141	0.576	0.054	2.967	1.106	-0.042
	20-40	4.79	20	0.8	0.015	0.001	0.009	0.008	0.313	0.042	0.225	0.026	0.606	0.007	0.026
	40-60	4.42	0	0.2	0.001	0	0.001	0.013	0.277	0.039	0.198	0.068	0.582	0	0.015
	60-80	4.38	10	1.1	0.003	0.002	0.006	0.010	0.854	0.120	1.345	0.067	2.386	0.013	0.008
Field capacity	0-20	6.32	440	6.2	0.706	0.025	0.499	0.099	3.314	0.108	0.984	0.101	4.507	1.577	-0.248
	20-40	4.15	30	1.4	0.023	0.005	0.017	0.016	0.259	0.059	0.178	0.030	0.526	0.017	0.044
	40-60	4.03	20	1.0	0.008	0.004	0.008	0.013	0.265	0.063	0.167	0.023	0.518	0.008	0.025
	60-80	4.02	20	1.1	0.006	0.004	0.006	0.010	0.186	0.062	0.137	0.033	0.418	0.003	0.023
	80-100	3.95	20	2.1	0.006	0.005	0.006	0.011	0.205	0.078	0.139	0.024	0.446	0.007	0.021
	100-120	4.36	20	1.5	0.005	0.004	0.006	0.010	0.203	0.068	0.132	0.038	0.441	0.008	0.017
Deficit	0-20	4.34	290	13.1	0.636	0.023	0.286	0.054	1.119	0.119	0.621	0.056	1.915	1.030	-0.031
	20-40	4.21	10	2.8	0.021	0.002	0.012	0.010	0.876	0.090	0.422	0.046	1.434	0.021	0.024
	40-60	4.64	20	1.0	0.009	0.002	0.007	0.011	1.746	0.069	0.340	0.053	2.208	0.002	0.027
	60-80	4.71	10	0.7	0.001	0.001	0.002	0.008	0.352	0.056	0.315	0.041	0.764	0.009	0.003
	80-100	4.26	30	1.1	0.027	0.004	0.026	0.019	0.990	0.112	1.226	0.068	2.396	0.074	0.002

Table A24. Soil chemical analysis for three intensive monitoring sites at pivot Tweefontein (wheat crop, beginning of 1998 winter season, Soil Science Laboratory, University of Pretoria).

Strategy	Depth (cm)	pH (H_2O)	EC (mS m^{-1})	Bray I P (mg kg^{-1})	Soluble cations (cmol$_c$ kg^{-1})				Exchangeable cations (cmol$_c$ kg^{-1})				Σ echangeable bases (cmol$_c$ kg^{-1})	SO_4^{2-} (cmol$_c$ kg^{-1})	Charge balance (cmol$_c$ kg^{-1})
					Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+			
Leaching fraction	0-20	4.06	320	13.3	0.285	0.008	0.142	0.027	0.749	0.147	1.026	0.124	2.046	1.244	-0.782
	20-40	4.04	200	4.0	0.408	0.013	0.231	0.053	0.297	0.101	0.582	0.057	1.037	0.745	-0.040
	40-60	4.56	50	5.0	0.099	0.001	0.023	0.003	0.516	0.046	0.344	0.054	0.96	0.053	0.073
	60-60	4.96	20	4.4	0.048	0.001	0.018	0.003	0.538	0.037	0.295	0.028	0.898	0.080	-0.010
	80-100	6.10	10	4.9	0.006	0	0.005	0.004	1.937	0.045	0.330	0.025	2.337	0	0.015
	100-120	5.37	110	3.6	0.216	0.005	0.118	0.018	0.799	0.084	0.968	0.048	1.899	0.364	-0.007
Field capacity	0-20	4.51	300	8.8	0.740	0.022	0.392	0.079	0.544	0.134	0.677	0.046	1.401	1.287	-0.054
	20-40	4.23	40	3.7	0.066	0.001	0.025	0.002	0.340	0.050	0.321	0.053	0.764	0.024	0.070
	40-60	4.17	20	1.9	0.026	0	0.011	0.005	0.269	0.035	0.271	0.043	0.618	0.020	0.022
	60-80	3.96	10	2.4	0.016	0	0.007	0.002	0.385	0.031	0.155	0.025	0.596	0.012	0.013
	80-100	4.06	30	3.1	0.056	0.001	0.009	0.021	0.431	0.036	0.263	0.005	0.735	0.008	0.079
	100-120	4.63	140	9.5	0.600	0.034	0.454	0.070	0.245	0.079	0.428	0.028	0.78	0.520	0.638
Deficit	0-20	5.88	350	37.7	1.000	0.028	0.431	0.105	2.160	0.212	1.260	0.080	3.732	2.128	-0.564
	20-40	4.88	20	7.2	0.021	0.001	0.011	0.006	0.405	0.048	0.359	0.047	0.859	0.002	0.037
	40-60	4.49	10	2.9	0.006	0.001	0.005	0.005	0.459	0.047	0.360	0.033	0.899	0	0.017
	60-80	4.22	40	3.9	0.050	0.002	0.028	0.019	0.525	0.070	0.570	0.054	1.219	0.040	0.059
	80-100	4.62	80	2.8	0.181	0.001	0.055	0.025	0.230	0.048	0.296	0.009	0.583	0.272	-0.010
	100-120	4.42	70	4.2	0.104	0.003	0.062	0.021	0.840	0.080	0.732	0.052	1.704	0.148	0.042

Table A25. Soil chemical analysis for three deficit irrigation strategies on 19/10/1998 (wheat crop, 1998 winter season, Soil Science Laboratory, University of Pretoria).

Pivot	Depth (cm)	pH (H_2O)	EC (mS m^{-1})	Bray I P (mg kg^{-1})	Soluble cations (cmol$_c$ kg^{-1})				Exchangeable cations (cmol$_c$ kg^{-1})				Σ echangeable bases (cmol$_c$ kg^{-1})	SO_4^{2-} (cmol$_c$ kg^{-1})	Charge balance (cmol$_c$ kg^{-1})
					Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+			
Major	0-20	-	360	9.4	0.530	0.002	0.698	0.102	3.875	0.059	1.339	0.267	5.54	1.661	-0.329
	20-40	-	400	7.8	0.437	0.010	0.847	0.103	0.814	0.076	0.812	0.253	1.955	1.711	-0.314
	40-60	-	130	1.7	0.160	0.007	0.172	0.021	0.492	0.074	0.597	0.009	1.172	0.361	-0.001
	60-80	4.72	30	0.7	0.031	0.003	0.026	0.006	0.646	0.068	0.488	0.004	1.206	0.060	0.006
	80-100	4.82	30	0.5	0.024	0.002	0.019	0.003	0.548	0.047	0.380	0	0.975	0.004	0.044
	100-120	4.74	30	0.4	0.020	0.003	0.018	0.004	0.337	0.048	0.258	0.	0.643	0.003	0.042
Jacuzzi	0-20	5.29	280	5.8	0.567	0.004	0.374	0.044	2.610	0.057	0.758	0.026	3.451	1.497	-0.508
	20-40	4.95	20	1.0	0.014	0.001	0.011	0.013	0.723	0.046	0.289	0.002	1.06	0.002	0.037
	40-60	4.79	10	1.0	0.010	0.001	0.009	0.009	0.483	0.045	0.365	0.004	0.897	0.001	0.028
	60-80	4.72	10	0.5	0.007	0.001	0.007	0.005	0.296	0.052	0.236	0	0.584	0.001	0.019
	80-100	-	10	2.4	0.006	0.001	0.006	0.005	0.427	0.055	0.418	0.023	0.923	0.001	0.017
Tweefontein	0-20	6.78	310	33.3	0.603	0.013	0.562	0.122	4.735	0.177	1.895	0.320	7.127	1.604	-0.304
	20-40	7.37	170	3.1	0.390	0	0.117	0.023	6.400	0.053	0.817	0.032	7.302	0.574	-0.044
	40-60	5.78	30	3.5	0.042	0.001	0.035	0.002	1.064	0.039	0.594	0.007	1.704	0.086	-0.006
	60-80	4.61	20	1.3	0.019	0.001	0.018	0.003	0.593	0.050	0.422	0.007	1.072	0.001	0.040
	80-100	4.63	10	1.4	0.014	0.001	0.013	0.003	0.473	0.044	0.304	0.012	0.833	0.003	0.028

Table A26. Soil chemical analysis for three intensive monitoring sites at pivot Major (maize crop, *beginning of* 1998/99 summer season, Soil Science Laboratory, *University of Pretoria*).

Strategy	Depth (cm)	pH (H_2O)	EC (mS m^{-1})	Bray I P (mg kg^{-1})	Soluble cations (cmol$_c$ kg^{-1})				*Exchangeable cations* (cmol$_c$ kg^{-1})				Σ echangeable bases (*cmol$_c$ kg^{-1}*)	SO_4^{2-} (cmol$_c$ kg^{-1})	Charge balance (cmol$_c$ kg^{-1})
					Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+			
Leaching fraction	0-20	6.47	10	8.2	0.016	0.001	0.010	0.010	2.723	0.104	1.291	0.024	4.142	0.010	0.027
	20-40	6.03	190	3.6	0.493	0.004	0.849	0.100	1.857	0.070	1.587	0.069	3.583	1.346	0.100
	40-60	5.80	160	2.4	0.599	0.001	0.395	0.134	1.336	0.037	0.856	0.052	2.281	1.060	0.069
	60-80	5.99	130	3.0	0.616	0.001	0.211	0.060	1.324	0.035	0.447	0.057	1.863	0.756	0.132
	80-100	6.05	100	2.3	0.460	0.001	0.109	0.020	1.466	0.035	0.393	0.062	1.956	0.514	0.076
Field capacity	0-20	6.29	240	12.5	0.706	0.011	1.106	0.158	3.061	0.114	1.640	0.068	5.083	1.847	0.134
	20-40	4.81	220	2.7	0.594	0.005	0.957	0.272	1.726	0.064	1.422	0.097	3.309	1.600	0.228
	40-60	5.15	140	1.9	0.494	0.003	0.361	0.167	0.958	0.066	0.890	0.081	1.995	0.835	0.190
	60-80	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	80-100	5.16	120	1.1	0.538	0.012	0.341	0.041	0	0.037	0.194	0.024	0.255	0.778	0.154
Deficit	0-20	6.49	180	8.7	0.831	0.014	0.673	0.058	2.746	0.163	1.500	0.072	4.481	1.422	0.154
	20-40	4.63	120	2.0	0.344	0.003	0.525	0.194	0.873	0.060	1.475	0.119	2.527	0.889	0.177
	40-60	4.76	10	1.2	0.014	0.001	0.009	0.008	0.599	0.053	0.444	0.066	1.162	0.005	0.027
	60-80	4.79	10	1.1	0.010	0.001	0.006	0.003	0.548	0.068	0.389	0.053	1.058	0.201	-0.161
	80-100	4.66	10	0.7	0.014	0.001	0.008	0.003	0.470	0.050	0.322	0.049	0.891	0.003	0.023

Table A27. Soil chemical analysis for three intensive monitoring sites at pivot Jacuzzi (sugarbeans crop, beginning of 1998/99 summer season, Soil Science Laboratory, University of Pretoria).

Strategy	Depth (cm)	pH (H_2O)	EC (mS m^{-1})	Bray I P (mg kg^{-1})	Soluble cations (cmol$_c$ kg^{-1})				Exchangeable cations (cmol$_c$ kg^{-1})				Σ echangeable bases (cmol$_c$ kg^{-1})	SO_4^{2-} (cmol$_c$ kg^{-1})	Charge balance (cmol$_c$ kg^{-1})
					Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+			
Leaching fraction	0-20	5.51	140	3.4	0.775	0.002	0.320	0.029	2.877	0.050	0.725	0.071	3.723	1.094	0.032
	20-40	4.61	100	2.5	0.407	0.002	0.263	0.028	0.841	0.049	0.626	0.063	1.579	0.635	0.065
	40-60	4.67	40	1.7	0.098	0.002	0.069	0.028	0.550	0.044	0.499	0.071	1.164	0.166	0.031
	60-80	4.95	10	1.7	0.006	0.001	0.007	0.008	0.477	0.060	0.750	0.053	1.34	0.014	0.008
	80-100	5.34	0	0.8	0.005	0.003	0.006	0.004	0.943	0.161	2.257	0.065	3.426	0.017	0.001
Field capacity	0-20	4.61	230	1.8	0.655	0.008	0.937	0.090	1.635	0.061	1.154	0.040	2.89	1.526	0.164
	20-40	4.37	110	1.9	0.292	0.008	0.351	0.055	0.541	0.068	0.793	0.071	1.473	0.593	0.113
	40-60	4.49	20	1.2	0.032	0.003	0.015	0.015	0.332	0.063	0.249	0.050	0.694	0.039	0.026
	60-80	4.54	10	1.2	0.025	0.003	0.010	0.049	0.294	0.064	0.254	0.011	0.623	0.021	0.066
	80-100	4.75	10	0.9	0.008	0.003	0.005	0.050	0.206	0.069	0.185	0.014	0.474	0.014	0.052
Deficit	0-20	5.03	160	3.9	0.732	0.014	0.379	0.026	1.049	0.106	0.683	0.048	1.886	1.094	0.057
	20-40	5.97	40	2.8	0.107	0.006	0.065	0.028	0.596	0.081	0.486	0.063	1.226	0.141	0.065
	40-60	4.67	20	1.6	0.037	0.002	0.045	0.027	0.511	0.062	0.745	0.069	1.387	0.043	0.068
	60-80	4.62	70	1.0	0.157	0.003	0.237	0.060	0.576	0.058	1.163	0.062	1.859	0.438	0.019
	80-100	4.85	70	0.7	0.170	0.006	0.257	0.063	1.166	0.089	1.165	0.080	2.500	0.494	0.002

Table A28. Soil chemical analysis for three intensive monitoring sites at pivot Tweefontein (sugarbeans crop, beginning of 1998/99 summer season, Soil Science Laboratory, University of Pretoria).

Strategy	Depth (cm)	pH (H_2O)	EC (mS m^{-1})	Bray I P (mg kg^{-1})	Soluble cations (cmol$_c$ kg^{-1})				Exchangeable cations (cmol$_c$ kg^{-1})				Σ echangeable bases (cmol$_c$ kg^{-1})	SO_4^{2-} (cmol$_c$ kg^{-1})	Charge balance (cmol$_c$ kg^{-1})
					Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+			
Leaching fraction	0-20	5.09	210	5.6	0.381	0.012	0.171	0.018	1.275	0.067	0.258	0.325	1.925	0.610	-0.028
	20-40	4.38	180	3.8	0.214	0.019	0.320	0.036	0.593	0.102	0.508	0.311	1.514	0.593	-0.004
	40-60	4.62	290	6.0	0.288	0.010	0.615	0.084	0.829	0.057	0.804	0.276	1.966	1.123	-0.126
	60-80	5.29	350	4.4	0.343	0.002	0.808	0.116	1.098	0.031	0.965	0.313	2.407	1.398	-0.129
	80-100	4.58	310	3.1	0.425	0.002	0.429	0.101	0.996	0.033	0.554	0.341	1.924	1.074	-0.117
	100-120	5.17	200	8.3	0.312	0.002	0.217	0.090	0.915	0.034	0.369	0.318	1.636	0.628	-0.007
Field capacity	0-20	6.29	280	22.5	0.607	0.034	0.254	0.027	3.064	0.376	0.545	0.376	4.361	1.079	-0.157
	20-40	6.35	290	5.3	0.408	0.011	0.561	0.078	1.357	0.082	0.875	0.338	2.652	1.183	-0.125
	40-60	6.08	280	5.4	0.344	0.001	0.520	0.138	1.132	0.036	0.924	0.361	2.453	1.112	-0.109
	60-80	4.91	30	2.2	0.029	0.001	0.002	0.033	0.499	0.033	0.270	0.305	1.107	0.091	-0.026
	80-100	4.89	20	5.9	0.025	0.001	0.002	0.003	0.602	0.032	0.288	0.309	1.231	0.078	-0.047
	100-120	6.14	250	42.1	0.552	0.052	0.172	0.015	2.855	0.283	0.376	0.245	3.759	0.802	-0.011
Deficit	0-20	5.67	260	17.2	0.691	0.016	0.430	0.032	3.814	0.177	0.974	0.316	5.281	1.406	-0.237
	20-40	6.53	270	1.8	0.492	0.002	0.486	0.061	3.249	0.055	1.296	0.378	4.978	1.207	-0.166
	40-60	5.26	100	1.3	0.137	0.001	0.065	0.113	1.224	0.039	0.470	0.338	2.071	0.238	0.078
	60-80	5.24	10	0.5	0.008	0.001	0.001	0.018	0.515	0.039	0.289	0.290	1.133	0.085	-0.057
	80-100	5.58	10	0.8	0.006	0.001	0.001	0.005	0.482	0.039	0.240	0.355	1.116	0.083	-0.070
	100-120	5.32	10	0.8	0.014	0.001	0.002	0.005	0.813	0.040	0.548	0.316	1.717	0.105	-0.083

Table A29. Soil chemical analysis for one intensive monitoring site at pivot Major (wheat crop, beginning of 1999 winter season, Soil Science Laboratory, University of Pretoria).

Strategy	Depth (cm)	pH (H_2O)	EC (mS m^{-1})	Bray I P (mg kg^{-1})	Soluble cations (cmol$_c$ kg^{-1})				Exchangeable cations (cmol$_c$ kg^{-1})				Measured CEC (cmol$_c$ kg^{-1})	Σ echangeable bases (cmol$_c$ kg^{-1})	SO_4^{2-} (cmol$_c$ kg^{-1})	Charge balance (cmol$_c$ kg^{-1})
					Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+				
Field capacity	0-20	5.6	226	21.7	0.694	0.053	0.251	0.024	4.625	0.397	0.931	0.158	4.67	6.111	1.020	0.002
	20-40	4.8	229	7.5	0.715	0.025	0.272	0.023	1.64	0.176	0.466	0.077	4.40	0.862	0.862	0.173
	40-60	4.4	200	5.2	0.618	0.022	0.249	0.032	1.019	0.152	0.398	0.103	2.40	0.794	0.794	0.127
	60-80	4.5	167	6.7	0.402	0.020	0.352	0.028	0.721	0.176	0.731	0.111	2.47	0.948	0.948	-0.146
	80-100	4.9	176	5.8	0.284	0.025	0.392	0.032	0.789	0.238	1.235	0.181	2.443		0.751	-0.018

Table A30. Soil chemical analysis for three intensive monitoring sites at pivot Fourth (replication 1, wheat crop, beginning of 1999 winter season, Soil Science Laboratory, University of Pretoria).

Strategy	Depth (cm)	pH (H_2O)	EC (mS m^{-1})	Bray I P (mg kg^{-1})	Soluble cations ($cmol_c$ kg^{-1})				Exchangeable cations ($cmol_c$ kg^{-1})				Measured CEC ($cmol_c$ kg^{-1})	Σ echangeable bases ($cmol_c$ kg^{-1})	SO_4^{2-} ($cmol_c$ kg^{-1})	Charge balance ($cmol_c$ kg^{-1})
					Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+				
Leaching fraction	0-20	5.7	78	14.1	0.128	0.018	0.064	0.013	1.099	0.161	0.548	0.061	1.869	1.869	0.172	0.051
	20-40	5.2	24	3.3	0.038	0.002	0.015	0.004	0.735	0.062	0.338	0.037	2.76	1.172	0.030	0.029
	40-60	5.3	14	3.1	0.049	0.001	0.008	0.003	0.809	0.050	0.228	0.060	2.20	1.147	0.021	0.040
	60-80	5.8	15	3.0	0.027	0.001	0.007	0.002	0.991	0.049	0.245	0.069	1.92	1.354	0.027	0.010
	80-100	5.8	15	2.8	0.030	0.000	0.006	0.001	2.944	0.073	0.206	0.082	3.305	3.305	0.039	-0.002
Field capacity	0-20	5.7	91	31.7	0.125	0.048	0.176	0.022	2.899	0.295	0.635	0.050	2.96	3.879	0.253	0.118
	20-40	5.7	34	24.0	0.051	0.008	0.056	0.004	3.043	0.180	0.563	0.082	2.76	3.868	0.028	0.091
	40-60	5.4	22	2.1	0.037	0.002	0.013	0.003	0.906	0.061	0.281	0.039	2.76	1.287	0.028	0.027
	60-80	5.3	20	1.2	0.033	0.001	0.010	0.004	0.491	0.030	0.141	0.055	3.00	0.717	0.044	0.004
	80-100	5.7	31	0.4	0.058	0.001	0.013	0.004	1.215	0.039	0.155	0.061	2.88	1.470	0.063	0.013
Deficit	0-20	6.3	1	24.4	0.054	0.003	0.031	0.002	1.902	0.091	0.660	0.064	1.84	2.717	0.023	0.067
	20-40	5.6	27	4.6	0.046	0.001	0.027	0.003	0.875	0.052	0.438	0.060	5.44	1.425	0.039	0.040
	40-60	5.8	20	0.7	0.033	0.001	0.017	0.002	0.960	0.044	0.493	0.064	6.40	1.561	0.031	0.022
	60-80	4.8	21	0.6	0.054	0.001	0.012	0.003	0.524	0.048	0.258	0.063	6.08	0.693	0.064	0.006
	80-100	5.4	35	0.4	0.128	0.001	0.021	0.006	1.135	0.039	0.273	0.062	2.00	1.509	0.098	0.058

Table A30 (continued). Soil chemical analysis for three intensive monitoring sites at pivot Fourth (replication 2, wheat crop, beginning of 1999 winter season, Soil Science Laboratory, University of Pretoria).

Strategy	Depth (cm)	pH (H_2O)	EC (mS m^{-1})	Bray I P (mg kg^{-1})	Soluble cations (cmol$_c$ kg^{-1})				Exchangeable cations (cmol$_c$ kg^{-1})				Measured CEC (cmol$_c$ kg^{-1})	Σ echangeable bases (cmol$_c$ kg^{-1})	SO_4^{2-} (cmol$_c$ kg^{-1})	Charge balance (cmol$_c$ kg^{-1})
					Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+				
Leaching fraction	0-20	5.5	127	25.3	0.331	0.017	0.171	0.033	1.231	0.171	0.841	0.093	2.88	2.336	0.471	0.081
	20-40	5.4	53	5.3	0.103	0.003	0.064	0.007	0.835	0.083	0.510	0.070	2.60	1.498	0.155	0.022
	40-60	5.3	31	3.9	0.064	0.001	0.029	0.000	0.640	0.064	0.323	0.040	2.36	1.067	0.039	0.055
	60-80	5.6	30	6.4	0.072	0.001	0.015	0.000	0.981	0.072	0.302	0.064	2.44	1.419	0.045	0.043
	80-100	5.9	19	4.8	0.041	0.001	0.012	0.000	1.821	0.068	0.288	0.076	3.32	2.253	0.053	0.001
Field capacity	0-20	5.7	123	20.8	0.240	0.026	0.154	0.029	1.267	0.255	0.908	0.101	3.16	2.531	0.546	-0.097
	20-40	5.8	20	6.5	0.027	0.001	0.026	0.000	1.130	0.083	0.629	0.108	3.44	1.950	0.055	-0.001
	40-60	5.2	15	5.4	0.022	0.001	0.016	0.000	0.532	0.081	0.367	0.239	2.84	1.219	0.050	-0.011
	60-80	5.3	17	4.5	0.023	0.002	0.012	0.000	0.920	0.091	0.339	0.147	3.53	1.497	0.043	-0.006
	80-100	5.8	21	3.5	0.042	0.001	0.014	0.000	1.345	0.090	0.287	0.165	2.33	1.887	0.057	0.000
Deficit	0-20	5.7	143	13.8	0.313	0.045	0.169	0.032	1.458	0.316	0.807	0.116	3.73	2.697	0.403	0.156
	20-40	4.9	91	4.8	0.203	0.011	0.111	0.020	2.766	0.172	0.602	0.123	3.07	3.663	0.227	0.118
	40-60	5.1	24	4.2	0.040	0.002	0.029	0.002	0.713	0.101	0.396	0.063	2.33	1.273	0.020	0.053
	60-80	5.5	28	6.1	0.059	0.002	0.016	0.005	1.189	0.107	0.285	0.116	2.27	1.697	0.046	0.036
	80-100	5.4	17	4.8	0.030	0.002	0.012	0.001	1.038	0.104	0.322	0.094	2.93	1.558	0.037	0.008

Table A31. Soil chemical analysis for one intensive monitoring site at pivot Tweefontein (wheat crop, beginning of 1999 winter season, Soil Science Laboratory, University of Pretoria).

Strategy	Depth (cm)	pH (H_2O)	EC (mS m^{-1})	Bray I P (mg kg^{-1})	Soluble cations (cmol$_c$ kg^{-1})				Exchangeable cations (cmol$_c$ kg^{-1})				Measured CEC (cmol$_c$ kg^{-1})	Σ echangeable bases (cmol$_c$ kg^{-1})	SO_4^{2-} (cmol$_c$ kg^{-1})	Charge balance (cmol$_c$ kg^{-1})
					Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+				
Field capacity	0-20	6.2	331	42.1	0.924	0.089	0.620	0.074	3.297	0.261	1.410	0.139	5.67	5.107	1.473	0.234
	20-40	5.2	306	14.3	0.746	0.024	0.643	0.136	1.993	0.107	0.778	0.081	2.33	2.959	1.298	0.251
	40-60	4.7	182	9.3	0.412	0.018	0.359	0.052	0.825	0.097	0.641	0.152	2.67	1.715	-	0.841
	60-80	4.5	175	7.1	0.371	0.015	0.218	0.044	0.622	0.092	0.495	0.121	2.67	1.330	0.409	0.239
	80-100	4.4	161	7.9	0.342	0.014	0.160	0.033	0.571	0.076	0.281	0.098	2.93	1.026	0.653	-0.104

Table A32. Soil chemical analysis for three intensive monitoring sites at pivot Fourth (replication 1, maize crop, beginning of 1999/00 summer season, *Soil* Science Laboratory, University of Pretoria).

Strategy	Depth (cm)	pH (H_2O)	EC (mS m^{-1})	Bray I P (mg kg^{-1})	Soluble cations (cmol$_c$ kg^{-1})				Exchangeable cations (cmol$_c$ kg^{-1})				Σ echangeable bases (cmol$_c$ kg^{-1})	SO_4^{2-} (cmol$_c$ kg^{-1})	Charge balance (cmol$_c$ kg^{-1})
					Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+			
Leaching fraction	0-20	5.0	206	54.9	0.332	0.072	0.318	0.025	0.914	0.251	0.321	0.028	1.514	0.396	0.351
	20-40	4.8	149	13.8	0.170	0.004	0.223	0.029	0.707	0.066	0.434	0.028	1.235	0.426	0.000
	40-60	4.6	245	4.1	0.347	0.003	0.565	0.083	0.525	0.050	0.359	0.000	0.934	1.035	-0.037
	60-80	5.1	184	2.4	0.265	0.002	0.449	0.059	0.876	0.051	0.639	0.073	1.639	0.819	-0.044
	80-100	5.6	215	1.4	0.359	0.001	0.599	0.081	0.951	0.046	0.605	0.090	1.692	1.134	-0.094
Field capacity	0-20	5.0	270	55.9	0.503	0.053	0.309	0.026	1.581	0.212	0.394	0.043	2.23	1.197	-0.306
	20-40	5.1	192	31.8	0.319	0.009	0.357	0.028	1.381	0.101	0.426	0.077	1.985	0.800	-0.087
	40-60	4.6	192	3.6	0.218	0.003	0.516	0.077	0.454	0.050	0.457	0.090	1.051	0.834	-0.020
	60-80	4.9	195	1.4	0.296	0.002	0.396	0.068	0.810	0.045	0.404	0.095	1.354	0.771	-0.009
	80-100	5.5	73	4.5	0.099	0.001	0.058	0.024	0.913	0.046	0.308	0.047	1.314	0.144	0.038
Deficit	0-20	5.6	177	30.5	0.391	0.024	0.251	0.014	1.649	0.189	0.396	0.032	2.266	0.701	-0.021
	20-40	5.5	183	13.0	0.204	0.005	0.398	0.035	0.883	0.073	0.665	0.115	1.736	0.699	-0.057
	40-60	4.8	193	4.9	0.319	0.003	0.481	0.110	0.662	0.047	0.377	0.083	1.169	1.014	-0.101
	60-80	5.1	91	2.0	0.136	0.002	0.096	0.045	0.751	0.050	0.334	0.064	1.199	0.198	0.081
	80-100	5.6	35	0.6	0.032	0.001	0.029	0.005	0.810	0.054	0.313	0.032	1.209	0.056	0.011

Table A32 (continued). Soil chemical analysis for three intensive monitoring sites at pivot Fourth (replication 2, maize crop, beginning of 1999/00 summer season, Soil Science Laboratory, University of Pretoria).

Strategy	Depth (cm)	pH (H_2O)	EC (*m*S m^{-1})	Bray I P (mg kg^{-1})	Soluble cations (cmol$_c$ kg^{-1})				Exchangeable cations (cmol$_c$ kg^{-1})				Σ echangeable bases (cmol$_c$ kg^{-1})	SO_4^{2-} (cmol$_c$ kg^{-1})	Charge balance (cmol$_c$ kg^{-1})
					Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+			
Leaching fraction	0-20	5.9	243	29.8	0.429	0.074	0.413	0.031	1.721	0.336	0.404	0.000	2.461	0.852	0.095
	20-40	5.0	159	5.7	0.211	0.004	0.380	0.040	0.696	0.081	0.535	0.000	1.312	0.592	0.043
	40-60	5.3	134	18.3	0.216	0.012	0.261	0.022	1.285	0.140	0.556	0.039	2.02	0.494	0.017
	60-80	5.1	143	2.1	0.204	0.002	0.417	0.046	0.873	0.061	0.597	0.002	1.533	0.657	0.012
	80-100	5.7	216	0.3	0.356	0.001	0.463	0.062	1.050	0.062	0.798	0.118	2.028	0.925	-0.043
Field capacity	0-20	5.8	262	33.0	0.547	0.080	0.379	0.025	2.037	0.374	0.446	0.000	2.857	0.756	0.275
	20-40	5.9	230	12.3	0.399	0.027	0.624	0.058	1.171	0.194	0.818	0.061	2.244	1.109	-0.001
	40-60	5.2	286	3.7	0.499	0.003	0.707	0.148	0.962	0.066	0.529	0.063	1.62	1.491	-0.134
	60-80	5.1	189	0.9	0.488	0.002	0.483	0.080	0.833	0.076	0.350	0.056	1.315	1.007	0.046
	80-100	5.8	60	0.5	0.086	0.001	0.065	0.016	1.040	0.073	0.375	0.000	1.488	0.068	0.100
Deficit	0-20	6.0	172	35.8	0.526	0.058	0.328	0.025	2.471	0.342	0.488	0.000	3.301	0.823	0.114
	20-40	5.5	175	17.0	0.299	0.017	0.459	0.037	0.932	0.165	0.752	0.036	1.885	0.783	0.029
	40-60	4.8	234	3.1	0.331	0.004	0.574	0.129	0.396	0.076	0.514	0.047	1.033	1.047	-0.009
	60-80	5.3	68	2.3	0.078	0.002	0.070	0.020	0.814	0.089	0.445	0.029	1.377	0.067	0.103
	80-100	5.7	36	2.1	0.050	0.001	0.031	0.009	0.962	0.072	0.350	0.000	1.384	0.066	0.025

Table A33. Soil chemical analysis for one intensive monitoring site at pivot Tweefontein (maize crop, beginning of 1999/00 summer season, Soil Science Laboratory, University of Pretoria).

Strategy	Depth (cm)	pH (H_2O)	EC (mS m^{-1})	Bray I P (mg kg^{-1})	Soluble cations ($cmol_c$ kg^{-1})				Exchangeable cations ($cmol_c$ kg^{-1})				Σ echangeable bases ($cmol_c$ kg^{-1})	SO_4^{2-} ($cmol_c$ kg^{-1})	Charge balance ($cmol_c$ kg^{-1})
					Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+			
Field capacity	0-20	6.3	-	28.4	0.453	0.036	0.36	0.033	3.373	0.259	0.522	0.072	4.226	0.899	0.003
	20-40	5.1	-	16.6	0.483	0.025	0.301	0.022	1.711	0.135	0.545	0.000	2.391	0.930	-0.099
	40-60	4.8	206	14.9	0.374	0.018	0.316	0.032	0.961	0.091	0.347	0.000	1.399	0.845	-0.105
	60-80	4.6	201	14.0	0.313	0.023	0.481	0.052	0.404	0.070	0.159	0.051	0.684	0.970	-0.101
	80-100	4.5	282	20.9	0.253	0.027	0.514	0.081	0.444	0.104	0.376	0.073	0.997	1.020	-0.145

Table A34. Soil chemical analysis of deep soil samples at pivot Fourth (wheat crop, beginning of 2000 winter season, *Soil Science Laboratory, University of Pretoria*).

Strategy	Depth (cm)	pH (H_2O)	EC (mS m^{-1})	Bray I P (mg kg^{-1})	Soluble cations (cmol$_c$ kg^{-1})				Exchangeable cations (cmol$_c$ kg^{-1})				Σ echangeable bases (cmol$_c$ kg^{-1})	SO_4^{2-} (cmol$_c$ kg^{-1})	Charge balance (cmol$_c$ kg^{-1})
					Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+			
Leaching Fraction	0-30	5.6	22.4	34.260	0.029	0.009	0.019	0.003	1.423	0.194	0.019	0.003	1.639	0.034	0.026
	30-60	5.0	26.8	20.730	0.000	0.000	0.000	0.000	1.292	0.248	0.000	0.000	1.540	0.032	-0.032
	60-90	4.3	97.1	4.250	0.000	0.000	0.000	0.000	7.934	0.788	0.000	0.000	8.722	0.320	-0.320
	90-120	4.3	58.6	2.310	0.121	0.010	0.041	0.011	0.846	0.141	0.041	0.011	1.039	0.163	0.020
	120-150	4.0	152.000	0.920	0.259	0.012	0.313	0.088	0.463	0.106	0.313	0.088	0.970	0.177	0.495
	150-180	4.0	155.0	0.530	0.176	0.009	0.144	0.151	0.169	0.071	0.144	0.151	0.535	0.005	0.475
	120-180	4.0	165.0	0.860	0.271	0.012	0.184	0.065	0.468	0.079	0.184	0.065	0.796	0.011	0.521
	210-240	4.0	71.9	0.590	0.128	0.005	0.093	0.017	0.397	0.052	0.093	0.017	0.559	0.005	0.238
	240-270	4.5	43.6	0.760	0.098	0.003	0.057	0.025	0.565	0.048	0.057	0.025	0.695	0.013	0.170
	300-330	4.9	13.9	1.160	0.000	0.000	0.000	0.000	0.165	0.040	0.000	0.000	0.205	0.029	-0.029
	330-360	5.5	6.5	1.310	0.000	0.000	0.000	0.000	0.093	0.022	0.000	0.000	0.115	0.047	-0.047
	360-390	5.5	5.2	0.520	0.009	0.001	0.003	0.007	0.640	0.102	0.003	0.007	0.752	0.004	0.016
Field Capacity	0-30	5.2	18.7	23.780	0.032	0.010	0.009	0.003	1.165	0.183	0.009	0.003	1.360	0.037	0.017
	30-60	5.1	25.3	1.430	0.027	0.002	0.016	0.003	1.096	0.060	0.016	0.003	1.175	0.022	0.026
	60-90	4.6	48.400	1.660	0.061	0.001	0.077	0.012	0.636	0.050	0.077	0.012	0.775	0.119	0.032
	90-120	4.7	47.0	0.980	0.000	0.000	0.000	0.000	2.021	0.060	0.000	0.000	2.081	0.110	-0.110
	120-150	4.9	79.100	0.990	0.117	0.002	0.142	0.016	0.815	0.068	0.142	0.016	1.041	0.212	0.065
	150-180	5.5	92.3	0.950	0.289	0.001	0.148	0.026	1.397	0.034	0.148	0.026	1.605	0.264	0.200
	180-210	4.7	8.1	0.740	0.005	0.001	0.002	0.018	0.358	0.064	0.002	0.018	0.442	0.015	0.011
	210-240	5.0	36.0	0.740	0.044	0.002	0.037	0.024	0.670	0.047	0.037	0.024	0.778	0.004	0.103
	240-270	5.0	5.200	1.470	0.002	0.001	0.000	0.007	0.481	0.075	0.000	0.007	0.563	0.023	-0.013
	270-300	5.3	3.000	0.590	0.001	0.000	0.000	0.005	0.646	0.077	0.000	0.005	0.728	0.028	-0.022
	270-300	5.1	6.800	0.620	0.009	0.001	0.001	0.018	0.509	0.080	0.001	0.018	0.608	0.021	0.008
	300-320	5.5	3.4	0.820	0.000	0.000	0.000	0.000	0.045	0.015	0.000	0.000.	0.060	0.004	-0.004

Table A34 (continued). Soil chemical analysis of deep soil samples at pivot Fourth (wheat crop, beginning of 2000 winter season, Soil Science Laboratory, University of Pretoria).

Strategy	Depth (cm)	pH (H_2O)	EC (mS m^{-1})	Bray I P (mg kg^{-1})	Soluble cations (cmol$_c$ kg^{-1})				Exchangeable cations (cmol$_c$ kg^{-1})				Σ echangeable bases (cmol$_c$ kg^{-1})	SO_4^{2-} (cmol$_c$ kg^{-1})	Charge balance (cmol$_c$ kg^{-1})
					Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+			
Deficit	0-30	5.4	29.800	31.490	0.013	0.007	0.004	0.002	1.743	0.153	0.004	0.002	1.902	0.045	-0.019
	30-60	5.7	16.0	37.310	0.039	0.003	0.006	0.003	2.302	0.082	0.006	0.003	2.393	0.080	-0.029
	60-90	4.9	40.8	1.410	0.000	0.000	0.000	0.000	2.435	0.059	0.000	0.000	2.494	0.080	-0.080
	90-120	5.1	42.5	1.260	0.064	0.001	0.081	0.005	0.939	0.037	0.081	0.005	1.062	0.130	0.021
	120-150	5.4	107.5	0.610	0.267	0.001	0.195	0.019	1.231	0.046	0.195	0.019	1.491	0.322	0.160
	150-180	4.6	83.7	0.590	0.000	0.000	0.000	0.000	3.922	0.044	0.000	0.000	3.966	0.014	-0.014
	180-210	4.6	20.8	0.710	0.021	0.002	0.026	0.009	0.179	0.041	0.026	0.009	0.255	0.003	0.055
	210-240	4.8	12.4	0.950	0.000	0.000	0.000	0.000	0.258	0.042	0.000	0.000	0.300	0.020	-0.020
	240-270	4.8	10.1	0.740	0.007	0.001	0.006	0.020	0.303	0.046	0.006	0.020	0.375	0.001	0.033
	270-300	5.4	5.7	1.160	0.005	0.000	0.002	0.011	0.160	0.053	0.002	0.011	0.226	0.001	0.017
	300-330	4.8	19.1	0.650	0.020	0.001	0.005	0.033	0.479	0.043	0.005	0.033	0.560	0.003	0.056
	330-360	4.9	6.2	0.630	0.008	0.001	0.000	0.011	0.431	0.054	0.000	0.011	0.496	0.003	0.017
	360-380	6.1	2.6	1.060	0.000	0.000	0.000	0.000	0.035	0.010	0.000	0.000	0.045	0.004	-0.004
	380-400	5.6	2.0	0.210	0.007	0.000	0.001	0.002	0.682	0.093	0.001	0.002	0.778	0.007	0.003
Outside pivot	0-30	5.0	16.400	58.040	0.019	0.004	0.003	0.002	1.253	0.147	0.003	0.002	1.405	0.070	-0.042
	30-60	6.2	14.7	15.130	0.000	0.000	0.000	0.000	0.978	0.066	0.000	0.000	1.044	0.112	-0.112
	60-90	4.8	18.8	3.080	0.000	0.000	0.000	0.000	1.173	0.076	0.000	0.000	1.249	0.024	-0.024
	90-120	5.1	14.1	1.090	0.000	0.000	0.000	0.000	1.043	0.023	0.000	0.000	1.066	0.018	-0.018
	120-150	4.9	13.900	0.900	0.022	0.001	0.005	0.003	0.950	0.047	0.005	0.003	1.005	0.025	0.006
	150-180	4.7	5.4	0.270	0.011	0.001	0.004	0.004	0.109	0.035	0.004	0.004	0.152	0.003	0.017
	180-210	4.5	3.400	0.640	0.003	0.001	0.001	0.004	0.136	0.054	0.001	0.004	0.195	0.087	-0.078
	210-240	4.7	3.3	0.460	0.008	0.001	0.002	0.014	0.044	0.046	0.002	0.014	0.106	0.003	0.022
	240-270	5.1	8.9	-0.050	0.025	0.001	0.005	0.007	0.135	0.062	0.005	0.007	0.209	0.003	0.035
	270-300	4.9	2.200	0.560	0.002	0.000	0.000	0.004	0.376	0.062	0.000	0.004	0.442	0.025	-0.019
	300-330	5.1	5.6	0.810	0.000	0.000	0.000	0.000	0.067	0.019	0.000	0.000	0.086	0.006	-0.006
	330-360	5.3	3.3	0.670	0.007	0.001	0.000	0.004	0.557	0.074	0.000	0.004	0.635	0.002	0.010
	360-390	5.3	4.6	0.570	0.011	0.001	0.000	0.004	0.638	0.086	0.000	0.004	0.728	0.004	0.012

Table A35. Soil chemical analysis of deep soil samples at pivot Major (wheat crop, beginning of 2000 winter season, Soil Science Laboratory, University of Pretoria).

Strategy	Depth (cm)	pH (H_2O)	EC (mS m^{-1})	Bray I P (mg kg^{-1})	Soluble cations (cmol$_c$ kg^{-1})				Exchangeable cations (cmol$_c$ kg^{-1})				Σ echangeable bases (cmol$_c$ kg^{-1})	SO_4^{2-} (cmol$_c$ kg^{-1})	Charge balance (cmol$_c$ kg^{-1})
					Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+			
Leaching Fraction	0-20	7.5	183.0	10.890	0.851	0.009	0.068	0.003	-	0.169	0.068	0.003	-	0.059	0.872
	20-40	6.8	197.0	1.830	0.000	0.000	0.000	0.000	25.549	0.435	0.000	0.000	25.984	0.647	-0.647
	40-60	5.6	196.0	1.330	0.668	0.011	0.260	0.007	3.379	0.092	0.260	0.007	3.738	0.798	0.148
	60-80	6.1	205.0	2.740	0.732	0.012	0.288	0.013	-	0.147	0.288	0.013	-	0.895	0.150
	80-96	5.5	198.0	1.060	0.466	0.012	0.410	0.040	1.340	0.082	0.410	0.040	1.872	0.831	0.097
	100-170	3.1	90.6	2.190	0.410	0.016	0.153	0.046	0.525	0.091	0.153	0.046	0.817	0.276	0.351
	230-290	5.3	9.8	1.160	0.000	0.000	0.000	0.000	0.110	0.071	0.000	0.000	0.181	0.003	-0.003
Field Capacity	0-20	5.9	72.2	15.860	0.000	0.000	0.000	0.000	8.034	0.366	0.000	0.000	8.400	0.104	-0.104
	20-42	4.7	97.2	1.040	0.336	0.015	0.121	0.017	1.151	0.110	0.121	0.017	1.399	0.285	0.204
	42-60	4.8	94.2	4.650	0.260	0.014	0.092	0.017	1.362	0.147	0.092	0.017	1.618	0.277	0.106
	60-80	4.9	43.1	0.800	0.054	0.009	0.057	0.026	0.526	0.125	0.057	0.026	0.734	0.104	0.042
	110-130	5.1	23.9	0.740	0.031	0.006	0.013	0.023	0.861	0.163	0.013	0.023	1.060	0.085	-0.012
	130-150	4.9	27.0	0.520	0.026	0.006	0.013	0.023	0.886	0.138	0.013	0.023	1.060	0.073	-0.005
	150-180	5.0	26.2	0.570	0.027	0.009	0.037	0.023	0.911	0.132	0.037	0.023	1.103	0.025	0.071
	180-210	4.7	26.0	0.350	0.018	0.007	0.012	0.026	1.223	0.186	0.012	0.026	1.447	0.042	0.021
	210-240	5.6	13.9	0.360	0.014	0.004	0.003	0.033	1.203	0.131	0.003	0.033	1.370	0.015	0.039
	240-270	5.5	6.2	0.800	0.002	0.001	0.001	0.017	0.955	0.107	0.001	0.017	1.080	0.024	-0.003
	270-300	5.2	20.1	0.880	0.018	0.007	0.007	0.025	1.035	0.158	0.007	0.025	1.225	0.031	0.026
	300-330	5.5	9.000	0.370	0.003	0.001	0.001	0.015	1.064	0.102	0.001	0.015	1.182	0.027	-0.007
	330-360	6.8	212.0	2.100	0.000	0.000	0.000	0.000	18.688	0.537	0.000	0.000	19.225	0.669	-0.669
	380-430	6.5	15.1	1.730	0.000	0.000	0.000	0.000	0.270	0.111	0.000	0.000	0.381	0.027	-0.027

Table A35 (continued). Soil chemical analysis of deep soil samples at pivot Major (wheat crop, beginning of 2000 winter season, Soil Science Laboratory, University of Pretoria).

Strategy	Depth (cm)	pH (H_2O)	EC (mS m^{-1})	Bray I P (mg kg^{-1})	Soluble cations (cmol$_c$ kg^{-1})				Exchangeable cations (cmol$_c$ kg^{-1})				Σ echangeable bases (cmol$_c$ kg^{-1})	SO_4^{2-} (cmol$_c$ kg^{-1})	Charge balance (cmol$_c$ kg^{-1})
					Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+			
Deficit	0-20	5.8	56.6	3.780	0.000	0.000	0.000	0.000	7.036	0.263	0.000	0.000	7.299	0.150	-0.150
	20-40	4.8	198.0	1.430	0.815	0.013	0.142	0.010	2.439	0.090	0.142	0.010	2.681	0.695	0.285
	40-60	4.7	156.000	0.710	0.463	0.013	0.339	0.019	1.113	0.066	0.339	0.019	1.537	0.873	-0.039
	60-70	4.8	100.5	1.240	0.151	0.020	0.176	0.018	0.638	0.080	0.176	0.018	0.912	0.275	0.090
	70-220	5.0	28.3	0.630	0.031	0.012	0.040	0.036	0.783	0.103	0.040	0.036	0.962	0.079	0.040
	220-370	5.3	12.9	1.130	0.025	0.008	0.006	0.021	2.225	0.242	0.006	0.021	2.494	0.015	0.045
Outside pivot	0-30	4.9	28.000	12.190	0.049	0.009	0.006	0.001	1.591	0.178	0.006	0.001	1.776	0.027	0.038
	30-60	4.6	22.200	22.070	0.032	0.007	0.003	0.002	0.726	0.133	0.003	0.002	0.864	0.032	0.012
	80-90	4.4	25.300	1.140	0.008	0.004	0.005	0.002	0.545	0.117	0.005	0.002	0.669	0.032	-0.013
	90-120	4.8	43.8	0.900	0.065	0.007	0.058	0.007	0.673	0.094	0.058	0.007	0.832	0.027	0.110
	170-230	5.2	9.600	2.000	0.003	0.003	0.001	0.022	0.420	0.091	0.001	0.022	0.534	0.020	0.009
	120-150	4.9	37.8	-	0.052	0.016	0.048	0.006	0.686	0.203	0.048	0.006	0.943	0.004	0.118
	150-180	4.8	20.2	0.520	0.018	0.011	0.007	0.015	0.077	0.120	0.007	0.015	0.219	0.007	0.044
	180-210	5.4	7.5	0.570	0.005	0.001	0.003	0.015	0.444	0.076	0.003	0.015	0.538	0.004	0.020
	210-240	5.7	4.4	0.060	0.004	0.001	0.000	0.009	0.829	0.105	0.000	0.009	0.943	0.003	0.011
	240-270	4.7	9.200	0.280	0.004	0.002	0.001	0.015	0.584	0.110	0.001	0.015	0.710	0.032	-0.010
	270-300	5.5	3.7	0.610	0.000	0.000	0.000	0.000	0.040	0.020	0.000	0.000	0.060	0.005	-0.005

Table A36. Soil chemical analysis of deep soil samples at pivot Tweefontein (wheat crop, beginning of 2000 winter season, Soil Science Laboratory, University of Pretoria).

Strategy	Depth (cm)	pH (H_2O)	EC (mS m^{-1})	Bray I P (mg kg^{-1})	Soluble cations ($cmol_c\ kg^{-1}$)				Exchangeable cations ($cmol_c\ kg^{-1}$)				Σ echangeable bases ($cmol_c\ kg^{-1}$)	SO_4^{2-} ($cmol_c\ kg^{-1}$)	Charge balance ($cmol_c\ kg^{-1}$)
					Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+			
Field capacity	0-30	5.6	79.2	5.280	0.270	0.014	0.035	0.007	2.365	0.167	0.035	0.007	2.574	0.280	0.046
	30-60	5.0	107.9	5.150	0.248	0.009	0.190	0.011	1.319	0.085	0.190	0.011	1.605	0.465	-0.007
	60-70	6.2	159.0	2.410	0.273	0.004	0.296	0.018	2.173	0.068	0.296	0.018	2.555	0.559	-0.032
Outside pivot	0-30	4.9	16.100	1.110	0.003	0.001	0.001	0.001	0.815	0.100	0.001	0.001	0.917	0.010	-0.004
	30-60	5.0	12.200	0.970	0.026	0.001	0.005	0.002	0.847	0.052	0.005	0.002	0.906	0.042	-0.008
	60-90	5.7	20.2	1.580	0.000	0.000	0.000	0.000	1.327	0.015	0.000	0.000	1.342	0.013	-0.013
	90-110	5.5	49.3	2.810	0.109	0.010	0.074	0.026	1.642	0.165	0.074	0.026	1.907	0.183	0.036
	90-120	6.2	36.1	0.800	0.094	0.001	0.029	0.004	1.369	0.024	0.029	0.004	1.426	0.075	0.053
	120-130	5.4	40.5	4.650	0.000	0.000	0.000	0.000	2.201	0.115	0.000	0.000	2.316	0.097	-0.097

Table A37. Soil chemical analysis for three intensive monitoring sites at pivot Fourth (replication 1, end of trial, Soil Science Laboratory, University of Pretoria).

Strategy	Depth (cm)	pH (H_2O)	EC (mS m^{-1})	Bray I P (mg kg^{-1})	Soluble cations (cmol$_c$ kg^{-1})				Exchangeable cations (cmol$_c$ kg^{-1})				Σ echangeable bases (cmol$_c$ kg^{-1})	SO_4^{2-} (cmol$_c$ kg^{-1})	Charge balance (cmol$_c$ kg^{-1})
					Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+			
Leaching fraction	0-20	6.3	84.1	5.6	0.528	0.022	0.278	0.045	2.303	0.046	0.278	0.045	2.672	0.796	0.077
	20-40	6.6	42.2	5.0	0.235	0.006	0.176	0.028	2.571	0.088	0.176	0.028	2.863	0.354	0.091
	40-60	6.1	31.8	2.3	0.174	0.009	0.129	0.026	1.075	0.086	0.129	0.026	1.316	0.282	0.056
	60-80	6.4	73.6	3.3	0.651	0.005	0.318	0.037	2.555	0.064	0.318	0.037	2.974	0.952	0.059
	80-100	5.9	69.1	3.8	0.481	0.003	0.239	0.027	2.084	0.064	0.239	0.027	2.414	0.746	0.004
Field capacity	0-20	5.1	85.5	15.0	0.359	0.008	0.266	0.033	1.618	0.083	0.266	0.033	2.2	0.678	-0.012
	20-40	5.5	69.9	12.6	0.355	0.008	0.359	0.045	1.612	0.082	0.359	0.045	2.098	0.756	0.011
	40-60	5.1	53.4	13.4	0.246	0.010	0.201	0.036	1.462	0.092	0.201	0.036	1.791	0.450	0.043
	60-80	5.0	71.8	12.5	0.385	0.011	0.277	0.045	1.512	0.088	0.277	0.045	1.922	0.782	-0.064
	80-100	4.9	57.7	2.9	0.274	0.004	0.256	0.031	1.394	0.063	0.256	0.031	1.744	0.583	-0.018
Deficit	0-20	5.1	60.2	17.1	0.373	0.018	0.233	0.031	1.609	0.123	0.233	0.031	1.996	0.621	0.034
	20-40	4.9	82.3	8.8	0.413	0.043	0.373	0.053	3.371	0.102	0.373	0.053	3.899	0.681	0.201
	40-60	4.9	48.8	6.9	0.232	0.017	0.202	0.029	1.421	0.137	0.202	0.029	1.789	0.471	0.009
	60-80	4.6	70.1	3.8	0.834	0.017	0.283	0.039	0.729	0.126	0.283	0.039	1.177	0.736	0.437
	80-100	5.2	75.1	1.6	0.455	0.013	0.038	0.060	1.622	0.100	0.038	0.060	1.82	0.997	-0.431

Table A37 (continued). Soil chemical analysis for three intensive monitoring sites at pivot Fourth (*replication 2, end of trial*, Soil Science Laboratory, University of Pretoria).

Strategy	Depth (cm)	pH (H_2O)	EC (mS m^{-1})	Bray I P (mg kg^{-1})	*Soluble cations* (cmol$_c$ kg^{-1})				*Exchangeable cations* (cmol$_c$ kg^{-1})				Σ echangeable bases (cmol$_c$ kg^{-1})	SO_4^{2-} (cmol$_c$ kg^{-1})	Charge balance (cmol$_c$ kg^{-1})
					Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+			
Leaching fraction	0-20	5.3	45.4	7.4	0.244	0.036	0.143	0.022	1.638	0.230	0.143	0.022	2.033	0.249	0.196
	20-40	5.0	70.3	7.0	0.365	0.019	0.375	0.047	1.432	0.126	0.375	0.047	1.98	0.885	-0.059
	40-60	5.1	84.4	0.9	0.457	0.005	0.337	0.078	1.710	0.095	0.337	0.078	2.22	0.962	-0.085
	60-80	5.4	48.7	2.2	0.318	0.007	0.269	0.039	1.719	0.079	0.269	0.039	2.106	0.656	-0.023
	80-100	5.4	83.9	2.4	0.509	0.009	0.407	0.045	1.568	0.086	0.407	0.045	2.106	0.980	-0.010
Field capacity	0-20	5.2	101.5	20.7	0.409	0.016	0.292	0.048	1.773	0.138	0.292	0.048	2.251	0.830	-0.065
	20-40	5.5	86.4	2.4	0.456	0.024	0.614	0.129	1.347	0.157	0.614	0.129	2.247	1.170	0.053
	40-60	4.8	120.8	1.0	0.427	0.016	0.045	0.078	1.351	0.117	0.045	0.078	1.591	1.093	-0.527
	60-80	5.4	103.6	1.3	0.582	0.006	0.667	0.078	1.604	0.080	0.667	0.078	2.429	1.282	0.051
	80-100	5.5	56.7	1.3	0.216	0.002	0.215	0.027	3.428	0.082	0.215	0.027	3.752	0.326	0.134
Deficit	0-20	5.6	28.8	7.0	0.170	0.011	0.108	0.020	1.947	0.144	0.108	0.020	2.219	0.282	0.027
	20-40	4.9	62.2	1.4	0.258	0.012	0.303	0.040	1.160	0.119	0.303	0.040	1.622	0.631	-0.018
	40-60	6.4	28.9	15.3	0.171	0.015	0.091	0.017	2.869	0.180	0.091	0.017	3.157	0.170	0.124
	60-80	5.5	84.8	0.8	0.494	0.005	0.549	0.061	1.348	0.085	0.549	0.061	2.043	0.850	0.259
	80-100	5.6	63.6	2.1	0.363	0.028	0.290	0.034	1.460	0.078	0.290	0.034	1.862	0.481	0.234

Table A38. Soil chemical analysis for three intensive monitoring sites at pivot Major (end of trial, Soil Science Laboratory, University of Pretoria).

Strategy	Depth (cm)	pH (H_2O)	EC (mS m^{-1})	Bray I P (mg kg^{-1})	Soluble cations (cmol$_c$ kg^{-1})				Exchangeable cations (cmol$_c$ kg^{-1})				Σ echangeable bases (cmol$_c$ kg^{-1})	SO_4^{2-} (cmol$_c$ kg^{-1})	Charge balance (cmol$_c$ kg^{-1})
					Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+			
Leaching fraction	0-20	6.7	99.5	5.6	1.099	0.028	0.354	0.031	6.977	0.146	0.354	0.031	7.508	1.378	0.134
	20-40	6.5	110.0	1.9	0.932	0.032	0.542	0.062	11.584	0.258	0.542	0.062	12.448	1.699	-0.131
	40-60	5.9	163.0	0.9	0.760	0.014	0.659	0.072	6.956	0.188	0.659	0.072	7.875	1.496	0.029
	60-80	5.8	106.0	0.4	0.625	0.035	0.041	0.060	3.363	0.099	0.041	0.060	3.563	1.134	-0.373
	80-100	5.0	88.2	1.0	0.405	0.010	0.343	0.046	4.890	0.069	0.343	0.046	5.348	0.778	0.026
Field capacity	0-20	5.1	90.6	6.2	0.920	0.013	0.331	0.037	5.169	0.099	0.331	0.037	5.636	1.399	-0.098
	20-40	4.5	106.0	1.6	0.661	0.019	0.462	0.041	1.781	0.110	0.462	0.041	2.394	1.150	0.033
	40-60	4.8	96.1	1.5	0.659	0.005	0.496	0.057	1.478	0.172	0.496	0.057	2.203	1.160	0.057
	60-80	6.2	106.2	1.0	0.866	0.034	0.676	0.078	1.905	0.261	0.676	0.078	2.92	1.629	0.025
	80-100	5.8	81.9	0.6	0.500	0.022	0.560	0.072	1.578	0.235	0.560	0.072	2.445	0.994	0.160
Deficit	0-20	5.1	94.8	16.3	0.867	0.017	0.038	0.059	5.247	0.126	0.038	0.059	5.47	1.361	-0.380
	20-40	4.4	97.8	4.0	0.625	0.026	0.201	0.030	1.777	0.224	0.201	0.030	2.232	0.763	0.119
	40-60	4.8	78.1	2.9	0.598	0.042	0.336	0.026	1.215	0.231	0.336	0.026	1.808	1.002	0.000
	60-80	5.5	97.0	1.3	0.590	0.039	0.585	0.062	4.341	0.282	0.585	0.062	5.27	1.218	0.058
	80-100	4.8	24.2	0.7	0.090	0.016	0.072	0.069	0.964	0.312	0.072	0.069	1.417	0.039	0.208

Table A39. Soil chemical analysis for one intensive monitoring site at pivot Tweefontein (*end of trial*, Soil Science Laboratory, University of Pretoria).

Strategy	Depth (cm)	pH (H_2O)	EC (mS m^{-1})	Bray I P (mg kg^{-1})	Soluble cations (cmol$_c$ kg^{-1})				Exchangeable cations (cmol$_c$ kg^{-1})				Σ echangeable bases (cmol$_c$ kg^{-1})	SO_4^{2-} (cmol$_c$ kg^{-1})	Charge balance (cmol$_c$ kg^{-1})
					Ca^{2+}	K^+	Mg^{2+}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Na^+			
Field capacity	0-20	5.7	34.1	22.8	0.172	0.016	0.105	0.018	2.334	0.122	0.105	0.018	2.579	0.243	0.068
	20-40	4.7	40.9	7.3	0.187	0.018	0.181	0.021	1.106	0.088	0.181	0.021	1.396	0.413	-0.006
	40-60	4.6	72.4	4.3	0.262	0.023	0.229	0.035	0.836	0.100	0.229	0.035	1.2	0.483	0.066
	60-80	4.5	55.2	3.0	0.270	0.004	0.277	0.035	0.679	0.107	0.277	0.035	1.098	0.440	0.146
	80-100	4.3	81.8	3.4	0.433	0.022	0.437	0.076	0.651	0.083	0.437	0.076	1.247	0.984	-0.016

Table A40. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers at pivot Major (sugarbean crops, 1997/98 summer season, Soil Science Laboratory, University of Pretoria).

Strategy	Date	Depth (m)	Ca^{2+} (mg l^{-1})	K^+ (mg l^{-1})	Mg^{2+} (mg l^{-1})	Na^+ (mg l^{-1})	CO_3^{2-} (mg l^{-1})	HCO_3^- (mg l^{-1})	Cl^- (mg l^{-1})	NH_4^+ (mg l^{-1})	NO_3^- (mg l^{-1})	SO_4^{2-} (mg l^{-1})	EC (mS m^{-1})	Charge balance (mmol$_c$ l^{-1})
Leaching fraction	18/03/1998	0.4	226.0	19.4	192.6	147.4	0	13.4	34.7	1.1	0.4	2449.0	338	-18.103
		1.0	6.4	1.3	6.2	8.5	0	9.1	13.1	1.4	1.1	4.8	15	0.674
		1.4	0.9	2.1	1.5	7.7	0	15.0	21.1	2.0	1.4	4.2	7	-0.283
Field capacity	18/03/1998	0.4	339.5	3.3	165.8	124.6	0	18.3	22.1	2.3	3.1	2414.0	332	-15.021
		1.0	1.1	1.3	0.7	20.4	0	20.4	3.0	2.2	1.1	6.0	9	0.593
		1.4	1.0	2.0	1.0	20.2	0	12.4	3.0	2.2	0.6	5.7	9	0.768

Table A41. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers at pivot Jacuzzi (sugarbean crops, 1997/98 summer season, Soil Science Laboratory, University of Pretoria).

Strategy	Date	Depth (m)	Ca^{2+} (mg l^{-1})	K^+ (mg l^{-1})	Mg^{2+} (mg l^{-1})	Na^+ (mg l^{-1})	CO_3^{2-} (mg l^{-1})	HCO_3^- (mg l^{-1})	Cl^- (mg l^{-1})	NH_4^+ (mg l^{-1})	NO_3^- (mg l^{-1})	SO_4^{2-} (mg l^{-1})	EC (mS m^{-1})	Charge balance (mmol$_c$ l^{-1})
Leaching fraction	18/03/1998	0.4	27.0	1.9	5.4	18.3	0	12.9	40.7	1.1	0	99.6	35	-0.736
		1.0	5.8	2.1	2.6	9.2	0	53.2	15.1	2.0	0.8	5.8	13	-0.364
		1.4	64.8	7.0	26.8	9.1	0	23.6	29.1	2.2	1.1	335.9	89	-2.085
Field capacity	18/03/1998	0.4	16.0	3.1	9.2	26.7	0	8.6	24.1	2.2	1.1	89.5	38	1.230
		1.0	2.2	0.9	1.5	13.0	0	24.2	12.6	2.8	1.4	111.5	14	-2.120
		1.4	5.6	3.2	3.5	10.8	0	5.9	36.2	2.0	1.4	75.6	24	-1.485

Table A42. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers at pivot Tweefontein (sugarbean crops, 1997/98 summer season, Soil Science Laboratory, University of Pretoria).

Strategy	Date	Depth (m)	Ca^{2+} (mg l^{-1})	K^+ (mg l^{-1})	Mg^{2+} (mg l^{-1})	Na^+ (mg l^{-1})	CO_3^{2-} (mg l^{-1})	HCO_3^- (mg l^{-1})	Cl^- (mg l^{-1})	NH_4^+ (mg l^{-1})	NO_3^- (mg l^{-1})	SO_4^{2-} (mg l^{-1})	EC (mS m^{-1})	Charge balance (mmol$_c$ l^{-1})
Leaching fraction	18/03/1998	0.4	72.6	3.9	28.8	98.0	0	25.2	30.2	2.0	1.1	554.4	111	2.360
		1.0	6.0	1.3	2.0	12.2	0	28.5	35.2	1.1	0.8	15.1	19	0.698
		1.4	3.3	1.6	2.2	10.6	0	17.7	35.2	2.0	1.1	57.8	18	1.546
Field capacity	18/03/1998	0.4	1.9	1.1	1.5	7.6	0	23.1	17.1	2.2	0.8	15.8	14	0.504
		1.0	6.0	0.5	2.4	9.0	0	24.2	17.6	2.0	1.1	8.2	13	-0.070
		1.4	7.0	0.5	2.9	7.8	0	13.4	11.6	3.5	2.1	4.8	7	0.453

Table A43. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers at pivot Major (lucerne-fescue pasture, 1998 winter and 1998/99 summer season, Soil Science Laboratory, University of Pretoria).

Strategy	Date	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})	HCO_3^- (mg l^{-1})	Cl^- (mg l^{-1})	SO_4^{2-} (mg l^{-1})	NH_4^+ (mg l^{-1})	NO_3^- (mg l^{-1})	P (mg l^{-1})	Charge balance (mmol$_c$ l^{-1})
Leaching fraction	10/09/1998	1.4	6.22	23	3	0.5	4	26	31	3	125	1.5	4.4	0.05	-1.053
	13/10/1998	0.4	-	513	266	0.1	547	31	32.34	0	3920	1.12	1.904	-	-21.969
		1.0	-	123	72	2.8	65.2	22.8	96.41	38.3	552.4	1.568	5.04	-	-2.557
		1.4	-	28	20	0.6	5.5	25	44.54	2.7	26.3	1.624	5.6	-	1.929
	19/10/1998	1.4	-	30	12	0	7	18	-	-	27	-	-	-	1.395
	12/11/1998	1.0	6.64	299	351	0.2	234	67	-	-	2547	-	-	-	-13.353
		1.4	6.49	29	13	1	7	19	-	-	21	-	-	-	1.639
	24/11/1998	0.4	6.05	286	289	0	277	12	-	-	2357	-	-	-	-11.349
		1.0	5.89	28	11	0.5	6	20	-	-	32	-	-	-	1.259
	17/12/1998	0.4	-	297	-	-	-	-	-	-	-	-	-	-	-
		1.4	-	22.3	-	-	-	-	-	-	-	-	-	-	-
	11/01/1999	0.4	5.35	486	380	0	474	22	-	-	3631	-	-	-	-16.694
		1.0	6.60	498	345	0.1	499	13	-	-	3759	-	-	-	-19.438
		1.4	6.46	58	19	0.8	14	34	-	-	358	-	-	-	-3.856
	01/02/1999	0.4	-	391	-	-	-	-	-	-	-	-	-	-	-
		1.4	-	58	-	-	-	-	-	-	-	-	-	-	-
	08/02/1999	1.0	-	444	-	-	-	-	-	-	-	-	-	-	-
		1.4	-	132	-	-	-	-	-	-	-	-	-	-	-

Table A43 (continued). Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers at pivot Major (lucerne-fescue pasture, 1998 winter and 1998/99 summer season, Soil Science Laboratory, University of Pretoria).

Strategy	Date	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})	HCO_3^- (mg l^{-1})	Cl^- (mg l^{-1})	SO_4^{2-} (mg l^{-1})	NH_4^+ (mg l^{-1})	NO_3^- (mg l^{-1})	P (mg l^{-1})	Charge balance (mmol$_c$ l^{-1})
Field capacity	10/09/1998	1.4	6.06	19	8	2	6	7	25	1	759	1.7	5.3	0.34	-15.172
	13/10/1998	1.4	-	22	19	1.7	8.5	1.8	23.19	0	16.7	1.456	8.96	-	0.978
	19/10/1998	1.0 1.4	- -	159 22	96 10	1 2	74 9	224 5	- -	- -	1019 6	- -	- -	- -	-0.569 1.383
	12/11/1998	1.4	7.38	18	9	1	9	1	-	-	23	-	-	-	0.780
	24/11/1998	1.4	5.96	19	17	0.5	5	0.2	-	-	9	-	-	-	1.094
	17/12/1998	1.4	-	13.6	-	-	-	-	-	-	-	-	-	-	-
	08/02/1999	1.4	-	14.5	-	-	-	-	-	-	-	-	-	-	-
Deficit	10/09/1998	0.4 1.4	6.17 6.44	100 16	466 7	0.2 2	516 6	95 5	0 9	0 0	4150 131.2	0 2.7	0 5.8	0.14 0.04	-16.575 -1.712
	13/10/1998	1.4		18	18	2.1	6.5	0.4	83.59	0	7.4	1.568	8.176	-	-0.239
	24/11/1998	1.4	5.89	5	1	0.1	2	0	-	-	2	-	-	-	0.175
	17/12/1998	1.4	-	2.6	-	-	-	-	-	-	-	-	-	-	-
	08/02/1999	1.0	-	416	-	-	-	-	-	-	-	-	-	-	-

Table A44. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers at pivot Major (maize crop, 1998/99 summer season, Soil Science Laboratory, University of Pretoria).

Strategy	Date	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})	HCO_3^- (mg l^{-1})	Cl^- (mg l^{-1})	SO_4^{2-} (mg l^{-1})	NH_4^+ (mg l^{-1})	NO_3^- (mg l^{-1})	P (mg l^{-1})	Charge balance (mmol$_c$ l^{-1})
Leaching fraction	11/01/1999	0.4	6.71	307	282	12.6	147	38	-	-	1619	-	-	-	-9.738
		1.0	6.42	186	100	3.7	86	50	-	-	889	-	-	-	-4.178
	26/04/1999	1.0	-	424	-	-	-	-	-	-	-	-	-	-	-
		1.4	-	84.9	-	-	-	-	-	-	-	-	-	-	-
Field capacity	11/01/1999	1.0	5.72	347	261	21.7	226	54	-	-	2229	-	-	-	-11.895
		1.4	6.42	25	10	4.4	6	5	-	-	336	-	-	-	-5.675
	26/04/1999	1.4	-	7.6	-	-	-	-	-	-	-	-	-	-	-
Deficit strategy	11/01/1999	1.0	5.96	71	19	10.4	22	31	-	-	379	-	-	-	-3.520
		1.4	6.04	23	6	4	6	7	-	-	325	-	-	-	-5.568
	26/04/1999	1.0	-	239	-	-	-	-	-	-	-	-	-	-	-
		1.4	-	2.6	-	-	-	-	-	-	-	-	-	-	-

Table A45. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers at pivot Jacuzzi (wheat crop, 1998 winter season, Soil Science Laboratory, University of Pretoria).

Strategy	Date	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})	HCO_3^- (mg l^{-1})	Cl^- (mg l^{-1})	SO_4^{2-} (mg l^{-1})	NH_4^+ (mg l^{-1})	NO_3^- (mg l^{-1})	Charge balance ($mmol_c$ l^{-1})
Leaching fraction	13/10/1998	0.4	-	10	16	1.1	1.6	3.3	33.56	0	16.6	1.008	1.96	0.230
		0.75	-	26	24	1.6	7.4	2.2	39.66	0	18	1.456	4.592	0.925
	19/10/1998	0.4	-	14	9	1	5	7	-	-	34	-	-	0.483
		0.75	-	18	12	1	6	6	-	-	148	-	-	-1.703
	12/11/1998	0.4	6.10	22	8	2	9	2	-	-	87	-	-	-0.534
		0.75	7.08	15	7	2	5	3	-	-	48	-	-	-0.057
	24/11/1998	0.4	6.47	23	15	1.9	9	8	-	-	81	-	-	0.199
		0.75	5.84	13	8	1.4	4	3	-	-	41	-	-	0.041
Field capacity	12/11/1998	1.0	7.36	44	32	12	10	2	-	-	82	-	-	1.106
	24/11/1998	1.0	6.11	53	46	12.6	19	10	-	-	141	-	-	1.680

Table A46. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers at pivot Tweefontein (wheat crop, 1998 winter season, Soil Science Laboratory, University of Pretoria).

Strategy	Date	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})	HCO$_3^-$ (mg l^{-1})	Cl$^-$ (mg l^{-1})	SO$_4^{2-}$ (mg l^{-1})	NH$_4^+$ (mg l^{-1})	NO$_3^-$ (mg l^{-1})	P (mg l^{-1})	Charge balance (mmol$_c$ l^{-1})
Leaching fraction	10/09/1998	0.4	6.66	393	512	1	262	165	85	115	4550	1.5	6.7	0.19	-45.204
		1.0	6.58	66	63	0.2	15	10	40	42	220	1.6	8.6	0.06	-1.830
		1.4	6.28	204	206	8	110	45	110	24	1331	1.6	4.8	0.06	-8.867
	12/11/1998	1.0	6.67	329	525	0.2	157	84	-	-	2809	-	-	-	-15.723
		1.4	7.23	152	157	9	98	14	-	-	969	-	-	-	-3.442
	24/11/1998	1.0	7.2	308	474	0.2	130	76	-	-	2605	-	-	-	-16.590
		1.4	7.43	139	474	0.2	130	76	-	-	830	-	-	-	20.376
Field capacity	24/11/1998	1.4	7.52	184	190	6.2	108	10	-	-	1039	-	-	-	-2.673
Deficit	24/11/1998	0.4	7.9	385	368	11.4	296	121	-	-	3042	-	-	-	-15.076

Table A47. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers at pivot Fourth (wheat crop, 1999 winter season, Soil Science Laboratory, University of Pretoria).

Strategy	Date	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})	SO_4^{2-} (mg l^{-1})	P (mg l^{-1})	Charge balance (mmol$_c$ l^{-1})
Leaching fraction	04/10/1999	0.4 (repl. 2) 1.4 (repl. 2)	6.58 6.15	440 29	322.0 10.9	3.6 0.9	527.0 15.4	214.0 12.0	3729.0 64.8	0 0	-8.816 1.007
	18/10/1999	0.4 (repl. 1) 0.4 (repl. 2) 1.4 (repl. 2)	- 6.80 -	130 377 67	361.0 439.0 68.9	178.0 874.0 111.0	- - -	- - -	2000.0 6812.0 945.5	0 0 0	-19.086 -97.610 -13.414
	01/11/1999	0.4 (repl. 1) 0.4 (repl. 2)	6.50 6.31	485 466	782.0 616.0	- -	708.0 739.0	- -	5634.0 5690.0	- -	-20.049 -26.948
	21/11/1999	0.4 (repl. 1) 1.0 (repl. 2) 1.4 (repl. 1) 1.4 (repl. 2)	6.48 6.35 6.91 6.09	432 293 156 24	423.0 479.0 187.0 17.0	- - - -	227.0 100.0 75.0 5.0	- - - -	3446.0 1930.0 1047.0 23.5	- - - -	-31.978 -8.062 -6.301 0.770
Field capacity	04/10/1999	1.4 (repl. 1) 1.4 (repl. 2)	5.54 5.93	22 27	7.9 10.4	1.3 0	6.4 15.2	13.0 1.9	3.0 60.1	0 0	1.457 0.601
	18/10/1999	1.4 (repl. 1)	5.60	11	6.2	5.2	-	-	0.9	0	0.424
	01/11/1999	1.4 (repl. 1)	5.64	28	11.0	-	12.0	-	21.8	-	1.082
	11/11/1999	0.4 (repl. 1) 1.4 (repl. 1)	5.99 6.38	376 57	528.0 50.0	- -	403.0 34.0	- -	7837.0 784.0	- -	-103.700 -11.034
	21/11/1999	1.4 (repl. 1)	6.54	21	8.0	-	3.0	-	-	-	0.646
Deficit	04/10/1999	1.4 (repl. 1) 1.4 (repl. 2)	6.42 5.86	19 51	13.1 43.8	5.1 0	4.7 25.6	0.1 2.0	19.2 233.8	0 0	0.775 -0.489
	18/10/1999	1.4 (repl. 1)	6.00	11	11.4	3.2	-	-	7.9	0	0.486
	11/11/1999	0.4 (repl. 1) 1.4 (repl. 2)	6.35 6.09	509 30	628.0 19.0	- -	643.0 22.0	- -	1583.1 784.0	- -	51.279 -13.569

Table A48. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers at pivot Fourth (maize crop, 1999/00 summer season, Soil Science Laboratory, University of Pretoria).

Strategy	Date	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})	SO_4^{2-} (mg l^{-1})	P (mg l^{-1})	Charge balance ($mmol_c$ l^{-1})
Leaching fraction	05/01/2000	0.4 (repl. 2)	-	270	2.85	-	218.0	-	1870.0	-	-20.863
		1.0 (repl. 2)	-	29	0.22	-	8.5	-	78.7	-	-0.929
		1.4 (repl. 2)	-	46	0.29	-	27.0	-	162.7	-	-1.152
	24/01/2000	0.4 (repl. 2)	-	258	342.0	-	220.0	-	-	-	35.169
		1.4 (repl. 1)	-	26	11.6	-	13.6	-	-	-	1.700
		1.4 (repl. 2)	-	28	14.0	-	12.0	-	-	-	1.686
	03/02/2000	1.4 (repl. 1)	6.36	24	12.6	-	14.6	-	5.0	-	1.726
		1.4 (repl. 2)	6.38	40	16.2	-	27.1	-	19.0	-	2.643
	27/03/2000	1.4 (repl. 1)	5.80	29	9.1	-	3.7	-	4.3	-	0.669
		1.4 (repl. 2)	5.60	62	18.9	-	33.8	-	52.2	-	2.637
Field capacity	03/02/2000	1.4 (repl. 2)	6.58	26	22.3	-	13.5	-	11.0	-	1.995
	27/03/2000	1.4 (repl. 1)	5.70	36	21.3	-	12.9	-	13.6	-	1.841
		1.4 (repl. 2)	6.60	26	18.9	-	4.2	-	5.1	-	1.183
Deficit	24/01/2000	1.0 (repl. 1)	-	319	424.0	-	218.0	-	-	-	39.096
		1.4 (repl. 1)	-	34	28.7	-	16.5	-	-	-	2.790
	03/02/2000	1.0 (repl. 1)	6.17	292	402.0	-	240.0	-	1957.0	-	-0.941
		1.4 (repl. 1)	5.97	37	36.0	-	23.2	-	36.0	-	2.956
		1.4 (repl. 2)	7.18	35	28.6	-	18.1	-	17.0	-	2.563
	27/03/2000	1.0 (repl. 1)	6.10	282	335.5	-	112.0	-	1299.0	-	-1.090
		1.4 (repl. 1)	5.80	71	55.8	-	24.5	-	106.0	0	2.593

Table A49. Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers at pivot Fourth (wheat crop, 2000 winter season, Soil Science Laboratory, University of Pretoria).

Strategy	Date	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})	SO_4^{2-} (mg l^{-1})	Cl^- (mg l^{-1})	Charge balance (mmol$_c$ l^{-1})
Leaching fraction	24/07/2000	0.4 (repl. 2)	-	-	243	4.9	41	51	442.8	125.9	5.070
		1.0 (repl. 2)	-	-	192	3.2	41	29	534.0	-	3.177
		1.4 (repl. 1)	6.54	103	384	2.43	140	86	1232.3	133.4	5.059
		1.4 (repl. 2)	7.46	45	110	3.01	58	20	233.4	71.5	4.331
	03/08/2000	0.4 (repl. 2)	7	46	135	18	49	16	225.3	90	4.694
		1.0 (repl. 1)	7.3	95	297	4	235	38	1300.1	41	7.681
		1.4 (repl. 1)	6.3	100	385	2	151	98	858.3	119	14.720
		1.4 (repl. 2)	7.2	37	85	2	47	19	257.1	82	1.319
	14/08/2000	0.4 (repl. 2)	5.8	32	122	16.1	42	12	239.1	92	2.903
		1.4 (repl. 2)	5.9	24	76	1.2	41	16	309.9	70	-0.535
	21/08/2000	0.4 (repl. 2)	5.9	87	141	19.2	48	16	229	94	4.752
		1.4 (repl. 1)	5.3	233	412	2.17	151	96	1347.9	96	6.437
		1.4 (repl. 2)	5.9	65	88	1.51	44	18	232.8	65	2.152
	04/09/2000	0.4 (repl. 2)	6.2	59	194	20.3	67	17	307.2	48	8.701
		1.4 (repl. 1)	5.2	126	383	2.22	142	83	1240.9	98	5.857
		1.4 (repl. 2)	6.1	38	78	1.59	43	16	235.1	62	1.522
	12/10/2000	0.4 (repl. 2)	6.1	190	557	14	201	74	1847.2	82	7.129
		1.4 (repl. 1)	5.2	147	368	2	129	79	969.5	106	9.286
		1.4 (repl. 2)	5.8	57	106	1	47	24	203.2	113	2.807
	09/11/2000	1.4 (repl. 1)	6.4	269	429	8	222	46	1853.9	23	2.628
		1.4 (repl. 2)	5.5	163	266	27	109	29	931.2	28	4.012

Table A49 (continued). Results of chemical analysis of soil water samples extracted with the ceramic cup soil water samplers at pivot Fourth (wheat crop, 2000 winter season, Soil Science Laboratory, University of Pretoria).

Strategy	Date	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})	SO_4^{2-} (mg l^{-1})	Cl^{-} (mg l^{-1})	Charge balance (mmol$_c$ l^{-1})
Field capacity	24/07/2000	1.4 (repl. 1)	7.32	99	413	7.62	125	70	1493.5	86.1	0.608
		1.4 (repl. 2)	7.59	48	103	12.9	61	27	271.1	82.1	3.702
	03/08/2000	1.0 (repl. 2)	7.1	85	305	8	190	36	1232.6	24	6.278
		1.4 (repl. 1)	7.4	106	483	6	155	92	1602.1	86	5.226
		1.4 (repl. 2)	7.2	38	76	7	49	25	243.3	80	1.768
	14/08/2000	1.0 (repl. 1)	5.4	81	433	2.29	134	97	1166.8	99	9.819
		1.4 (repl. 1)	6.1	88	570	4.14	138	97	2158.2	78	-3.013
		1.4 (repl. 2)	5.6	22	56	3.55	37	20	231.4	75	-0.134
	21/08/2000	1.0 (repl. 2)	5.6	61	285	3.42	45	26	1430.2	79	12.870
		1.4 (repl. 1)	6.1	254	535	4.34	147	97	1867.8	77	2.060
	04/09/2000	1.4 (repl. 1)	6	155	560	3.97	151	93	1576	75	9.580
		1.4 (repl. 2)	5.9	38	63	2.78	43	24	144.4	86	2.364
	12/10/2000	1.4 (repl. 1)	6.2	164	525	2	121	82	1505.9	84	6.042
		1.4 (repl. 2)	6.1	60	83	2	59	37	223.7	119	2.642
	09/11/2000	1.4 (repl. 1)	6.8	264	545	1	115	72	1648.6	97	2.754
		1.4 (repl. 2)	6.5	114	157	2	58	50	258.7	187	4.171

Table A49 (continued). Results of chemical analysis of soil water samples extracted with the *ceramic cup soil water samplers* at pivot Fourth (wheat crop, 2000 winter season, Soil Science Laboratory, University of Pretoria).

Strategy	Date	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})	SO_4^{2-} (mg l^{-1})	Cl^- (mg l^{-1})	Charge balance (mmol$_c$ l^{-1})
Deficit	24/07/2000	0.4 (repl. 1)	7.03	35	122	4.83	29	12	238.9	130.4	0.467
		1.0 (repl. 2)	6.79	38	49	2.93	56	30	115.7	82.6	3.694
		1.4 (repl. 1)	7.31	101	544	1.75	109	63	1574.8	79.6	3.865
		1.4 (repl. 2)	-	-	189	3.5	127	18	820.4	42.8	2.463
	03/08/2000	1.0 (repl. 2)	7.2	74	247	3	169	24	760.2	21	10.929
		1.4 (repl. 1)	7.5	105	633	2	106	87	1728.7	90	5.612
		1.4 (repl. 2)	7.2	34	41	3	54	28	39	107	3.954
	14/08/2000	1.0 (repl. 2)	6.2	59	240	1.9	154	22	946.7	19	5.402
		1.4 (repl. 1)	6.3	84	614	1.28	102	85	2092.6	74	-2.895
		1.4 (repl. 2)	5.6	24	33	3	51	33	145.4	127	0.745
	21/08/2000	1.0 (repl. 2)	6.5	170	274	2.1	169	28	1264.8	21	1.921
		1.4 (repl. 1)	6.1	252	569	2.17	105	84	2007.4	70	-3.028
		1.4 (repl. 2)	5.4	114	68	4.28	132	70	277.7	155	7.254
	04/09/2000	1.0 (repl. 2)	6.4	100	276	1.99	178	29	1321.2	21	1.628
		1.4 (repl. 1)	6.5	152	623	2.48	112	78	1587.1	69	8.762
		1.4 (repl. 2)	5.7	99	136	4.53	215	73	953.2	146	3.801
	12/10/2000	1.0 (repl. 2)	6.2	148	344	1	201	41	1502.9	23	3.571
		1.4 (repl. 1)	6.2	174	550	1	98	76	1673.5	107	0.978
	09/11/2000	1.4 (repl. 1)	7.3	284	613	0.3	99	75	1722.5	167	1.430
		1.4 (repl. 2)	6.8	253	400	1	211	41	1866.5	30	-0.580

Table A50. Results of chemical analysis for Jacuzzi water (Kleinkopje Colliery, personal communication).

Date	Al^{3+} (mg l^{-1})	HCO_3^- (mg l^{-1})	F^- (mg l^{-1})	Ca^{2+} (mg l^{-1})	Cl^- (mg l^{-1})	EC (mS m^{-1})	Fe^{2+} (mg l^{-1})	Mg^{2+} (mg l^{-1})	Mn^{2+} (mg l^{-1})	M. Alk (mg l^{-1})	P. Acid (mg l^{-1})	Na^+ (mg l^{-1})	SO_4^{2-} (mg l^{-1})	TDS (mg l^{-1})	NO_3^- as N (mg l^{-1})	Langelier saturation Index	pH
03/12/1997	0.25	144	-	503.8	18	301	0.07	154.9	4.94	118	28	66.1	2015	2859	-	-	6.4
17/12/1997	0.18	144	-	498.8	16	322	0.06	161.3	5.16	118	28	48.1	2067	2936	-	-	6.6
22/01/1998	0.05	149	1.4	578.1	16	306	0.35	167.9	6.20	122	-	51.3	2062	2328	-	-0.73	6.1
04/02/1998	0.05	142	1.5	520.6	18	284	0.17	155.4	5.86	116	22	48.0	1968	2778	1	-0.82	6.1
11/02/1998	1.05	137	1.4	489.1	18	262	0.84	164.9	6.20	112	30	52.7	2032	2846	0.5	-0.97	6.0
02/03/1998	-	-	-	-	-	327	-	-	-	120	16	-	2035	-	-	-	6.6
12/03/1998	0.06	144	1.5	485.2	20	258	0.27	143.7	5.91	118	22	41.0	2009	2846	0.3	-0.05	6.9
25/03/1998	0.12	159	1.4	581.5	26	286	0.44	164.2	7.08	130	18	42.5	2030	2887	0.3	-0.33	6.5
03/04/1998	0.01	122	1.3	605.1	20	265	0.01	181.8	7.08	100	20	41.8	1760	2503	0.5	-0.3	6.6
22/04/1998	0.03	139	1.3	716.4	18	252	0.60	237.5	7.78	114	22	47.5	2078	2941	0.4	-0.6	6.2
30/04/1998	0.04	141	1.6	462.5	18	349	0.20	146.6	5.85	116	16	43.1	1904	2714	0.4	-0.07	6.9
06/05/1998	0.11	-	1.3	257.6	20	298	0.26	93.68	0.5	108	24	27.7	2059	2888	0.1	-1.17	6.1
13/05/1998	0.04	-	1.3	523.9	20	267	0.22	159.1	6.78	108	20	42.7	2028	2855	0.4	-0.16	6.8
26/05/1998	-	-	-	-	-	328	-	-	-	108	16	-	2003	-	-	-	7.3
03/06/1998	0.5	-	1.4	555.2	18	250	60	132.3	8.58	108	18	24.5	2073	2894	0.5	-0.23	6.7
12/06/1998	0.3	-	1.6	471.7	18	2492	1	156.3	6.11	110	18	45.2	2044	3096	0.3	-0.21	6.8
17/06/1998	0.4	-	1.5	504.8	20	260	1.2	158.2	7.07	106	18	45.9	2032	3131	0.4	-0.4	6.6
01/07/1998	0.3	-	1.3	459.9	16	251	0.01	261.3	12.51	102	8	47.4	2021	3142	0.3	-0.26	6.8
08/07/1998	0.8	-	1.3	591.7	18	254	0.01	134.9	7.22	108	12	57.8	2019	2978	0.8	-0.41	6.5
15/07/1998	0.6	-	-	484.6	16	261	0.01	223.1	11.01	100	14	47.1	2003	3003	0.6	-0.13	6.9
22/07/1998	0.3	-	-	581.6	16	235	0.01	242	16.99	112	20	49.4	1991	2804	0.3	0.01	6.9
29/07/1998	0.7	-	-	415.3	20	241	0.01	282.6	38.1	110	18	56	2024	3158	0.7	-0.27	6.8
05/08/1998	0.8	-	-	487.8	18	258	0.01	225.2	51.25	108	16	65.3	2087	3096	0.8	-0.1	6.9

Table A50 (continued). Results of chemical analysis for Jacuzzi water (Kleinkopje Colliery, personal communication).

Date	Al^{3+} (mg l^{-1})	HCO$_3^-$ (mg l^{-1})	F$^-$ (mg l^{-1})	Ca^{2+} (mg l^{-1})	Cl$^-$ (mg l^{-1})	EC (mS m^{-1})	Fe^{2+} (mg l^{-1})	Mg^{2+} (mg l^{-1})	Mn^{2+} (mg l^{-1})	M. Alk (mg l^{-1})	P. Acid (mg l^{-1})	Na$^+$ (mg l^{-1})	SO$_4^{2-}$ (mg l^{-1})	TDS (mg l^{-1})	NO$_3^-$ as N (mg l^{-1})	Langelier saturation index	pH
15/08/1998	0.3	-	-	379.5	18	250	0.8	239.9	15.47	112	20	43.1	1952	3029	0.3	-0.59	6.5
19/08/1998	0.4	-	-	379.5	16	249	7	319.8	52.73	128	20	45.2	1970	2979	0.4	-0.63	6.4
26/08/1998	0.5	-	-	537.2	16	239	0.12	198.8	39.88	114	40	31.9	1904	2858	0.5	-0.52	6.4
09/09/1998	0.3	-	-	-	18	269	-	-	-	106	18	-	1901	2857	0.3	-	6.7
16/09/1998	1.2	-	-	500	18	268	0.01	166	7.19	96	24	27.6	1823	2838	1.2	-0.43	6.6
23/09/1998	0.5	-	-	-	12	301	-	-	-	84	30	-	1904	3278	0.5	-	6.2
30/09/1998	0.3	-	-	-	20	275	-	-	-	84	20	-	886	2930	0.3	-	6.6
07/10/1998	0.1	-	-	542.1	16	302	0.08	206.2	8.37	98	22	33.8	1934	2948	0.1	-1.09	5.9
14/10/1998	0.9	-	-	462	12	261	0.05	142.5	7.03	102	26	28	1916	2942	0.9	-0.84	6.2
21/10/1998	0.7	-	-	491.7	22	265	0.04	197.3	5.88	100	26	34.5	1901	2806	0.7	-0.71	6.3
28/10/1998	0.3	-	-	446.4	18	256	0.01	360.5	34.7	86	26	46.7	1939	2812	0.3	-0.92	6.2
04/11/1998	0.8	-	-	485.7	18	291	0.01	162.2	7.71	98	32	31	1867	2972	0.8	-0.84	6.2
11/11/1998	0.6	-	-	495.5	20	300	0.01	160.8	7.43	102	30	31.9	1939	2959	0.6	-0.61	6.4
25/11/1998	0.8	-	-	470.9	14	237	0.33	187.9	5.1	108	16	34.1	1746	2884	0.8	-0.6	6.4
02/12/1998	0.9	-	-	397.9	14	275	0.42	169.8	4.47	114	18	29.1	1885	3080	0.9	-0.07	7

Table A50 (continued). Results of chemical analysis for Jacuzzi water (Kleinkopje Colliery, personal communication).

Date	TDS (mg l^{-1})	Suspended solids (mg l^{-1})	NO_3^- as N (mg l^{-1})	Cl^- (mg l^{-1})	Total alkalinity as $CaCO_3$ (mg l^{-1})	F^- (mg l^{-1})	SO_4^{2-} (mg l^{-1})	Total hardness as $CaCO_3$ (mg l^{-1})	Ca hardness as $CaCO_3$ (mg l^{-1})	Mg hardness as $CaCO_3$ (mg l^{-1})	Ca^{2+} (mg l^{-1})	Mg^{2+} (mg l^{-1})
08/03/1999	-	-	-	-	-	-	1914	-	-	-	-	-
03/06/1999	-	-	-	-	-	-	1942	-	-	-	-	-
02/09/1999	2412	9.2	<0.1	14	68	0.91	1702	1803	1161	641	465	156
07/09/1999	2580	18	<0.1	12	66	0.94	1800	2670	1942	728	485	177
14/09/1999	2814	14.4	0.7	12	76	0.75	2024	2002	1204	798	482	194
28/09/1999	3040	23.2	0.6	18	76	1.05	1939	2180	1349	831	540	202
05/10/1999	2536	35.2	<0.1	45	10	0.97	1774	1986	1356	630	543	153
12/10/1999	2468	25.6	<0.1	16	70	0.66	1744	1787	1096	691	439	168
18/10/1999	2710	19.2	0.63	17	78	0.61	1879	1952	1141	811	457	197
26/10/1999	2726	24.4	<0.1	15	76	1	1888	2039	1171	868	469	211

Table A50 (continued). Results of chemical analysis for Jacuzzi water (Kleinkopje Colliery, personal communication).

Date	Na^+ (mg l^{-1})	K^+ (mg l^{-1})	Fe^{2+} (mg l^{-1})	Mn^{2+} (mg l^{-1})	EC (mS m^{-1})	pH	pH at 21 °C	Langelier saturation index	Turbidity as N.T.U.	Al^{3+} (mg l^{-1})	Total acidity as $CaCO_3$ to pH = 8.3
08/03/1999	-	-	-	-	285	7	-	-	-	-	-
03/06/1999	-	-	-	-	266	6.9	-	-	-	-	-
02/09/1999	28.6	9.96	2.96	4.72	325	6.45	7.39	-0.94	53	<0.01	16.8
07/09/1999	30.6	10.5	0.26	4.78	322	6.52	7.35	-0.84	39	<0.01	16.3
14/09/1999	47.3	10.9	0.65	4.44	342	6.62	7.38	-0.76	21	<0.01	6.2
28/09/1999	44	13.1	1.09	4.75	339	6.73	7.34	-0.61	14	0.01	13
05/10/1999	20.3	7.62	81.8	8.43	331	3.51	8.19	-4.68	191	0.19	116
12/10/1999	23.6	4.6	<0.01	3.93	342	6.96	7.44	-0.46	15	<0.01	10.7
18/10/1999	62.8	13.4	0.54	5.28	335	6.86	7.4	-0.54	23	<0.01	1.9
26/10/1999	34.2	8.16	2.69	6.41	327	6.44	7.37	-0.93	33	<0.01	15.2

Table A51. Results of chemical analysis for Tweefontein dam water (Kleinkopje Colliery, personal communication).

Date	Al^{3+} (mg l^{-1})	HCO_3^- (mg l^{-1})	Ca^{2+} (mg l^{-1})	Cl^- (mg l^{-1})	EC (mS m^{-1})	Fe^{2+} (mg l^{-1})	Mg^{2+} (mg l^{-1})	Mn^{2+} (mg l^{-1})	M. Alk (mg l^{-1})	P. Acid (mg l^{-1})	Na^+ (mg l^{-1})	SO_4^{2-} (mg l^{-1})	TDS (mg l^{-1})	Langelier saturation index	pH
22/12/1997	0.01	68	405.4	32	192	0.08	195.6	0.01	56	6	46.8	1493	-	-	6.5
05/03/1997	-	-	-	-	217	-	-	-	86	6	-	1434	-	-	7.5
03/05/1998	-	-	-	-	217	-	-	-	86	8	-	1434	-	-	7.5
26/05/1998	-	-	-	-	273	-	-	-	114	10	-	1644	-	-	7.2
07/07/1998	0.01	-	268.3	34	220	0.1	284.8	0.5	116	10	56.7	1678	-	0.01	7.2
30/09/1998	-	-	-	38	265	-	-	-	110	-	-	1730	-	-	8.6

Table A51 (continued). Results of chemical analysis for Tweefontein dam water (Kleinkopje Colliery, personal communication).

Date	TDS (mg l^{-1})	Suspended solids (mg l^{-1})	NO_3^- as N (mg l^{-1})	Cl^- (mg l^{-1})	Total alkalinity as $CaCO_3$ (mg l^{-1})	F^- (mg l^{-1})	SO_4^{2-} (mg l^{-1})	Total hardness as $CaCO_3$ (mg l^{-1})	Ca hardness as $CaCO_3$ (mg l^{-1})	Mg hardness as $CaCO_3$ (mg l^{-1})	Ca^{2+} (mg l^{-1})	Mg^{2+} (mg l^{-1})
13/01/1999	-	-	-	-	-	-	1753	-	-	-	-	-
08/03/1999	-	-	-	-	-	-	1885	-	-	-	-	-
03/06/1999	-	-	-	-	-	-	1872	-	-	-	-	-
02/09/1999	2508	8.8	1.03	36	88	0.96	1762	2018	1034	984	414	189
07/09/1999	2632	16.4	<0.1	39	94	1.16	1823	2037	1041	996	417	242
14/09/1999	2826	18.8	<0.1	35	90	0.86	2031	1981	1014	967	406	235
28/09/1999	3088	10	<0.1	82	94	1.02	1745	2159	1126	1033	451	251
05/10/1999	2580	12.8	0.1	41	88	1	1789	2149	1116	1033	447	251
12/10/1999	2742	10	<0.1	39	86	0.89	1827	2187	1179	1008	472	245
18/10/1999	2786	11.2	0.49	42	88	0.83	1894	2116	1124	992	450	241
26/10/1999	2858	16	<0.1	41	86	1.05	1929	2297	1239	1058	496	257

Table A51 (continued). Results of chemical analysis for Tweefontein dam water (Kleinkopje Colliery, personal communication).

Date	Na^+ (mg l^{-1})	K^+ (mg l^{-1})	Fe^{2+} (mg l^{-1})	Mn^{2+} (mg l^{-1})	EC (mS m^{-1})	pH	pH at 21 °C	Langelier saturation index	Turbidity as N.T.U.	Al^{3+} (mg l^{-1})	Total acidity as $CaCO_3$ to pH = 8.3
13/01/1999	-	-	-	-	275	7.8	-	-	-	-	-
08/03/1999	-	-	-	-	288.8	7.8	-	-	-	-	-
03/06/1999	-	-	-	-	304	8.2	-	-	-	-	-
02/09/1999	55.4	16.8	<0.01	0.11	342	8.56	7.35	+1.21	2.5	<0.01	0
07/09/1999	62.6	19.5	0.04	0.1	342	8.4	7.34	+1.06	2.3	<0.01	0
14/09/1999	58.3	19.4	<0.01	0.11	344	8.27	7.36	+0.91	2.7	<0.01	3.2
28/09/1999	61.9	23.4	<0.01	0.08	346	8.29	7.35	+0.94	2	<0.01	0.9
05/10/1999	60.2	22.4	0.39	0.22	353	8.32	7.36	+0.96	2.2	0.15	0
12/10/1999	55.7	16.3	<0.01	<0.01	355	8.34	7.3	+1.04	1.1	<0.01	0
18/10/1999	48.3	19.7	<0.01	0.05	352	8.36	7.39	+0.97	1.5	<0.01	0
26/10/1999	46.7	13.5	0.01	0.16	352	8.37	7.28	+1.09	1.5	0.01	0

Table A52. Results of chemical analysis for Jacuzzi water (Soil Science Laboratory, University of Pretoria).

Pivot	Date	pH	EC (mS m^{-1})	Ca^{2+} (mg l^{-1})	K^{+} (mg l^{-1})	Mg^{2+} (mg l^{-1})	Na^{+} (mg l^{-1})	HCO$_3^-$ (mg l^{-1})	Cl$^-$ (mg l^{-1})	SO$_4^{2-}$ (mg l^{-1})	NH$_4^+$ (mg l^{-1})	NO$_3^-$ (mg l^{-1})	Charge Balance (mmol$_c$ l^{-1})
Major	13/10/1998	-	291	210	9	146	30	94	5	2064	5	3	-20.397
	12/11/1998	7.39	261	316	9	144	16	-	-	2100	-	-	-15.178
Jacuzzi	13/10/1998	-	294	216	9	147	31	104	3	1844	1	5	-15.753
	12/11/1998	7.10	251	323	9	145	17	-	-	2275	-	-	-18.346

Table A53. Results of chemical analysis for Tweefontein dam water (Soil Science Laboratory, University of Pretoria).

Date	pH	EC (mS m^{-1})	Ca^{2+} (mg l^{-1})	K^{+} (mg l^{-1})	Mg^{2+} (mg l^{-1})	Na^{+} (mg l^{-1})	HCO$_3^-$ (mg l^{-1})	Cl$^-$ (mg l^{-1})	SO$_4^{2-}$ (mg l^{-1})	NH$_4^+$ (mg l^{-1})	NO$_3^-$ (mg l^{-1})	Charge Balance (mmol$_c$ l^{-1})
19/10/1998	-	280	180	2	162	38	-	-	1800	-	-	-13.459
12/11/1998	7.30	252	245	19	189	43	-	-	2182	-	-	-15.295

Table A54. Results from chemical analyses of water samples from the Jacuzzi dam.

SiteName	Date	pH	EC	Ca	Mg	Na	K	MALK	Cl	SO4	NO3-N	F	NO2-N
			mS/m	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
DAM	13-Jun-00	6.21	266	449	180	37	10.9	9.5	7.7	2001	2.31	0.54	0.060
DAM	14-Sep-99	7.68	278	524	192	33	10.6	53	9.0	2210	0.44	0.67	
DAM	15-Jul-99	5.71	272	561	185	26	8.8	9.0	7.8	2269	0.20	0.97	<0.01
Average		*6.53*	*272*	*511*	*186*	*32*	*10.1*	*24*	*8.2*	*2160*	*0.98*	*0.73*	*0.060*

SiteName	Date	PO4	Br	Al	Fe	Mn	Ag	As	B	Ba	Be	Cr	Cd
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
DAM	13-Jun-00	1.090		0.095	0.773	3.902			0.153	0.108		<0.01	<0.006
DAM	14-Sep-99			0.042	0.112	0.420			0.148	0.005			
DAM	15-Jul-99	<0.01	0.500	0.056	24.070	4.120	0.004	<0.015	0.114	0.028	<0.002	<0.01	<0.006
Average		*1.090*	*0.500*	*0.064*	*8.318*	*2.814*	*0.004*		*0.138*	*0.047*			

SiteName	Date	Co	Cu	Li	Mo	Ni	Pb	Sb	Se	Sr	Zn
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
DAM	13-Jun-00	0.027	0.048	0.091	<0.004	0.187	<0.025		0.013	2.480	
DAM	14-Sep-99	0.006	0.007	0.054		0.024				2.310	0.150
DAM	15-Jul-99	0.063	0.005	0.039	0.010	0.177	<0.025	<0.02	<0.02	2.610	0.209
Average		*0.032*	*0.020*	*0.061*	*0.010*	0.129			*0.013*	2.467	*0.179*

Table A55. *Summary of soil characterization tests performed.*

Descriptor	Depth (m)	Laboratory						In-situ		Date
		Tex.	Bulk Density	COC h(O)	B-K D(O)	Perm Ks	BTC C(t)	K(h)	Ks	
Pivot Major	0.00							y (35)		Jun-00
Major: Field Capacity	0.00		y	y				y	y	Mar-98
Major: Field Capacity	0.00		y (4)	y (4)						Jun-00
Major: Field Capacity	0.05		y	y				y	y	Mar-98
Major: Field Capacity	0.50		y (4)	y (4)						Jun-00
Major: Field Capacity	0.55							y	y	Jun-97, Mar-98
Major: Field Capacity	0.85		y	y	y			y	y	Jun-97, Mar-98
Major: Plinthite	1.80		y	y	y					
Major: Repacked topsoil			y			y	y (2)			Jun-99
Major: Repacked topsoil V3			y	y						Feb-99
Major: Repacked topsoil V2			y	y						Feb-99
Jacuzzi: Deficit	0.00		y	y	y			y	y	Mar-98
Jacuzzi: Deficit	0.15							y	y	Mar-98
Jacuzzi: Deficit	0.55							y	y	Mar-98
Jacuzzi: Deficit	0.85							y	y	Mar-98
Jacuzzi: Deficit - Spoil	1.20		y	y	y			y	y	Mar-98
Jacuzzi: Leach Fraction	0.00							y	y	Mar-98
Jacuzzi: Leach Fraction	0.15							y	y	Mar-98
Jacuzzi: Leach Fraction	0.85							y	y	Mar-98
Jacuzzi: Field Capacity	0.00		y	y	y			y		Jan-98
Jacuzzi: Field Capacity	0.05							y		Jan-98
Jacuzzi: Field Capacity	0.15							y	y	Jan-98
Jacuzzi: Field Capacity	Spoil		y	y						
Tweefontein: repacked topsoil						y	y (2)			Jun-99
Tweefontein FC	0.00		y	y				y	y	Jun-97, Mar-98
Tweefontein FC	0.10		y	y	y					Jun-00
Tweefontein FC	0.55		y	y				y	y	Mar-98
Tweefontein FC	0.75							y	y	Mar-98
Tweefontein FC	0.90		y	y						Jun-00
Tweefontein FC Spoil	1.20		y	y						Jun-00
Pivot Four: repacked topsoil						y	y(4)			Aug-99
Pivot Four: PF2	0.20		y			y				Jun-00
Pivot Four: PF3	1.60		y			y				Jun-00
Pivot Four: PF1	2.50		y			y				Jun-00
Pivot Four: PF1	3.80		y			y				Jun-00

Quantity in brackets indicates number of repetitions or samples analyzed

Table A56. Summary of soil characteristics data.

Descriptor	Depth (m)		Laboratory				In situ		
		Density (kg m^{-3}	Porosity (m^3 m^{-3})	DUL (m^3 m^{-3}	WP (m^3 m^{-3}	Ks (mm h^{-1}	Ks (mm h^{-1}	K(60) (mm h^{-1})	K(150) (mm h^{-1}
Pivot Major (Ave 35 reps)	0.00							12.60	7.20
Major: Field Capacity	0.00	1812	0.316	0.107	0.000		271.11	60.36	18.27
Major 1	0.00	1420	0.464	0.220	0.000			8.98	6.96
Major 2	0.00	1522	0.426	0.160	0.000			8.30	0.90
Major 3	0.00	1730	0.347	0.130	0.000			8.90	5.92
Major 4	0.00	1610	0.392	0.170	0.000			8.38	5.87
Major: Field Capacity	0.05	1728	0.348	0.235	0.000		116.47	31.64	1.83
Major 1	0.50	1763	0.335	0.260	0.000				
Major 2	0.50	1522	0.426	0.220	0.000				
Major 3	0.50	1421	0.464	0.185	0.000				
Major 4	0.50	1392	0.475	0.188	0.000				
Major: Field Capacity	0.55						583.59	20.72	6.38
Major: Field Capacity	0.85	1609	0.393	0.210	0.000			8.59	4.01
Major: Plinthite	1.80	1813	0.316	0.295	0.200				
Major: Repacked topsoil		*1500*	*0.434*			*27.70*			
Major: Gypsum treated topsoil	V2H1	1603	0.395	0.175	0.000				
Major: Gypsum treated topsoil	V1H3	1601	0.396	0.360	0.100				
Jacuzzi: Deficit	0.00	1558	0.412	0.218	0.130		71.70	34.43	23.58
Jacuzzi: Deficit	0.15						43.78	5.79	3.85
Jacuzzi: Deficit	0.55						6.84	3.44	3.33
Jacuzzi: Deficit	0.85						5.03	2.48	1.34
Jacuzzi: Deficit - Spoil	1.20	1765	0.334	0.312	0.000		0.91	4.94	1.46
Jacuzzi: Leach Fraction	0.00						8.36	1.96	0.09
Jacuzzi: Leach Fraction	0.15						5.14	5.26	0.60
Jacuzzi: Leach Fraction	0.85						3.22	8.14	0.68
Jacuzzi: Field Capacity	0.00	1346	0.492	0.260	0.000			4.96	0.32
Jacuzzi: Field Capacity	0.05							4.85	0.99
Jacuzzi: Field Capacity	0.15						3.16	22.01	1.46
Jacuzzi: Field Capacity	Spoil	2048	0.227	0.202	0.000				
Tweefontein repacked topsoil		1600	0.396			19.70			
Tweefontein FC	0.00	1410	0.467	0.250	0.000		91.98	12.42	1.70
Tweefontein FC	0.10	1783	0.327	0.157	0.000				
Tweefontein FC	0.55	1982	0.252	0.160	0.000		34.83	8.06	1.80
Tweefontein FC	0.75						13.80	3.05	1.62
Tweefontein FC Spoil	0.90	1760	0.336	0.330	0.000				
Tweefontein FC Spoil	1.20	1929	0.272	0.265	0.000				
Pivot Four	0.25								
Pivot Four repacked topsoil		1500				27.85			
Pivot Four Profile 2 repacked	0.20	1810				8.60			
Pivot Four Profile 1 repacked	2.50	1621				5.30			
Pivot Four Profile 1 repacked	3.80	1600				0.02			

Table A57. Van Genuchten soil hydraulic characteristic parameters.

Descriptor	Depth (m)	Model parameters					Rating
		THETAS ($m^3\ m^{-3}$)	THETAR ($m^3\ m^{-3}$)	ALPHA (mm^{-1})	n	Ks ($mm\ h^{-1}$)	
Major: Topsoil	0.00	0.318	0.000	0.0857	1.235		6
Major: Topsoil	0.05	0.341	0.000	0.0040	1.236		8
Major: Field Capacity	1.00	0.410	0.000	0.0052	1.361	1.32	5
Major: Plinthite	1.80	0.323	0.200	0.0008	1.971	0.40	5
Major 1	0.00	0.481	0.000	0.0081	1.433	8.98	8
Major 2	0.00	0.426	0.000	0.0083	1.434	8.30	7
Major 3	0.00	0.478	0.000	0.0026	1.373	8.90	8
Major 4	0.00	0.392	0.000	0.0034	1.579	8.38	7
Major 1	0.50	0.335	0.000	0.0030	1.232		8
Major 2	0.50	0.426	0.000	0.0087	1.319		9
Major 3	0.50	0.464	0.000	0.0395	1.268		7
Major 4	0.50	0.475	0.000	0.0446	1.345		9
Major: Gypsum treated topsoil	V2H1	0.395	0.000	0.0038	1.539		9
Major: Gypsum treated topsoil	V1H3	0.396	0.000	0.0007	1.509		8
Jacuzzi: Deficit	0.00	0.412	0.130	0.0035	2.467	71.70	8
Jacuzzi: Deficit - Spoil	1.20	0.224	0.000	0.0074	1.043	1.00	5
Jacuzzi: Field Capacity	0.00	0.554	0.000	0.0022	1.772	50.00	8
Tweefontein: Field Capacity	0.00	0.468	0.000	0.0038	1.336	138.00	7
Tweefontein FC	0.10	0.327	0.000	0.0187	1.236		9
Tweefontein FC	0.55	0.252	0.000	1.1500	1.132		9
Tweefontein FC Spoil	0.90	0.336	0.000	0.0001	1.252		9
Tweefontein FC Spoil	1.20	0.272	0.000	0.0000	1.436		9

The van Genuchten relationship for the soil water retention characteristic is:

$$Se = \left(\frac{1}{1+(\alpha h)^n}\right)^m$$

where

Se - Effective saturation, $\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)$, and
θ - Volumetric water content,
θ_r - Residual volumetric water content,
θ_s - Saturated volumetric water content,
α - Air entry parameter, (mm^{-1}),
h - Matric pressure head, (mm),
n - Pore size distribution parameter, and
m - Pore connectivity parameter and is taken as *1-1/n*.

The hydraulic conductivity function derived by substituting the van Genuchten retention characteristic into the Mualem conductivity model is written as:

$$K(h) = Ks\left[\frac{\left(1-(\alpha h)^{n-1}\left(1+(\alpha h)^{n}\right)^{-m}\right)^{2}}{\left(1+(\alpha h)^{n}\right)^{m/2}}\right]$$

where *K(h)* - Unsaturated hydraulic conductivity (mm h^{-1}) and
Ks - Saturated hydraulic conductivity (mm h^{-1})

Table A58. Brooks-Corey soil hydraulic characteristic parameters.

Descriptor	Depth (*m*)	Model parameters					Rating
		THETAS ($m^3\ m^{-3}$)	THETAR ($m^3\ m^{-3}$)	hd mm	Lamda	Ks ($mm\ h^{-1}$)	
Major: Topsoil	0.00	0.266	0.000	120.8	0.403		6
Major: Topsoil	0.05	0.337	0.000	147.1	0.189	1.32	9
Major: Field Capacity	1.00	0.410	0.000	167.2	0.332	0.41	5
Major: Plinthite	1.80	0.382	0.000	480.8	0.377	8.98	8
Major 1	0.00	0.464	0.000	92.7	0.403	8.30	8
Major 2	0.00	0.426	0.000	80.2	0.370	8.90	7
Major 3	0.00	0.347	0.000	95.2	0.511	8.36	8
Major 4	0.00	0.392	0.000	212.8	0.519		7
Major 1	0.50	0.335	0.000	167.5	0.180		8
Major 2	0.50	0.426	0.000	59.0	0.261		9
Major 3	0.50	0.464	0.000	33.5	0.293		7
Major 4	0.50	0.475	0.000	16.0	0.318		9
Major: Gypsum treated topsoil	V2H1	0.395	0.000	212.3	0.498		9
Major: Gypsum treated topsoil	V1H3	0.396	0.000	714.3	0.342		8
Jacuzzi: Deficit	0.00	0.412	0.065	114.7	0.390	71.70	8
Jacuzzi: Deficit - Spoil	1.20	0.318	0.180	144.9	1.018	1.00	7
Jacuzzi: Field Capacity	0.00	0.554	0.000	200.0	0.509	184.00	8
Tweefontein: Field Capacity	0.00	0.466	0.000	185.2	0.334	35.80	8
Tweefontein FC	0.10	0.327	0.000	44.2	0.227		9
Tweefontein FC	0.55	0.252	0.000	0.8	0.131		9
Tweefontein FC Spoil	0.90	0.336	0.000	2040.8	0.113		9
Tweefontein FC Spoil	1.20	0.272	0.000	2083.3	0.118		9

The Brooks-Corey function for the soil water retention characteristic is written as:

$Se = (h_d/h)^{\lambda}$ for $h > h_d$ and

$Se = 1$ for $0 < h < h_d$

where h_d - Air entry pressure (mm), and
λ - Pore size distribution parameter.

The Brooks-Corey retention characteristic, applied to the Burdine model of hydraulic conductivity yields:

$$K(h) = Ks\,[Se]^{(2+3\lambda)/\lambda}$$

Table A59. Campbell soil hydraulic characteristic parameters.

Descriptor	Model parameters						Rating
	Depth (m)	THETAR ($m^3 m^{-3}$)	he (mm)	hi (mm)	b	Ks ($mm h^{-1}$)	
Major: Topsoil	0.00	0.266					
Major: Topsoil	0.05	0.337					
Major: Field Capacity	1.00	0.410	30.0	48.3	5.0	1.3	7
Major: Plinthite	1.80	0.382	520.0	842.8	7.0	0.4	8
Major 1	0.00	0.464	180.0	281.3	2.0	8.9	8
Major 2	0.00	0.426	25.0	40.0	4.0	8.3	7
Major 3	0.00	0.347	25.0	39.6	2.8	8.9	8
Major 4	0.00	0.392	24.0	38.4	4.0	8.3	7
Major 1	0.50	0.335	180.0	289.9	5.0		8
Major 2	0.50	0.426	30.0	48.2	4.5		9
Major 3	0.50	0.464	10.0	16.1	4.5		7
Major 4	0.50	0.475	20.0	31.8	3.0		9
Major: Gypsum treated topsoil	V2H1	0.395	120.0	188.0	2.1		9
Major: Gypsum treated topsoil	V1H3	0.396	380.0	605.0	3.3		9
Jacuzzi: Deficit	0.00	0.412	35.0	56.4	5.0	71.7	9
Jacuzzi: Deficit - Spoil	1.20	0.318				1.	
Jacuzzi: Field Capacity	0.00	0.554	35.0	56.4	5.0	184.0	8
Tweefontein: Field Capacity	0.00	0.466	40.0	64.4	5.0	35.8	8
Tweefontein FC	0.10	0.327	90.0	143.5	3.4		9
Tweefontein FC	0.55	0.252	20.0	32.0	4.0		9
Tweefontein FC Spoil	0.90	0.336	1400.0	2273.8	8.0		9
Tweefontein FC Spoil	1.20	0.272	1300.0	2111.4	8.0		9

The Campbell function for the soil water retention characteristic comprises two functions:

$(\theta/\theta_s) = (h_e/h)^{1/b}$ for $h > h_i$

where h_e	-	Campbell air entry parameter (mm),
b	-	Campbell pore size distribution parameter, and
h_i	-	Inflection point where the equation changes from exponential to quadratic.

$\theta = \theta_s(1 - c\,h^2)$ for $0 < h < h_i$,

Many researchers relate the inflection point (h_i) to the pore size distribution parameter (b) and air entry parameter (h_e), via:

$$h_i = h_e/a^b \qquad c = (1-a)/h_i^2 \qquad a = 2b/(1+2b)$$

The Campbell hydraulic conductivity function is:

$K(h) = Ks(\theta/\theta_s)^{b.\eta}$

where η is fitted directly to the hydraulic conductivity data.

Appendix B

Automated tensiometers

Automated tensiometer nests, comprising a logger and three or four tensiometers were installed at different depths, in the centre of each irrigation application rate zone on each of the pivots. The records were used initially to determine the direction and magnitude of the hydraulic gradients and ultimately to verify detailed modelling of the liquid fluxes.

A four-channel logger was developed to record signals from differential pressure transducers attached to tensiometers as shown in Figure B1. The automatic tensiometer housed the water phase in a hydraulic hose, which was protected using PVC conduit. Hydraulic hose fittings sealed the water phase and provided a convenient connection to the differential pressure transducer pressure port. The high pressure port was left open to the atmosphere. A section of clear hydraulic hose was used to connect the pressure transducer low pressure port to the main hose. This allowed for inspection of air pockets in the upper part of the tensiometer. The components were all modular, which allowed for convenient assembly in the field to lengths determined *in-situ*. After careful installation, the depths D1 and D2 (Figure B1) had to be recorded for later resolution of the data. A 6V battery provided the excitation signal to the differential pressure transducer and the response, reflecting the difference between the ambient air pressure and the negative water pressure in the tensiometer, was transmitted to the logger at 12 min intervals. The logger and battery were housed in the weatherproof case on a stand above the ground.

The soil matric pressure head, h_m, was taken as the difference between the ambient air pressure and the negative water pressure (or suction) at the depth D2 below the surface. As the ambient air pressure was taken as the reference zero pressure, the matric pressure head was expressed as a positive quantity. The soil matric pressure head was determined from the recorded differential pressure head, h_{dp}, from :

$$h_m = h_{dp} - D1$$

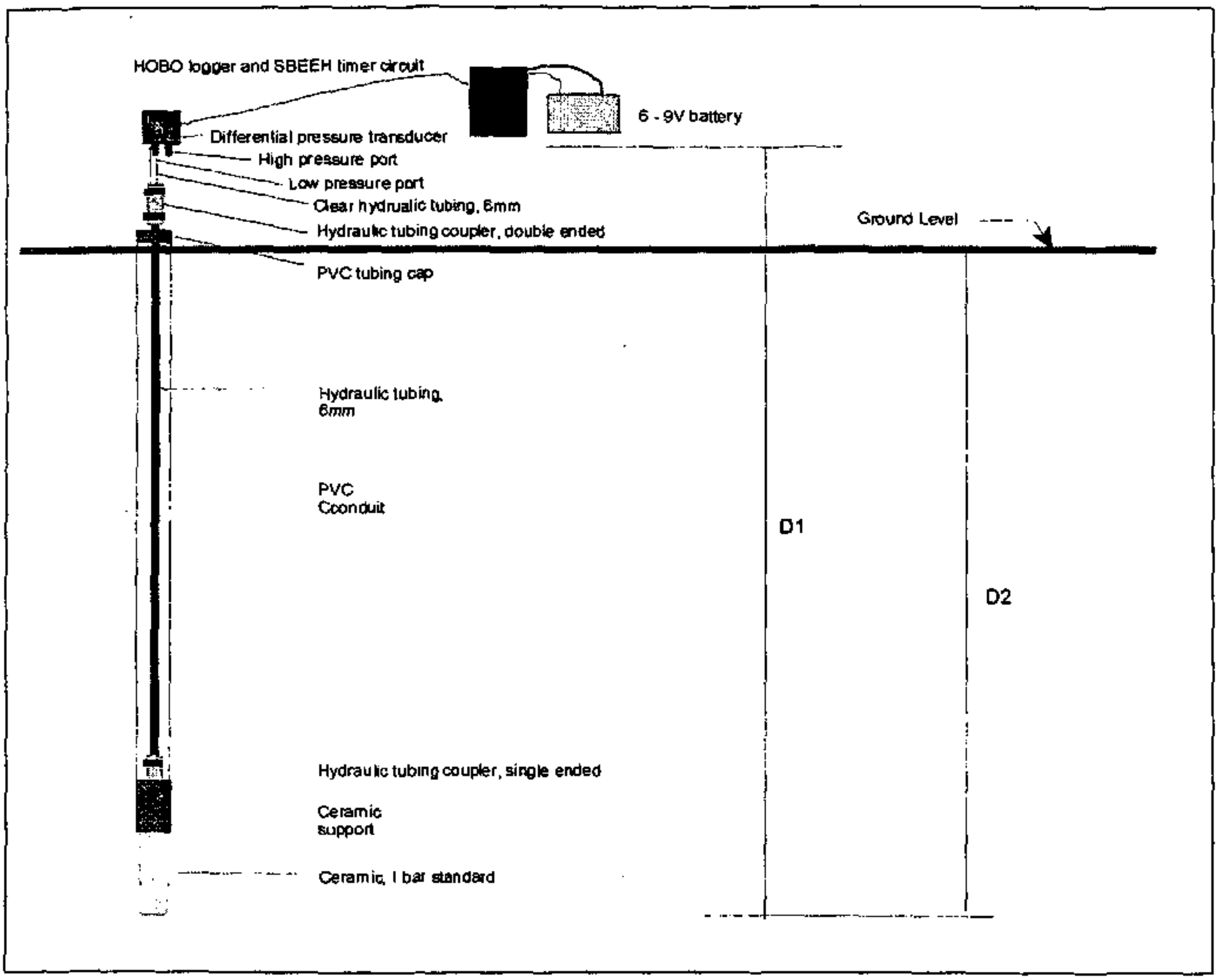


Figure B1. Schematic view of automated tensiometer and logging system for recording soil matric pressure head (three or four tensiometers were installed at each intensive monitoring site).

Appendix C

Methods for characterization of soil material

Bulk density

The material dry bulk densities were determined by a variety of methods. Where the materials were soft enough, undisturbed cores were taken after the *in situ* hydraulic conductivity measurements. Where the materials were unstructured, disturbed samples were excavated from cylindrical holes of measured volume and where stiff material was difficult to excavate, solid undisturbed bulk samples of irregular shape were taken and bulk densities measured by an Archimedes principle, wax coating method.

Hydraulic characteristics

The hydraulic characteristics determined for the soils and disturbed materials comprised:

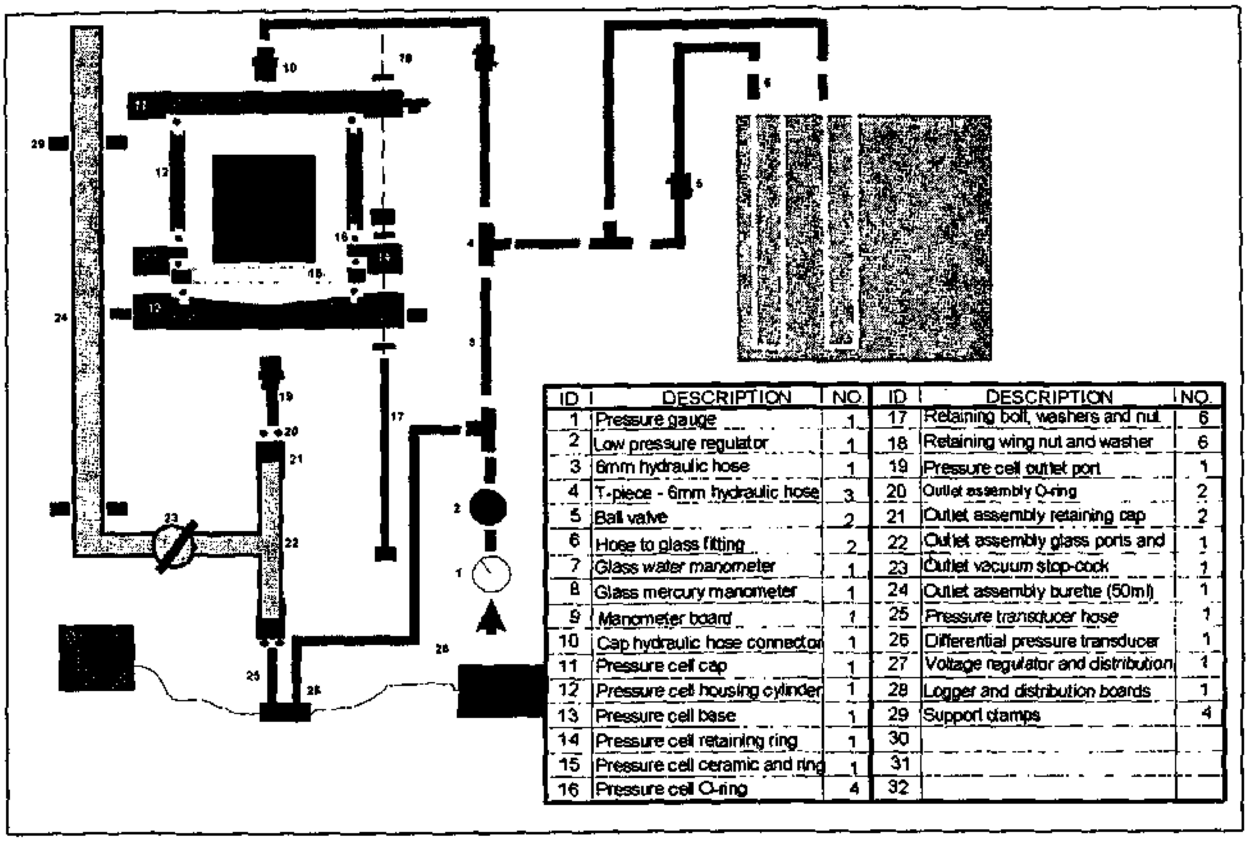
i) Laboratory determinations of water retention characteristics;
ii) Laboratory determinations of saturated and unsaturated hydraulic conductivity; and
iii) *In situ* determinations of saturated and unsaturated hydraulic conductivity.

Water retention characteristics

Conventional methods for determining soil water retention characteristics include both laboratory and field techniques (Klute, 1986; Bruce and Luxmore, 1986). Although many of the standard laboratory techniques have been used to determine the water retention characteristics of the porous media in this study, a controlled outflow method is reported in detail. This method holds some promise for the accurate characterization of the soil pore structure over the range of moisture contents close to saturation and up to a matric pressure head of 1 bar. Accurate measurements over this range are desirable in order to characterize the large pores, which may conduct water rapidly during irrigation and intense rainfall. The retention characteristics of undisturbed samples are used together with *in situ* measurements of both saturated and unsaturated conductivity to define the possible macro-pore nature of the material and to evaluate changes in pore structure due to precipitation of gypsum.

The controlled outflow method used in this study is a new methodology for defining the liquid retention characteristic of porous media. In this method each point on the characteristic curve is determined by monitoring equilibration of the matric pressure rather than equilibration of the liquid volumetric content, as in conventional methods.

Monitoring the matric pressure allows for control of the volume of outflow rather than allowing the outflow to continue until equilibrium is reached. By observing the matric pressure during the equilibration cycle, the operator is able to discern the time at which equilibrium occurs. This results in a considerable time saving in running the test. A controlled outflow cell has been developed to measure the water retention characteristics of porous media, specifically over the range 0 to 1 bar. The apparatus, shown in Figure C1, includes a data logging system to record and display the progress towards equilibration of the matric pressure at each setting.



ID	DESCRIPTION	NO.	ID	DESCRIPTION	NO.
1	Pressure gauge	1	17	Retaining bolt, washers and nut	6
2	Low pressure regulator	1	18	Retaining wing nut and washer	6
3	6mm hydraulic hose	1	19	Pressure cell outlet port	1
4	T-piece - 6mm hydraulic hose	3	20	Outlet assembly O-ring	2
5	Ball valve	2	21	Outlet assembly retaining cap	2
6	Hose to glass fitting	2	22	Outlet assembly glass ports and	1
7	Glass water manometer	1	23	Outlet vacuum stop-cock	1
8	Glass mercury manometer	1	24	Outlet assembly burette (50ml)	1
9	Manometer board	1	25	Pressure transducer hose	1
10	Cap hydraulic hose connector	1	26	Differential pressure transducer	1
11	Pressure cell cap	1	27	Voltage regulator and distribution	1
12	Pressure cell housing cylinder	1	28	Logger and distribution boards	1
13	Pressure cell base	1	29	Support clamps	4
14	Pressure cell retaining ring	1	30		
15	Pressure cell ceramic and ring	1	31		
16	Pressure cell O-ring	4	32		

Figure C1. Schematic layout of the controlled outflow cell apparatus for determination of the water retention characteristic of undisturbed and packed samples.

Air pressure is applied to the cell and a predetermined quantity of liquid allowed to drain via the open stopcock. This comprises the drainage phase and is recorded by the pressure transducer as the difference between applied air pressure and head of the liquid phase in the burette. The stopcock is then closed and the pore liquid pressure increases until it is in equilibrium with the applied air pressure and the capillary forces retaining the liquid in the porous medium. This comprises the equilibration phase and is recorded by the pressure transducer as the difference between applied air pressure and the pore water pressure in the sample. This difference in pressures decreases gradually as the pore liquid pressure increases, until it reaches an equilibrium, steady state value. This final difference in air and water pressure is the matric pressure related to the water content at that stage of the measurement. After the sample has been drained to an air pressure of 1 bar, the sample is removed and the volumetric water content determined. The water contents associated with each of the final equilibrium stages of the test can then be calculated from the incremental volume of outflow, recorded in the burette.

Saturated hydraulic conductivity (laboratory)

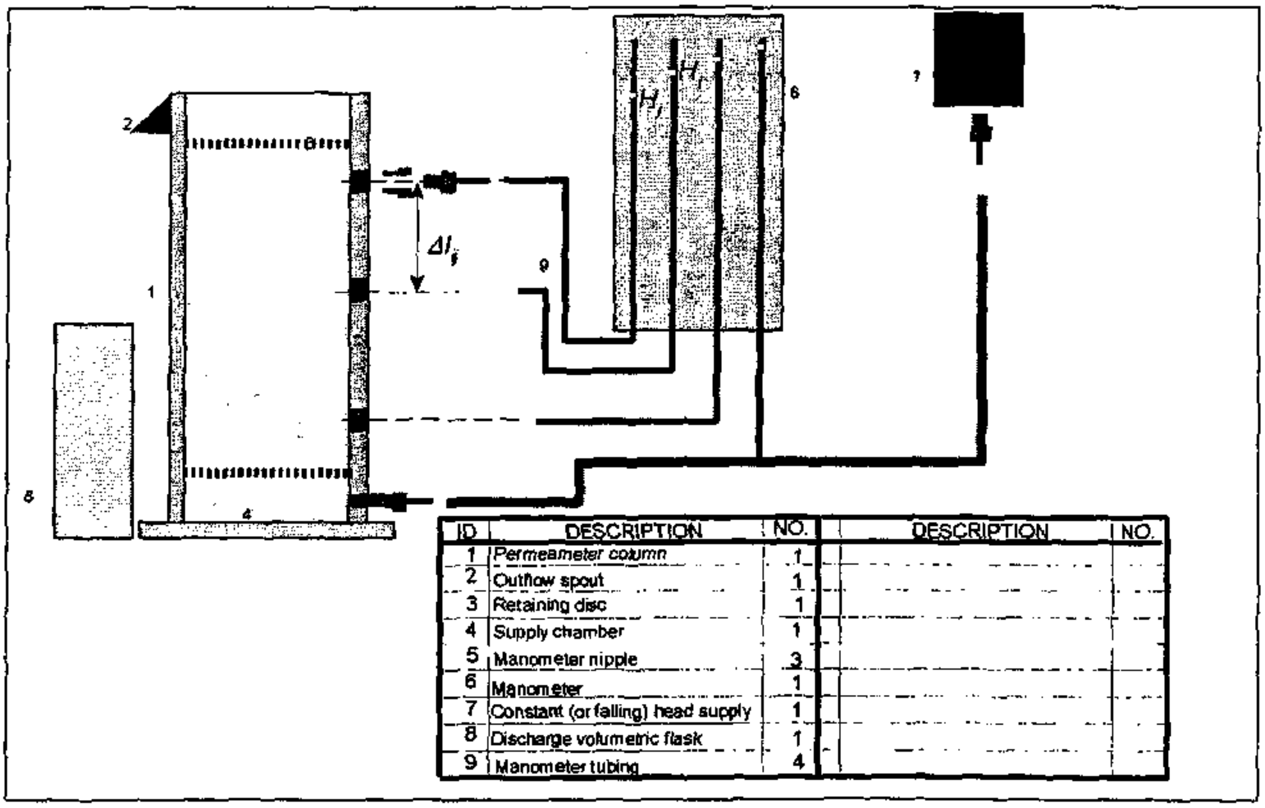
Saturated hydraulic conductivity is measured by means of a permeameter (Figure C2), by applying Darcy's Law across the permeameter pressure ports. The pressure gradient across each set of ports, including the gradient across the inlet and first manometer port, should be used in a separate determination of the hydraulic conductivity.

Darcy's Law is used in the form:

$$Ks_{ij} = \left(\frac{\Delta l_{ij}}{H_i - H_j}\right)\left(\frac{Q}{A}\right)$$

where

Ks_{ij} - Saturated hydraulic conductivity of material between port i and j,
Δl_{ij} - Length of porous medium between ports i and j,
$H_{i\,or\,j}$ - Total hydraulic head at port i or j,
Q - Volumetric outflow rate and
A - Total cross sectional area of the column.

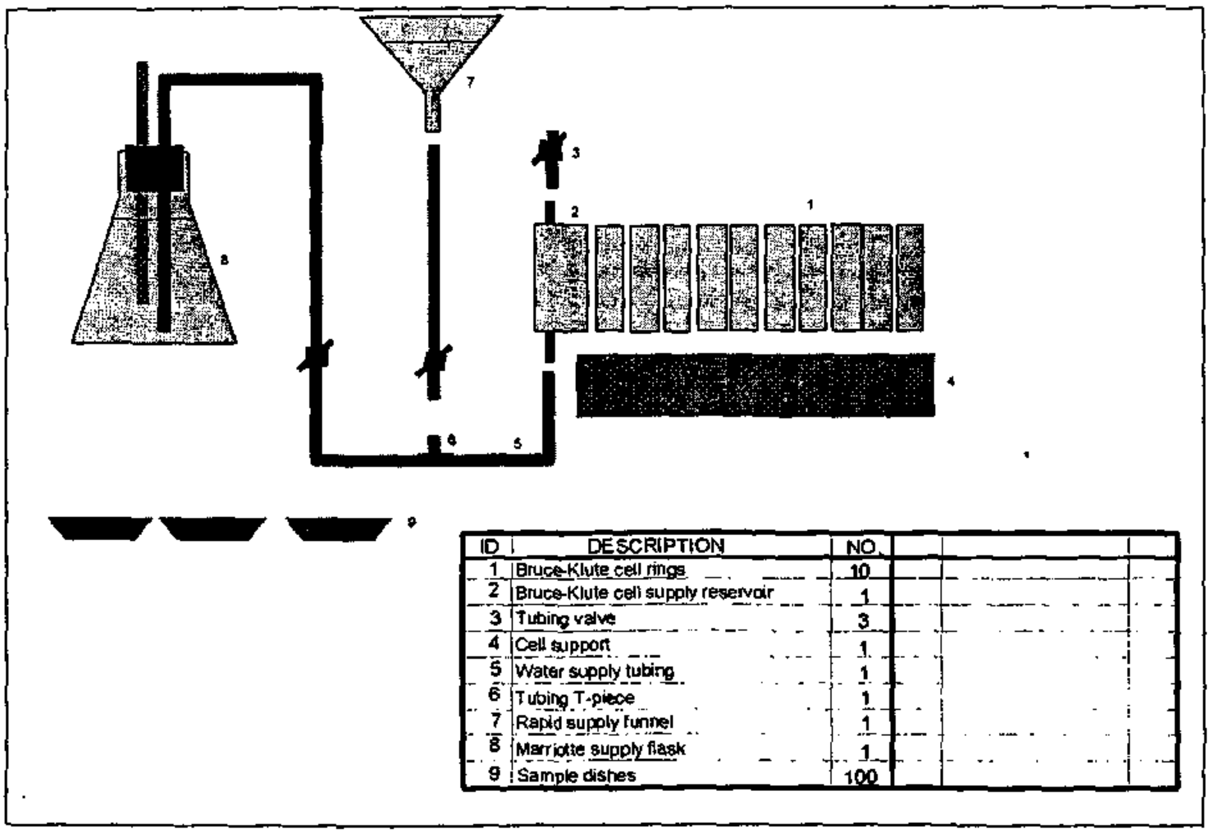


ID	DESCRIPTION	NO.	DESCRIPTION	NO.
1	Permeameter column	1		
2	Outflow spout	1		
3	Retaining disc	1		
4	Supply chamber	1		
5	Manometer nipple	3		
6	Manometer	1		
7	Constant (or falling) head supply	1		
8	Discharge volumetric flask	1		
9	Manometer tubing	4		

Figure C2. Constant head permeameter for measuring saturated hydraulic conductivity.

Unsaturated hydraulic conductivity (laboratory)

The unsaturated hydraulic conductivity of porous media varies significantly with the liquid content or matric pressure head. Hence the characterization of the unsaturated hydraulic conductivity requires a set of measurements or the fitting of an assumed relationship for the characteristic to test data. Direct methods for measuring the unsaturated hydraulic conductivity characteristic are rare and difficult to perform. Indirect methods are generally used to estimate the characteristic via a simpler test and an assumed relationship for the characteristic. One such simple method is the Bruce-Klute diffusivity test. In the Bruce-Klute cell method an instantaneous front of water is introduced to a sample packed or contained in a series of separate rings, held together temporarily for the duration of the test. The wetting front is allowed to diffuse into the sample at a constant head, held at the level of the sample inlet by a marriotte tube supply flask (Figure C3). Before the front reaches the last of the sample rings, the source is removed and the sample rapidly sectioned into the individual rings.



ID	DESCRIPTION	NO.			
1	Bruce-Klute cell rings	10			
2	Bruce-Klute cell supply reservoir	1			
3	Tubing valve	3			
4	Cell support	1			
5	Water supply tubing	1			
6	Tubing T-piece	1			
7	Rapid supply funnel	1			
8	Marriotte supply flask	1			
9	Sample dishes	100			

Figure C3. Schematic of the Bruce-Klute diffusivity cell assembly.

The volumetric water content, θ, of the sample in each of the rings is determined and plotted against the distance from the source in terms of the Boltzman variable, $\theta_B = l.t^{-0.5}$, where l is the distance from the inlet to the point of determination of the water content and t is the duration of the imbibition. This allows a theoretical curve to be fitted to the data (Clothier et al., 1983).

$$\lambda_B(\theta) = \frac{(p+1)S}{\theta_s - \theta_r}\left[1 - \frac{\theta_s - \theta_r}{\theta_s - \theta_r}\right]^p$$

where

p - A curve fitting parameter,
S - Sorptivity, calculated by integrating the area under the imbibition curve (θ versus θ_B),
θ_r - Residual water content and
θ_s - Saturated water content.

Once the sorptivity and parameter, *p*, have been established from the data, the diffusivity, *D*, is calculated from

$$D(\theta) = p(p+1)S^2\left[\frac{(1-\theta)^{p-1} - (1-\theta)^{2p}}{2(\theta_s - \theta_r)^2}\right]$$

If the retention characteristic (matric pressure head, h versus volumetric water content, θ) has been determined separately for the sample, the unsaturated hydraulic conductivity, $K(\theta)$, can then be determined for the material since diffusivity and conductivity are related via the slope of the retention characteristic as

$$K(\theta) = \frac{D(\theta)}{dh/d\theta}$$

Saturated hydraulic conductivity (in situ)

The saturated *in situ* hydraulic conductivity is determined by a ponded test known as the double ring infiltrometer. Here the steady state infiltration rate from a central ring is determined while maintaining an outer source of water at the same ponded head. The apparatus is shown in Figure C4.

Unsaturated hydraulic conductivity (in situ)

The unsaturated hydraulic conductivity is determined in the field by means of a tension infiltrometer. This method requires maintaining a tension in the water supply and recording the steady state inflow rate at different tension settings. The tension infiltrometer is shown in Figure C4.

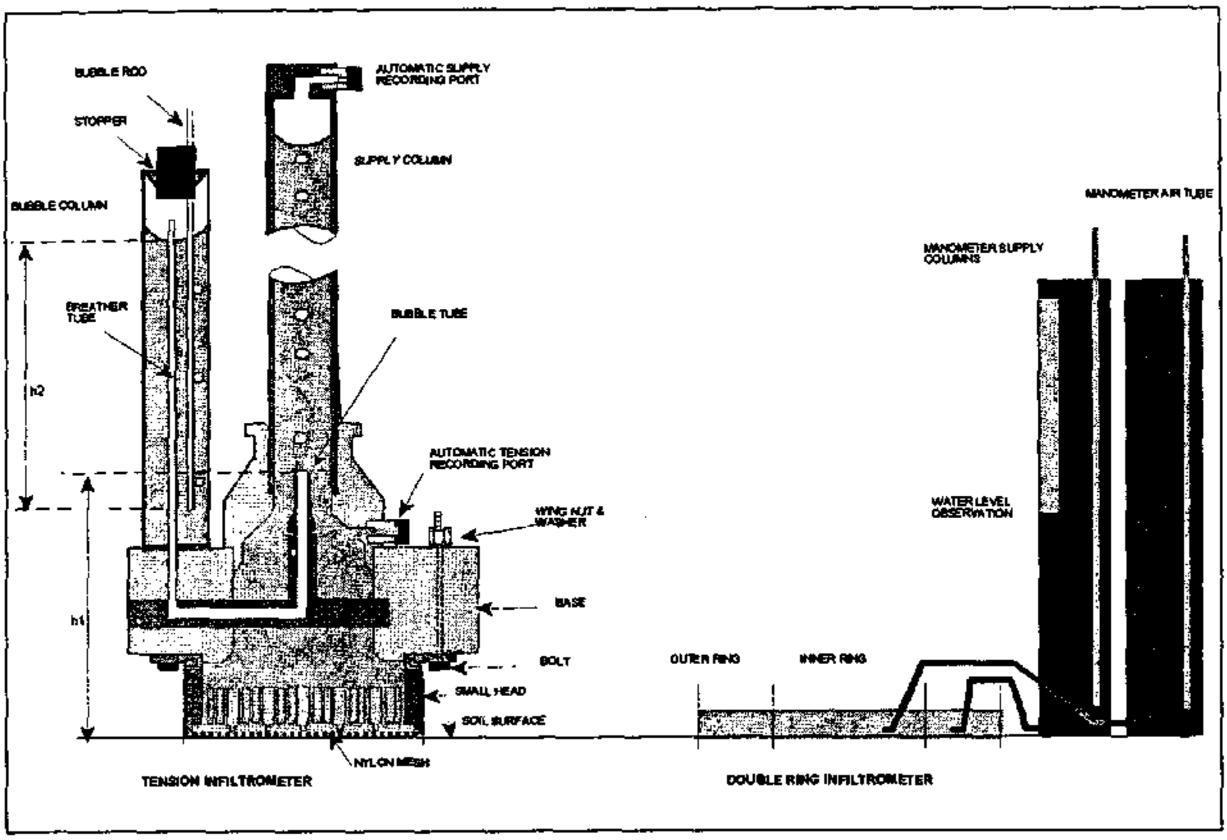
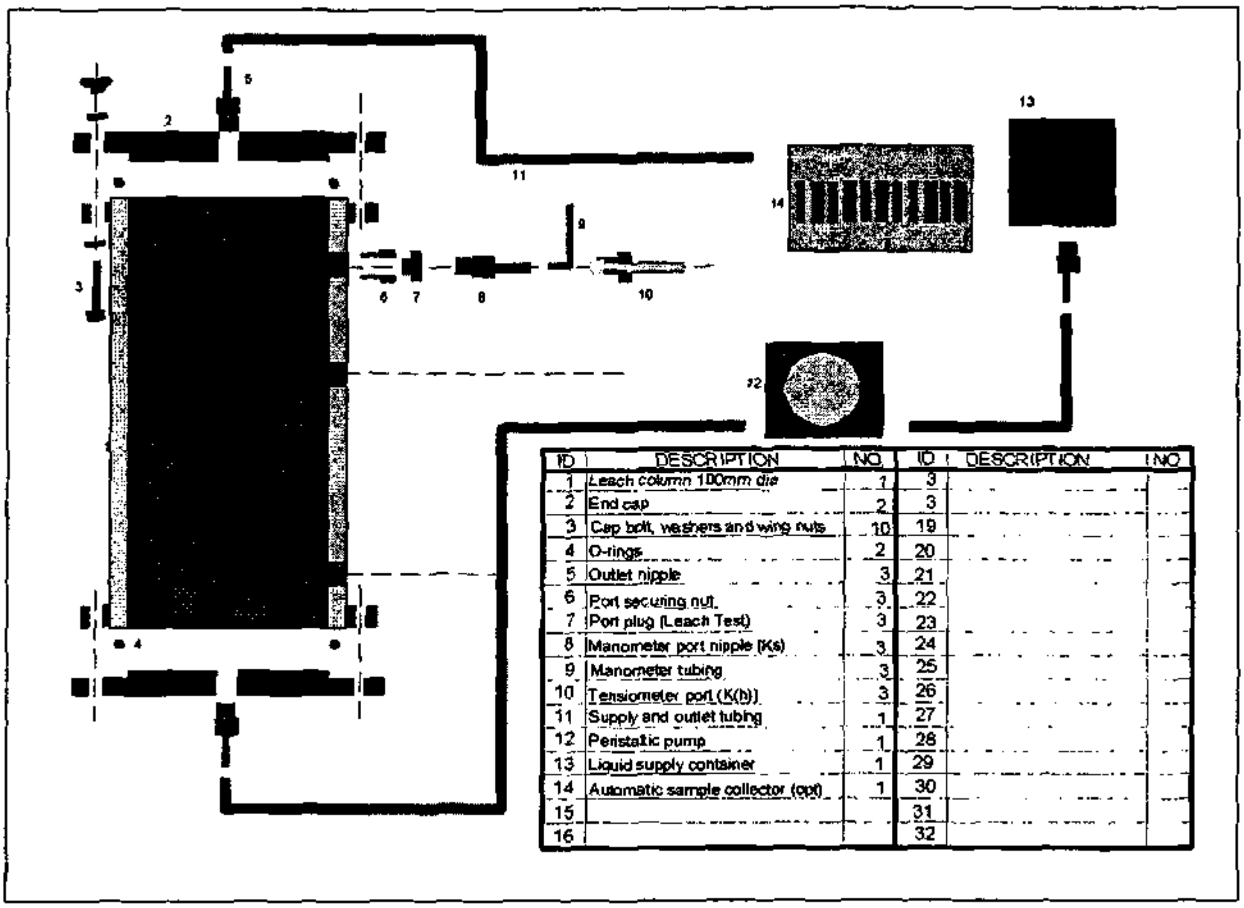


Figure C4. Schematic views of the tension (left) and double ring (right) infiltrometers.

Solute transport characteristics

In addition to the soil hydraulic characteristics, the solute transport characteristics of the porous media have also been investigated in this study. These are determined by evaluating the breakthrough characteristics from an equilibrated soluble mass leach column. The apparatus is shown in Figure C5. The column is packed with a material, wetted to a pre-determined water content. The liquid and material are allowed to equilibrate over a 24 h period before the introduction of an invading liquid. In order to simulate typical chemical processes and rate transfers in the profiles, samples were prepared using a saturated gypsum and chloride salt solution as the initial liquid. The invading liquid was distilled water and samples of the outflow solution were collected with an automatic sampler and analysed to define the breakthrough characteristic of certain species. The breakthrough of calcium and sulphates ions was determined and compared with the breakthrough of the conservative chloride ion, which acted as a tracer. The mathematical solution to the solute transport process was fitted to each of the observed breakthrough characteristics to yield the solute transport parameters.

The apparatus, shown in Figure C5, has been designed to include for piezometric and tensiometric porting on the sides so that saturated and unsaturated hydraulic conductivities can be estimated during the leach test.



ID	DESCRIPTION	NO.	ID	DESCRIPTION	NO
1	Leach column 100mm dia	1	3		
2	End cap	2	3		
3	Cap bolt, washers and wing nuts	10	19		
4	O-rings	2	20		
5	Outlet nipple	3	21		
6	Port securing nut	3	22		
7	Port plug (Leach Test)	3	23		
8	Manometer port nipple (Ks)	3	24		
9	Manometer tubing	3	25		
10	Tensiometer port (K(h))	3	26		
11	Supply and outlet tubing	1	27		
12	Peristaltic pump	1	28		
13	Liquid supply container	1	29		
14	Automatic sample collector (opt)	1	30		
15			31		
16			32		

Figure C5. Schematic view of the equilibrated soluble mass column leach test apparatus.

Appendix D

Methods of measurement of gypsum precipitated in the soil (Soil Science Laboratory, University of Pretoria)

In this Appendix of the report, an overview of the methods to determine gypsum precipitated in the soil is given. The following methods were considered:

- ***The method of Bower and Huss (1948)***

A suitable amount of soil is shaken with deionised water (usually 1:5 soil to water ratio) for 30 min. The sample is then centrifuged, filtrated and a 20 ml aliquot is taken from the supernatant liquid and the EC is then determined. Soil gypsum content is then determined by reference to a graph correlating the relationship between increase in gypsum concentration in water up to saturation, and EC of these gypsum solutions at 25°C.

However, this method must be repeated with a wider soil to solution ratio, if the gypsum concentration approaches the saturation level of the particular volume of water chosen. This procedure must be repeated until the gypsum concentration in solution is well below the gypsum saturation level of chosen volume of water (Bower and Huss, 1948).

Drawbacks of this method
This method becomes time consuming and impractical if the gypsum concentration of a large amount of samples must be determined. Furthermore, because of the presence (or potential presence) of other salts, like $MgSO_4$ and $NaSO_4$, it is erroneous to assume that the EC of the soil solution is solely the result of gypsum in solution. This problem might influence the accuracy of this method.

- ***Method of U.S. Soil Conservation Service (1972)***

In this method, gypsum is extracted with successively wider soil to solution ratios, similar to the method of Bower and Huss (1948). The difference between the method of Bower and Huss (1948) and this method is that the sulphate concentration in the solution is determined (instead of EC) of each successively wider soil to solution ratios until the sulphate concentration in solution becomes constant which means all the gypsum is dissolved. The sulphate concentration in solution is determined according to the conventional gravimetric $BaSO_4$ procedure described in U.S. Salinity Laboratory Staff, 1954, method 14a (U.S. Soil Conservation Service, 1972; Nelson et al., 1978).

Drawbacks of this method
Sulphates of sources other than gypsum will influence the accuracy of this method. The biggest drawback of this method can be the cost. To determine the gypsum concentration of a single soil sample, two, three and most often more sulphate determinations must be made. At a cost of R15 per sulphate determination this method can become significantly more expensive than the previous method if the gypsum concentration of a large amount of samples must be determined. Furthermore, this method can be time consuming and impractical, if the gypsum content of a large amount of samples must be determined.

- ***Method of Frenkel, Gerstl, Renger and van de Veen (1986)***

Frenkel et al. (1986) used Na- and Cl-resin, which act as a gypsum sink by adsorbing the gypsum in solution. The resin decreases the gypsum concentration in solution, which increases dissolution of precipitated gypsum. The increase in NaCl concentration in solution (because of the displacement of Na^+ and Cl^- by Ca^{2+} and SO_4^{2-} respectively), also increases the gypsum saturation point of the water. Keren and Shainberg (1980) found that the solubility of gypsum in a 0.1N NaCl solution is 1.5 times higher than in deionised water. The method of Frenkel et al. (1986) solved the problem to find the right soil to solution ratio to dissolve all the gypsum because the volume of water used in this method doesn't matter as long as there is enough Na-and Cl-resins to adsorb all the gypsum and to keep the gypsum in solution low enough to cause dissolution of precipitated gypsum.

The samples with resin are shaken for 48 hours, centrifuged, filtrated and EC of the supernatant liquid is determined. The soil gypsum content is determined by reference to a graph correlating the relationship between the difference of the EC of a sample with and without resin (ΔEC between solution with and without NaCl) and the increase in amount of gypsum applied to a certain soil.

Drawbacks of this method

According to Frenkel et al. (1986), the correlation between ΔEC and amount of gypsum applied should be constant for all soils after the interference of background electrolyte is eliminated. However, in a preliminary trial it was found (after the interference of background electrolyte is eliminated) that this relation between ΔEC and amount of gypsum applied differs from soil to soil. This difference is especially significant between clayey (in this study a 2:1 swelling clay was used) and sandy soils.

To accurately determine the gypsum content of a sample, a standard series must be made for every single sample before the gypsum content of the sample can be determined. This method can also be time consuming and impractical, if the gypsum content of a large amount of samples must be determined. The other problem is the determination of the amount of resin that will be sufficient to extract all gypsum.

- **Method of Nelson (1982)**

Nelson (1982) overcame the time consuming trial and error determination to find the right soil to solution ratio, by using the crystal water loss method originally described by Nelson et al. (1978) to estimate the amount of gypsum in the soil and the right soil to solution ratio that will be sufficient to dissolve all the gypsum in the soil. The gypsum content is then determined by analysing sulphate concentration in solution according to the gravimetric $BaSO_4$ procedure (U.S. Salinity Laboratory Staff, 1954). The principle of the method of Nelson et al. (1978), is that when a sample is oven dried for 24 hours at 105°C, gypsum loses its two molecules of crystal water, whereupon the crystal water stays intact if the sample is air dried for 48 hours. The mass difference between oven drying and air drying a sample can thus be attributed to the loss of the crystal water of gypsum (Nelson et al., 1978). The gypsum content of the sample is then determined with the mass of the crystal water to total mass of a gypsum molecule ratio.

Drawbacks of this method

Nelson et al. (1978) recommended this method only for taxonomic uses, while Nelson (1982) used the crystal water loss method only to determine the soil to solution ratio. This is despite the fact that Nelson et al. (1978) found a good correlation ($r^2 = 0.999$) between gypsum content determined with the crystal water loss method and gypsum content determined by analysing sulphate concentration in solution. The biggest drawback of the crystal water loss method is how to correct for dehydration of the sample that is not a result of crystal water loss of gypsum upon oven drying. Using the crystal water loss method, it takes three days just to estimate the amount of water necessary to dissolve all the gypsum in the sample.

- **Adapted Dilution Method (ADM)**

This method is a modification to the methods of Bower and Huss (1948) and the U.S. Soil Conservation Service (1972). The following procedure is applied to measure precipitated gypsum in soil samples:

1. 5 g to 10 g soil samples are placed in screw top bottles, and 100 cm^3 of deionised water is added.
2. The samples are shaken for 12 h to dissolve all the gypsum.
3. After the 12 h shaking period, the EC of the soil solution of each sample is determined. According to the literature, the EC of a saturated gypsum solution varies between 190 mS m^{-1} and 235 mS m^{-1} (Shainberg et al., 1989). If the EC of the soil solution approaches 190 mS m^{-1}, another 100 cm^{-3} is added and step (2) and (3) are repeated until the EC is well below 190 mS m^{-1}. This is done to ensure that all gypsum dissolved. The EC is determined in the bottles, to make sure no solution is lost. The exact amount of water used has to be known to calculate the gypsum concentration.
4. The SO_4^{2-} concentration in solution is determined after all gypsum is dissolved.
5. The SO_4^{2-} concentration in saturated paste extracts with deionised water is also determined for the same soil samples.
6. The difference between the total dissolved sulphate and sulphate in the saturated paste extract represents precipitated sulphate salts. Due to the low solubility of gypsum compared to magnesium sulphate, this difference originates predominantly from precipitated gypsum.

Appendix E

Calculation of the gypsum saturation index as a method for detecting gypsum in soils, and a preliminary study of sulphate adsorption in soils irrigated with saline mine water at Kleinkopje Colliery

(Dept. of Geology, University of Cape Town)

Gypsum detection in irrigated soils by the analysis of water soluble ions and calculation of the gypsum saturation index

Introduction

The approach followed in Campbell (2001) to detect gypsum in the irrigated soils involved the analysis of the major ion composition of saturated paste extracts and the calculation of the ion activities and gypsum saturation index (SI) using PHREEQC (Parkhurst and Appelo, 1999). All saturated paste extracts were found to be under-saturated with respect to gypsum, and it was deduced that gypsum was probably absent as a solid phase when the soils were saturated with water (25-30% water). It was considered possible, however, that the method of preparing saturated paste extracts may not have allowed complete equilibration of the solution with gypsum in the soil. In further analyses, soluble ions in selected soils were extracted at higher water:soil ratios, with continuous shaking for 18 h. The solutions obtained were considered to be well equilibrated with any gypsum that might have been present in the soil. It was found that the amount of soluble sulphate (per unit mass of soil) in these solutions increased with the water:soil ratio, to a maximum at a 10:1 water:soil ratio. At higher water:soil ratios no further sulphate came into solution. However, every solution was under-saturated with respect to gypsum. It was deduced that gypsum was not the source of soluble sulphate, which was probably desorbing from anion exchange sites on iron oxide surfaces or kaolinite edge sites. It was concluded that gypsum was absent from the soil.

A preliminary re-assessment of the PHREEQC gypsum saturation index method

The PHREEQC model calculates ion activities and saturation indices using empirical thermodynamic data and algorithms, and it is possible that the program's outputs are misleading. A simple check of the program was carried out, firstly by preparing a saturated solution of gypsum, determining its calcium and sulphate concentrations and using PHREEQC to calculate the gypsum SI for this solution, which, theoretically, should have been equal to 0. The results are given in Table E1.

Table E1. Composition and gypsum saturation indices of a saturated gypsum solution.

Ca^{2+} (mg l^{-1})	SO_4^{2-} (mg l^{-1})	Gypsum SI at 20°C	Gypsum SI at 25°C
603	1407	-0.01	-0.03

The temperature in the lab was between 20°C and 25°C when the gypsum solution was being prepared, sampled and analysed. The SIs calculated by PHREEQC (Table E1) were considered to be equal to zero, within analytical uncertainty. This exercise confirmed that the gypsum SI calculated by PHREEQC is realistic, at least for a simple $CaSO_4$ solution.

Further testing of PHREEQC: calculation of gypsum saturation indices of 1:1 soil:water slurries with known additions of gypsum

In order to test the PHREEQC calculation of gypsum saturation indices in aqueous soil extracts, the following experiment was carried out: 25 g sub-samples of PM2 (0.2-0.4 m depth), the soil sample with the highest gypsum SI in its saturated paste extract (gypsum SI_{SPE} = -0.2; Campbell, 2001), were placed in four 100 ml centrifuge tubes with quantities of gypsum equivalent to 0, 1.5, 3 and 6 g gypsum per kilogram of soil. Twenty-five ml of distilled water was added to each tube. The slurries were allowed to equilibrate for 24 h, 8 hours of which involved shaking on an end-over-end shaker. The solution was separated from the soil by centrifuging the slurries at 5000 rpm for 5 min and filtering the supernatant through Whatman No. 42 filter paper. Concentrations of Ca^{2+}, Mg^{2+} and Na^{+} in the solutions were determined by atomic absorption spectroscopy, and of SO_4^{2-} and Cl^{-} by ion chromatography. The gypsum saturation indices for each solution were calculated using PHREEQC. The results are given in Table E2.

Table E2. *Composition and gypsum saturation indices of solutions equilibrated with soils and treated with gypsum as indicated.*

Gypsum added to soil (g kg^{-1})	Ca^{2+} (mg l^{-1})	Mg $^{2+}$ (mg l^{-1})	Na $^{+}$ (mg l^{-1})	SO_4^{2-} (mg l^{-1})	Gypsum SI at 20°C
0.0	102	18	13	301	-1.05
1.5	339	30	14	872	-0.34
3.0	538	33	15	1504	-0.05
6.0	524	33	15	1464	-0.06

In considering these results, it is useful to bear in mind that the solubility of gypsum at 25°C is about 2.7 g l^{-1} and that 1 g of gypsum per litre is equivalent to about 230 mg l^{-1} Ca^{2+} and 560 mg l^{-1} SO_4^{2-}. Also, for these 1:1 soil:solution extracts, mg l^{-1} are equivalent to mg kg^{-1}.

Beginning with the largest gypsum addition, 6 g kg^{-1}, the results show that only about 2-3 g kg^{-1} of gypsum has dissolved. The second part of this Appendix (Sulphate adsorption in soils *under mine water irrigation at Kleinkopje*) shows that these soils can be expected to adsorb Ca^{2+} and SO_4^{2-} in quantities equivalent to a maximum of about 1.6 g of gypsum per kg from a saturated gypsum solution. Thus at least 1.4 to 2.4 g kg^{-1} of the added gypsum has not dissolved. Assuming that the system has reached equilibrium, the solution must be saturated with respect to gypsum. This is confirmed by the fact that the calculated gypsum SI is zero, within analytical error.

The results for the 3 g kg^{-1} gypsum addition are sufficiently similar to the 6 g kg^{-1} addition that it can be safely assumed that this solution is also saturated with respect to gypsum. The 1.5 g kg^{-1} gypsum addition has resulted in a more dilute solution, with Ca^{2+} and SO_4^{2-} concentrations indicating that all of the added gypsum has dissolved, and that the solution is under-saturated. The gypsum SI of -0.34 supports this conclusion. The zero gypsum addition has resulted in a still more dilute solution, with an SI indicative of significant under-saturation.

Conclusions

This experiments confirm that an analysis of the ionic composition of the solution, followed by the calculation of the gypsum SI using PHREEQC, is a suitable method of determining the presence or absence of gypsum in an equilibrated soil and water mixture. For the purposes of the mine water irrigation project the most direct assessment of the presence of gypsum in irrigated soils would be to extract samples of the soil solution from soil samples at their field water content, analyse their composition, and calculate the gypsum SI. Laboratory proxies of soil solution composition, such as that of saturated paste extracts, are also suitable. However, considering that the solubility of gypsum is about 2.7 g l^{-1}, and that saturated paste extracts in the Kleinkopje soils are prepared at a water:soil ratio of 25 to

30% (250 – 300 ml of water per kg soil), saturated paste extracts will be under-saturated with respect to gypsum when there is less than about 0.8 g of gypsum per kg of soil.

Sulphate adsorption in soils under mine water irrigation at Kleinkopje

There is evidence that surface reactions, such as the adsorption of SO_4^{2-} ions to anion exchange sites and the formation of SO_4^{2-}-surface complexes, are important mechanisms for the retention of SO_4^{2-} in the soils currently under irrigation with mine water at Kleinkopje Colliery (Campbell, 2001). It has also been found that the adsorption of SO_4^{2-} in acid soils is enhanced by the presence of Ca^{2+} in the soil solution (Marcano-Martinez and McBride, 1989). The work presented here provides a preliminary description of SO_4^{2-} adsorption by Kleinkopje soils, and the role of Ca^{2+} in enhancing SO_4^{2-} adsorption in these soils.

Methods

The soils used in the initial phase of this work were from pivot Major:

PM2 0-0.2 m	Pivot Major, irrigated to field capacity, 0-0.2 m depth.
PM2 0.4-0.6 m	Pivot Major, irrigated to field capacity, 0.4-0.6 m depth.
PM4 0-0.3 m	Pivot Major, not irrigated, 0-0.3 m depth.
PM4 0.9-1.2 m	Pivot Major, not irrigated, 0.9-1.2 m depth.

These soils are either topsoils or subsoils selected as having the highest phosphate-extractable sulphate content of all the pivot Major samples (Campbell, 2001). It was considered likely that the topsoils would have the lowest sulphate adsorption capacity, because they contain elevated concentrations of negatively charged organic matter, and that the soils with the highest phosphate-extractable sulphate concentrations would have the highest SO_4^{2-} adsorption capacity. The soils were equilibrated at a 1:10 soil:solution ratio with 0, 2.5, 5, 10, 15 and 20 mM Na_2SO_4 solutions for 24 h with 8 h of shaking on an end-over-end shaker. Sufficient NaCl was added to each solution to raise the ionic strength to 60 mM. Sulphate concentration was measured in solution by ion chromatography (IC) before and after equilibration.

This method was abandoned, principally because of the high dilution factor required (100 or 200 times) to bring solution Cl^- or SO_4^{2-} concentration to within the IC operating range, entailing a risk of unacceptable error. The results obtained did suggest strongly, however, that the soils studied have a negligible SO_4^{2-} sorption capacity.

A new series of soil samples were equilibrated with sulphate solutions of lower concentration. The soils used in this case were:

PM4 0.9-1.2 m	Pivot Major, not irrigated, 0.9-1.2 m depth (also used above)
PM4 1.8-2.1m	Pivot Major, not irrigated, 1.8-2.1 m depth
PF4 0.3-0.6 m	Pivot Fourth, not irrigated, 0.3-0.6 m depth
PF4 3.0-3.3 m	Pivot Fourth, not irrigated, 3.0-3.3 m depth

PM4 0.9-1.2 m had the highest extractable sulphate concentration in the non-irrigated profile from pivot Major, and the other three soils had extractable sulphate concentrations which were below the detection limit of the method used by Campbell (2001).

The soil PM4 0.9-1.2 m was used in both the first and second adsorption experiments. This was done so as to be able to compare the results obtained using high sulphate concentrations with those obtained at lower concentrations. The soils were equilibrated as described above with 0, 0.125, 0.25, 0.5, 0.75, 1, 2 and 5 mM solutions of Na_2SO_4 and

$CaSO_4$, and the solution sulphate concentration measured before and after equilibration by ion chromatography. The concentration of calcium and magnesium in the latter solutions was measured by atomic adsorption spectroscopy.

Results

Figure E1 shows the results of the adsorption experiments on the topsoils and high-sulphate samples from pivot Major, as a plot of sulphate concentration in solution before equilibration versus concentration after equilibration with soil. It can be seen that there is no significant difference between the sulphate concentration in solution before and after equilibration with the soils, indicating that there has been negligible adsorption of sulphate by the soils.

Figure E2 shows the results of the second batch of sorption experiments as adsorption isotherms for the four soils. PF4 0.3-0.6 m and PM4 0.9-1.2 m have negligible capacity to adsorb sulphate from Na_2SO_4 solutions. In fact, about 1 $mmol_c$ SO_4^{2-} kg^{-1} dissolved from the latter soil.

PM4 1.8-2.1m has the capacity to adsorb up to about 10 $mmol_c$ kg^{-1} of sulphate from Na_2SO_4 solution. Its sorption behaviour is well described by either Langmuir or Freundlich type isotherms (Drever, 1997). A reasonably fitting Freundlich isotherm expression for this soil is:

$$M_{ads} = 7M_{sol}^{0.2}$$

while the corresponding Langmuir isotherm is

$$M_{ads} = 11(1.8M_{sol} / 1+1.8M_{sol})$$

where M_{ads} is the equilibrium concentration of the species of interest in the soil, expressed in $mmol_c$ kg^{-1}, and M_{sol} is its equilibrium concentration in solution, expressed in mmol l^{-1}.

PF4 3-3.3 m adsorbs a maximum of 5 $mmol_c$ kg^{-1}, and sorption behaviour may be described by either

$$M_{ads} = 5M_{sol}^{0.2}$$

or

$$M_{ads} = 5(10M_{sol} / 1+10M_{sol})$$

These isotherms are also depicted in Figure E2 (marked Freundlich 2 and Langmuir 2, respectively).

Both these soil samples adsorbed significantly more SO_4^{2-} from gypsum solutions than from Na_2SO_4 solutions (Figure E3). PM4 1.8-2.1 m adsorbed 50% more sulphate from the most concentrated gypsum solution than it did from Na_2SO_4 solution, while PF4 3-3.3 m adsorbed more than 100% more sulphate. Both soils adsorbed similar quantities of sulphate from solutions of the same sulphate concentration, and adsorption was described by the following Freundlich isotherm:

$$M_{ads} = 8M_{sol}^{0.3}$$

The extent of calcium adsorption by these two soils (Figure E4) from gypsum solutions was more than double that of sulphate at the highest equilibrium concentration, and adsorption was described by a Freundlich expression of the form:

$$M_{ads} = 15M_{sol}^{0.4}$$

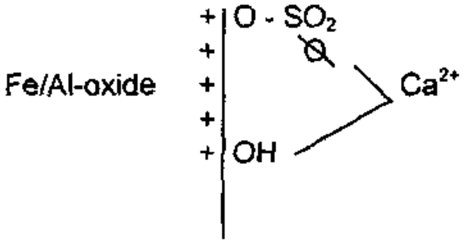
A plot of sulphate vs. calcium adsorption (Figure E5) suggests that there is a 1:1 relationship between these ions' adsorption at lower solution concentrations adsorption, with Ca^{2+} adsorption overtaking SO_4^{2-} adsorption at higher concentrations to give something approaching a 1:2 ratio of sorbed SO_4:Ca.

Discussion and conclusions

Although the number of soils used for this study was small, certain tentative conclusions can be drawn regarding sulphate adsorption behaviour in the soils under irrigation with mine water at Kleinkopje Colliery.

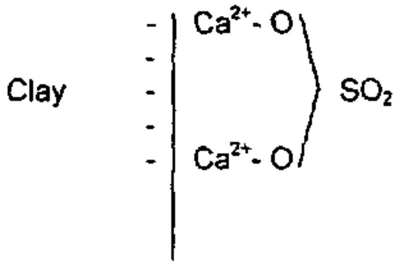
Adsorption from Na_2SO_4 solutions suggests that the capacity of the irrigated soil in pivot Major to adsorb sulphate may already be saturated – i.e. these soils will not adsorb any additional sulphate from solution. The sulphate adsorption capacity of the non-irrigated soils, down to a depth of 1 to 1.5 m, may also be saturated, possibly as a result of significant inputs of atmospheric sulphate over a number of decades.

It is clear, however, that the presence of Ca^{2+} rather than Na^+ in solution enhances SO_4^{2-} adsorption in the sub-soil samples. A possible mechanism for the mutual enhancement of Ca^{2+} and SO_4^{2-} is the formation of a surface complex such as:



(Marcano-Martinez and McBride, 1989)

or



The latter conformation might explain why roughly twice as much Ca^{2+} is adsorbed as SO_4^{2-} from the gypsum solutions.

The non-irrigated shallow subsoil PF4 0.3-0.6 m showed no such enhancement of SO_4^{2-} adsorption by Ca^{2+}, and a limited degree of Ca^{2+} adsorption. However, it is clear that irrigated soils from the same pivot area and depth interval have adsorbed significant quantities of Ca^{2+} and SO_4^{2-} (Campbell, 2001). This discrepancy may indicate that Ca^{2+} may only enhance SO_4^{2-} adsorption once a certain critical level of Ca^{2+} saturation of the cation exchange sites has been achieved. It is possible that this adsorption study simply did not expose the soil to sufficiently high solution concentrations of Ca^{2+} for this critical level of Ca^{2+} saturation to be reached.

Finally, turning to the relationship between sulphate adsorption and gypsum precipitation, the capacity of the soils PM4 1.8-2.1 m and PF4 3.0-3.3 m to adsorb sulphate from the soil solution can described by the Freundlich isotherm:

$$M_{ads} = 8M_{sol}^{0.3}$$

If M_{sol} is set to 15.6 mmol l^{-1}, the concentration of sulphate in a saturated solution of gypsum, then M_{ads} has a value of 18.2 $mmol_c$ kg^{-1}. This is an estimate of the concentration of adsorbed sulphate in these soils at equilibrium with a saturated solution of gypsum. Put another way, and assuming that SO_4^{2-} is bound in surface complexes with equivalent quantities of Ca^{2+}, the adsorption of Ca^{2+} and SO_4^{2-} is equivalent to 9.1 mmol of gypsum, i.e. 1.6 g gypsum per kg of soil.

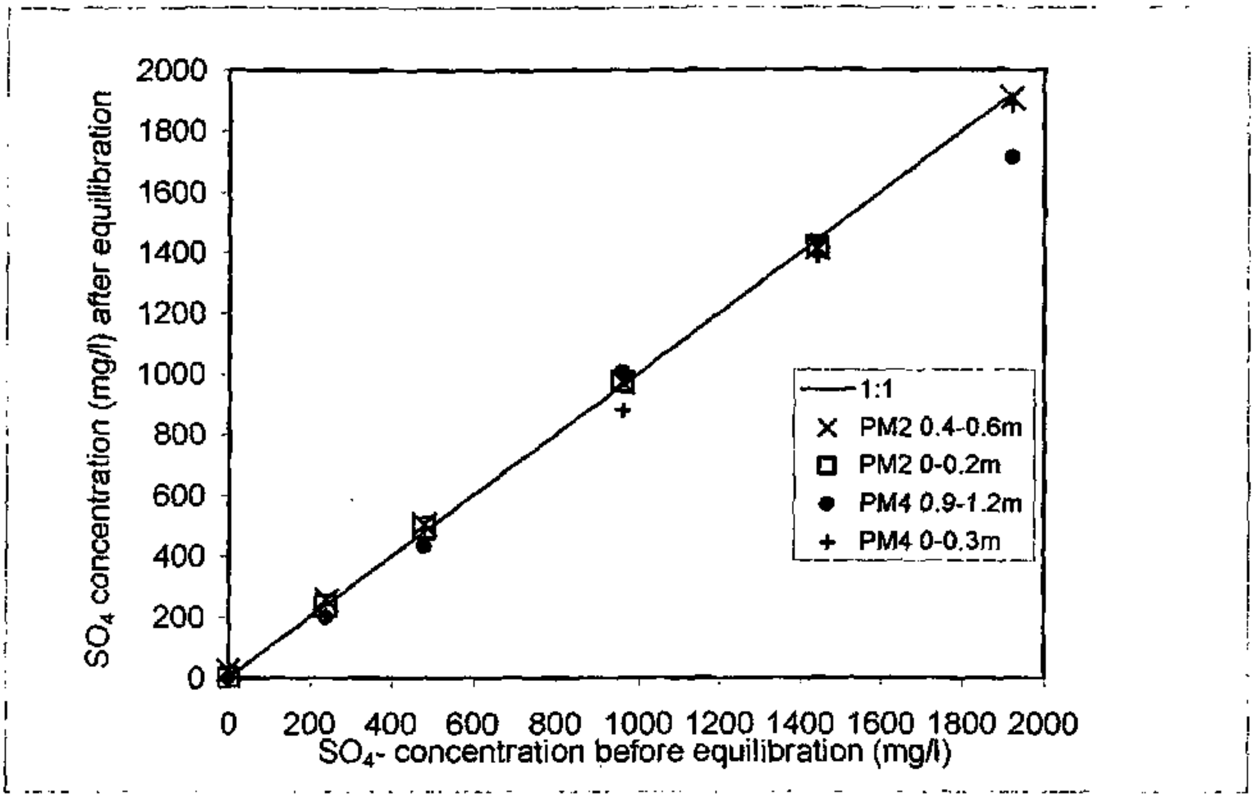


Figure E1. Sulphate concentration in solution before and after equilibration with four soils. PM2 = Pivot Major (field capacity treatment); PM4 = Pivot Major (outside pivot).

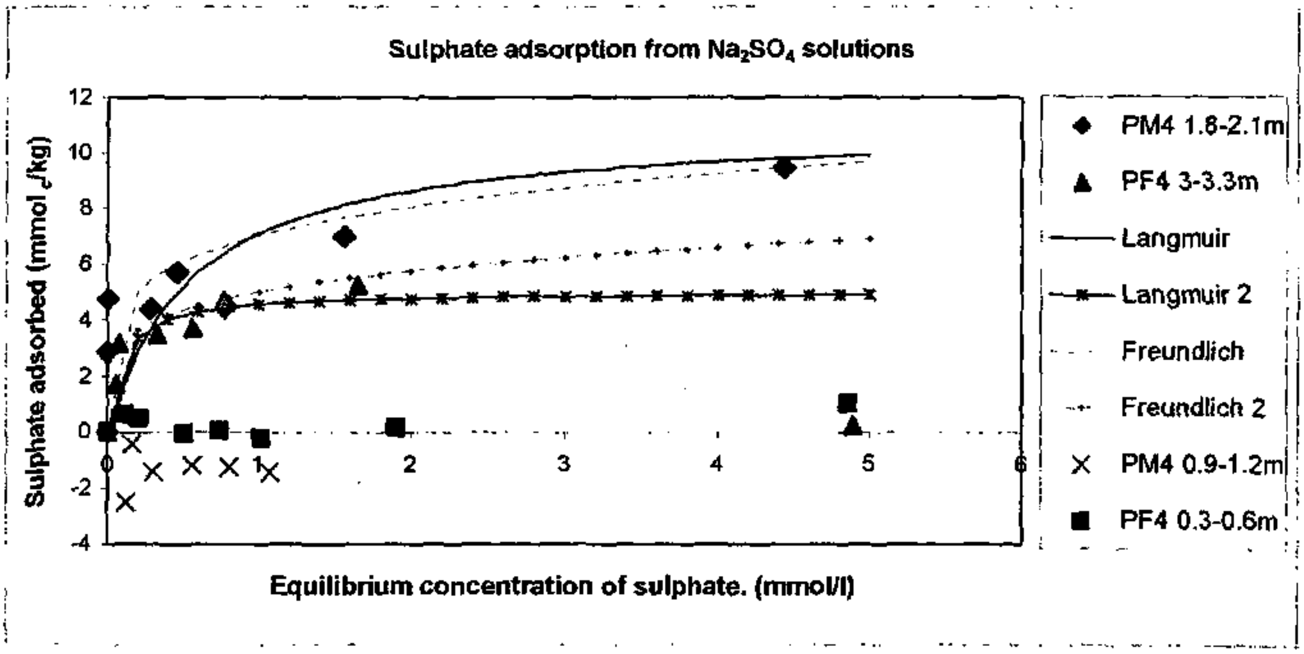


Figure E2. Adsorption of sulphate by soils from sodium sulphate solutions. Best-fit Langmuir and Freundlich isotherms are indicated. PM4 = Pivot Major (outside pivot); PF4 = Pivot Fourth (outside pivot).

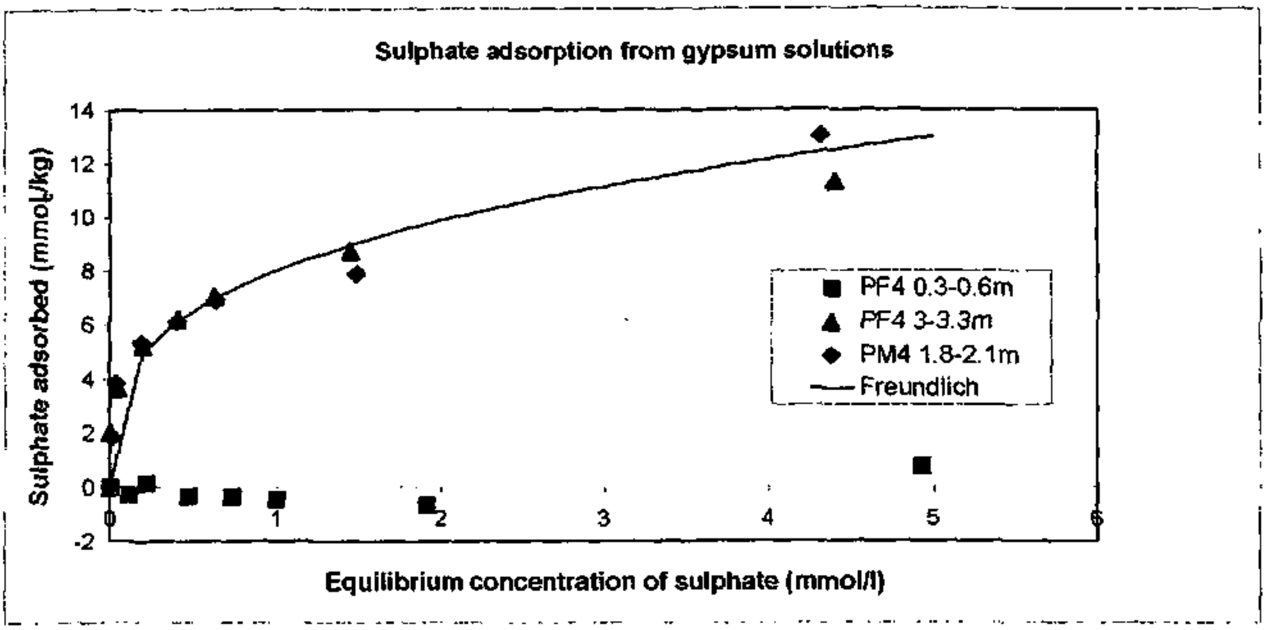


Figure E3. Sulphate adsorption by soils from gypsum solutions. A best-fit Freundlich isotherm is indicated. PM4 = Pivot Major (outside pivot); PF4 = Pivot Fourth (outside pivot).

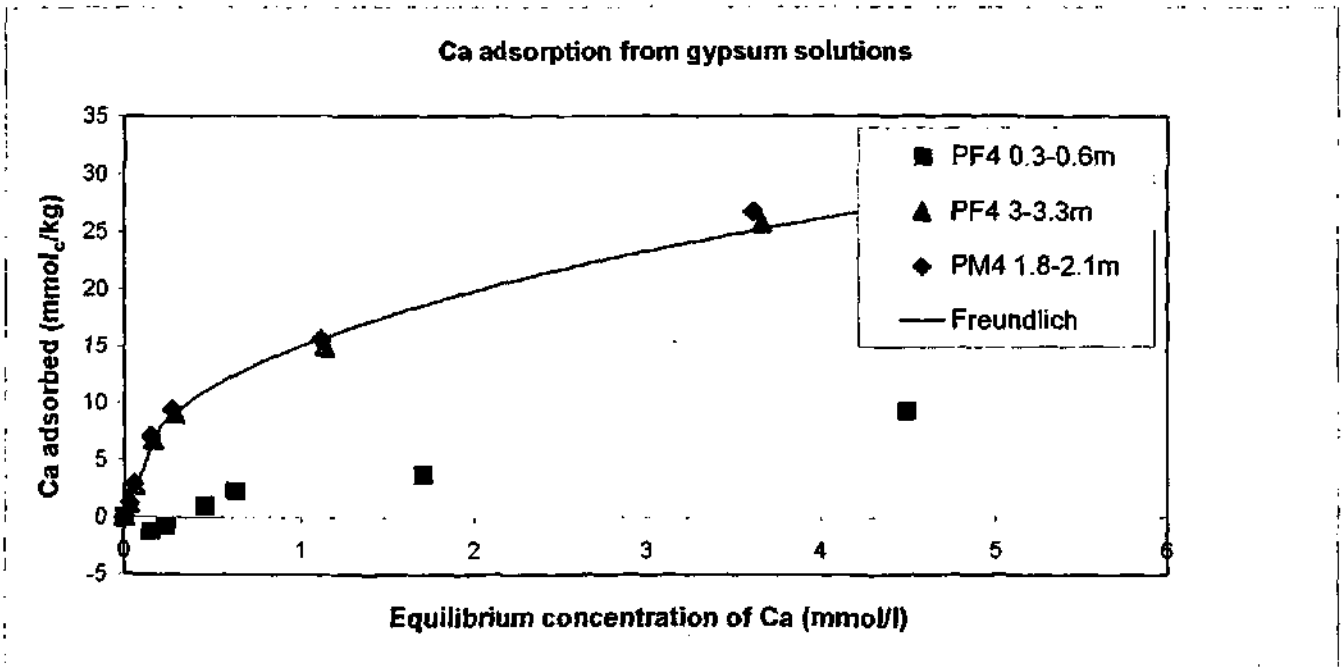


Figure E4. Calcium adsorption by soils from gypsum solutions. A best-fit Freundlich isotherm for two of the soils is indicated. PM4 = Pivot Major (outside pivot); PF4 = Pivot Fourth (outside pivot).

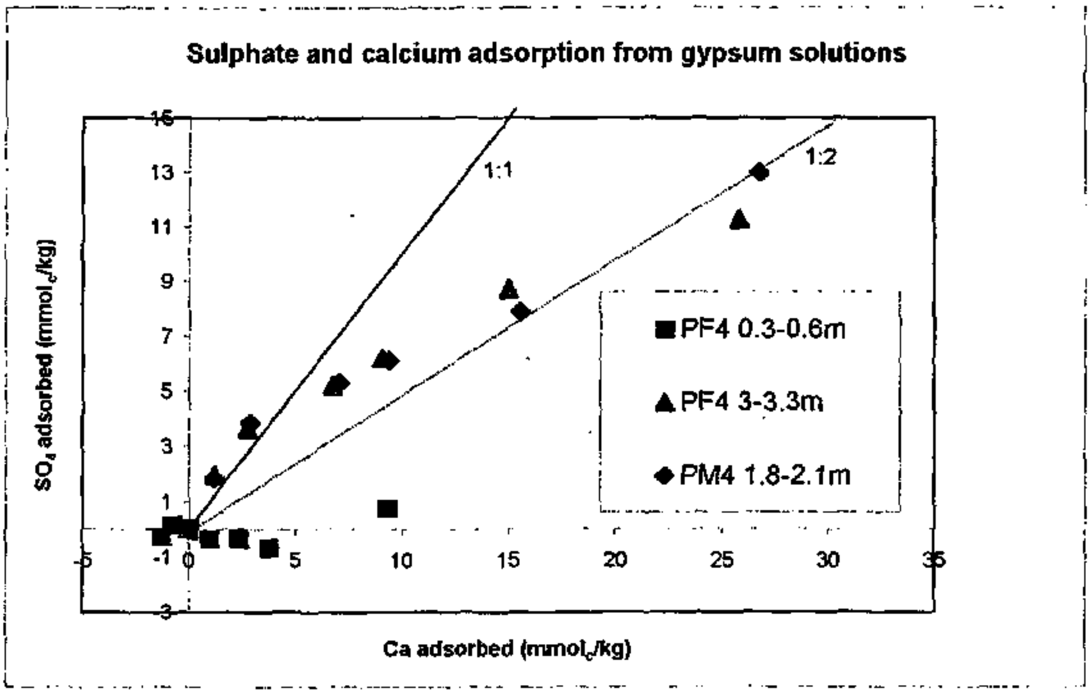


Figure E5. Plot of sulphate adsorbed vs. calcium adsorbed by three soils from gypsum solutions. PM4 = Pivot Major (outside pivot); PF4 = Pivot Fourth (outside pivot).

Appendix F

Borehole logs

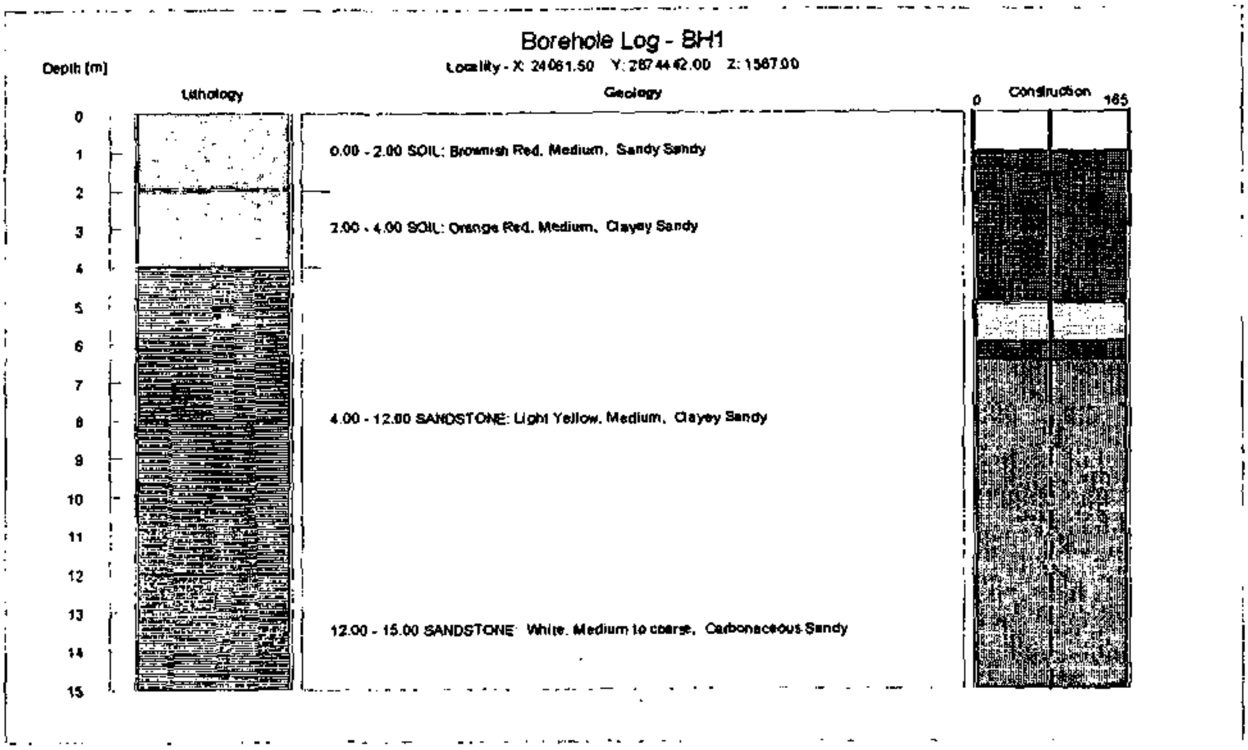


Figure F1. Geological log of borehole BH1 at pivot Major.

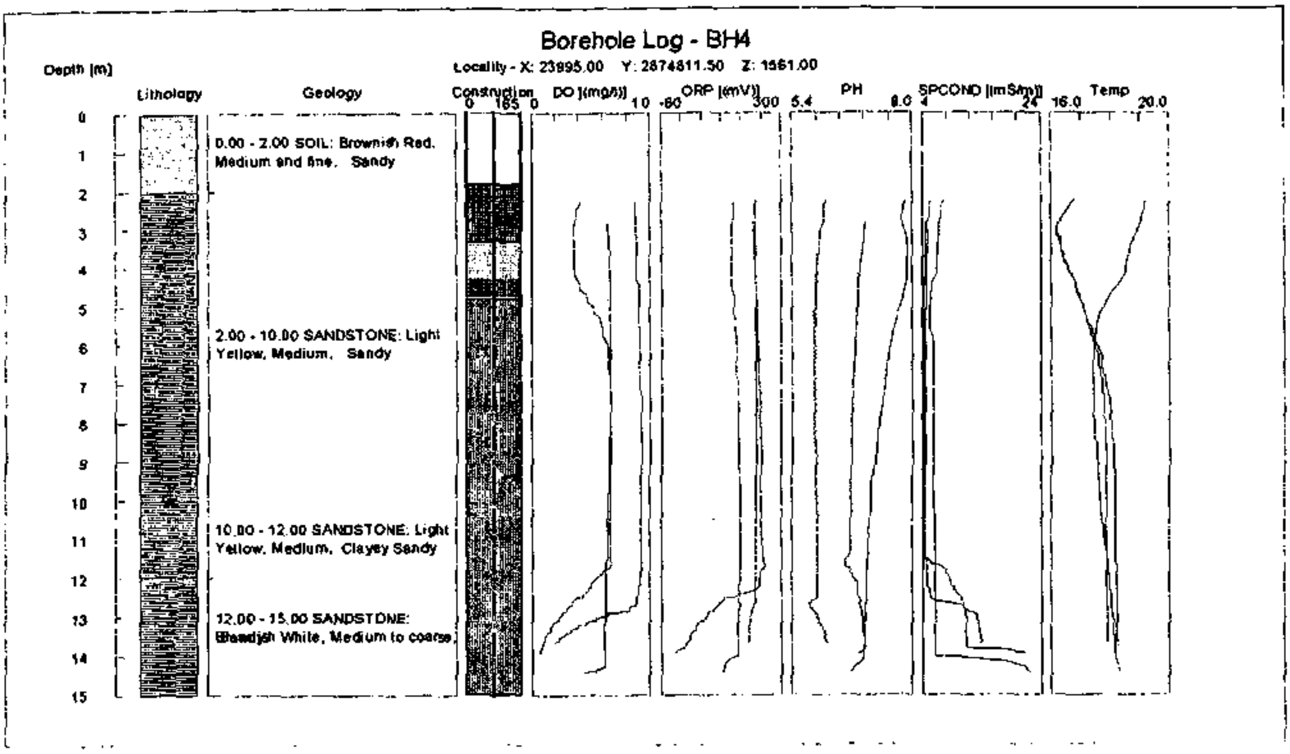


Figure F2. Geological log of borehole BH4 at pivot Major.

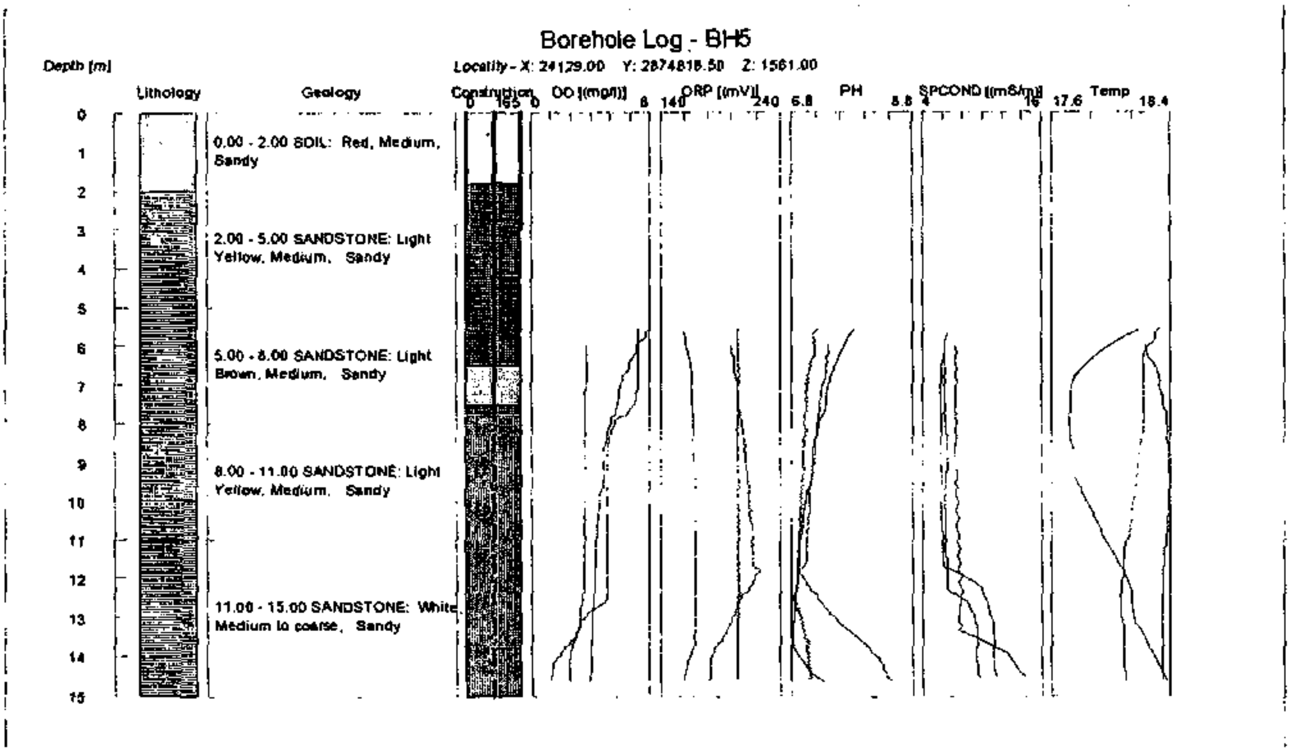


Figure F3. Geological log of borehole BH5 at pivot Major.

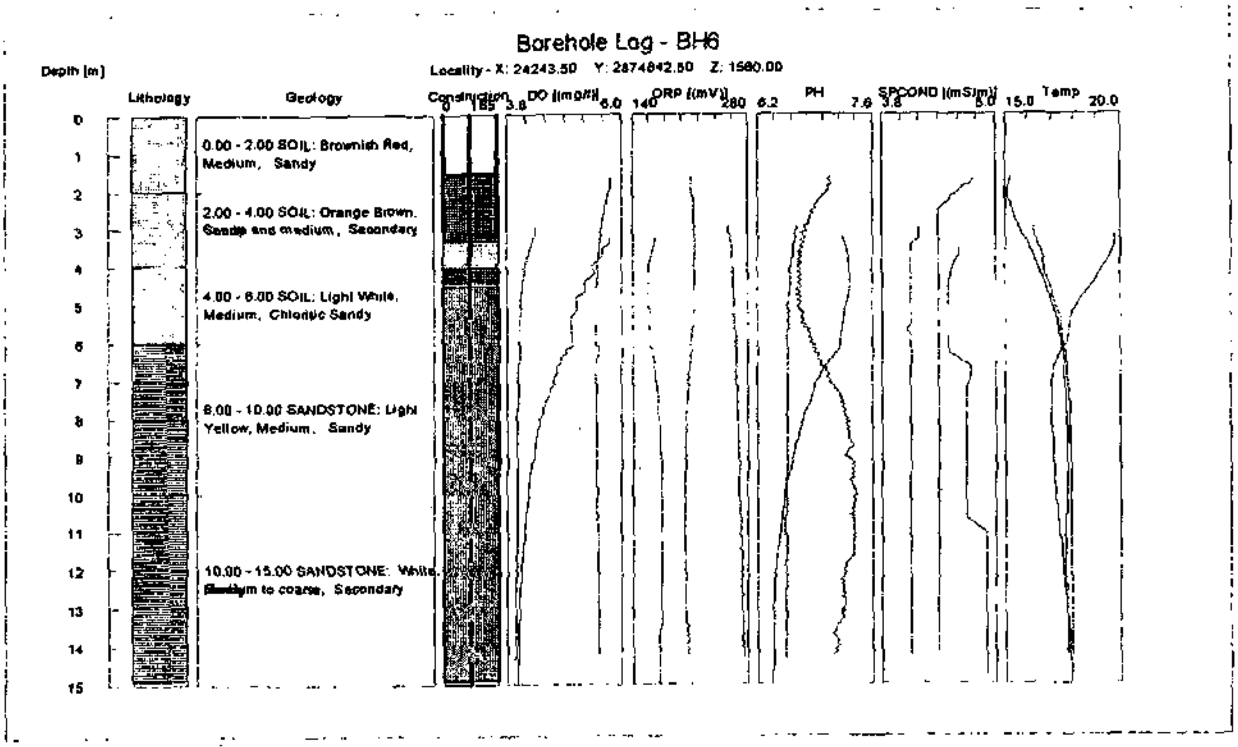


Figure F4. Geological log of borehole BH6 at pivot Major.

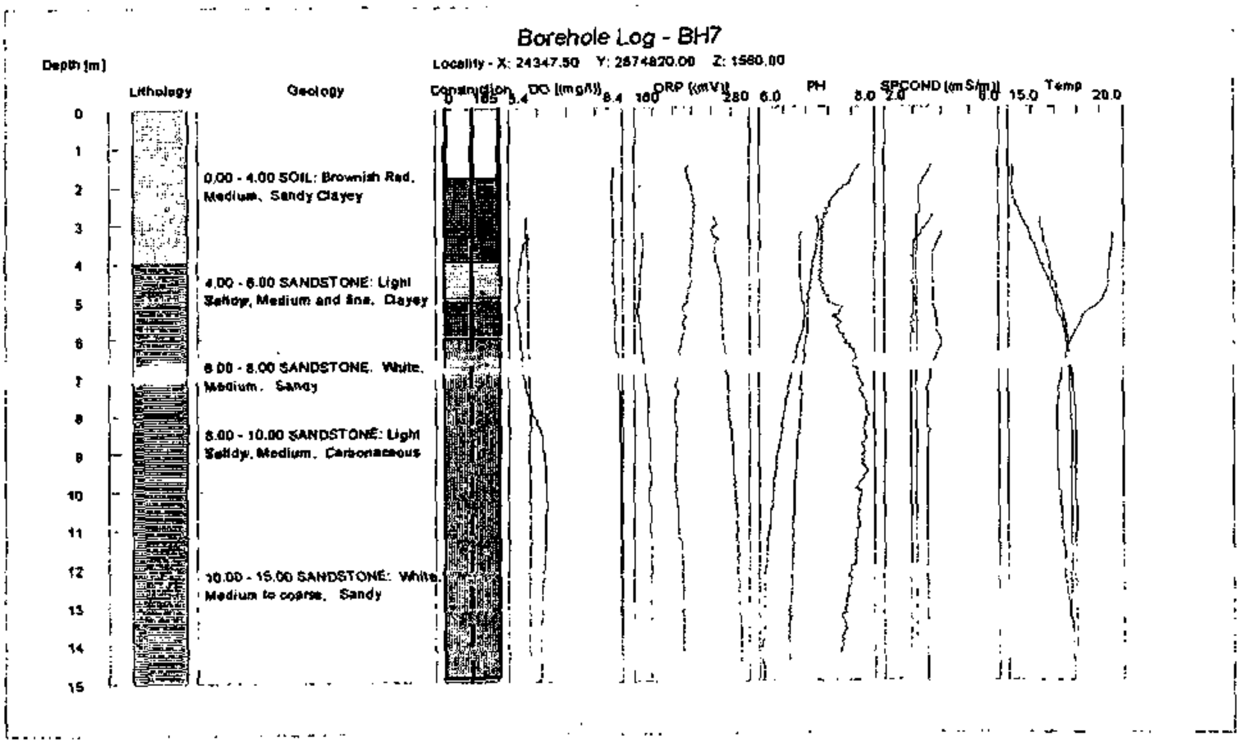


Figure F5. Geological log of borehole BH7 at pivot Major.

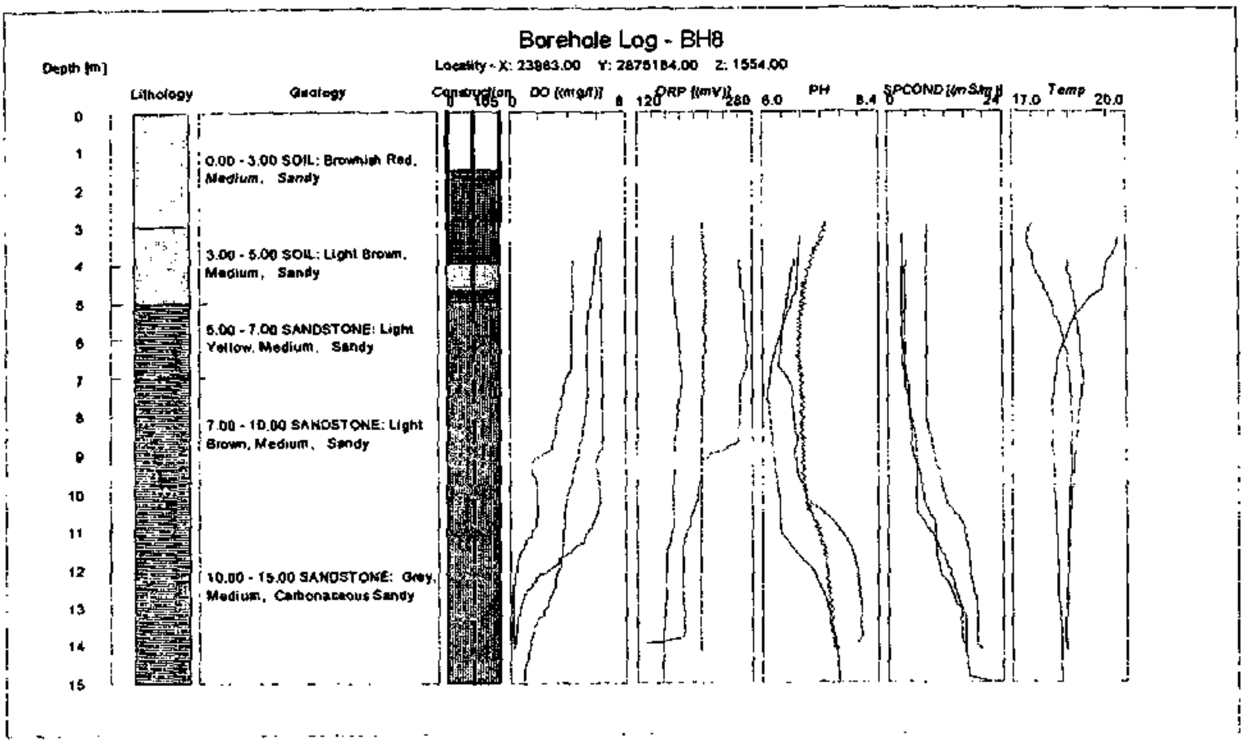


Figure F6. Geological log of borehole BH8 at pivot Major.

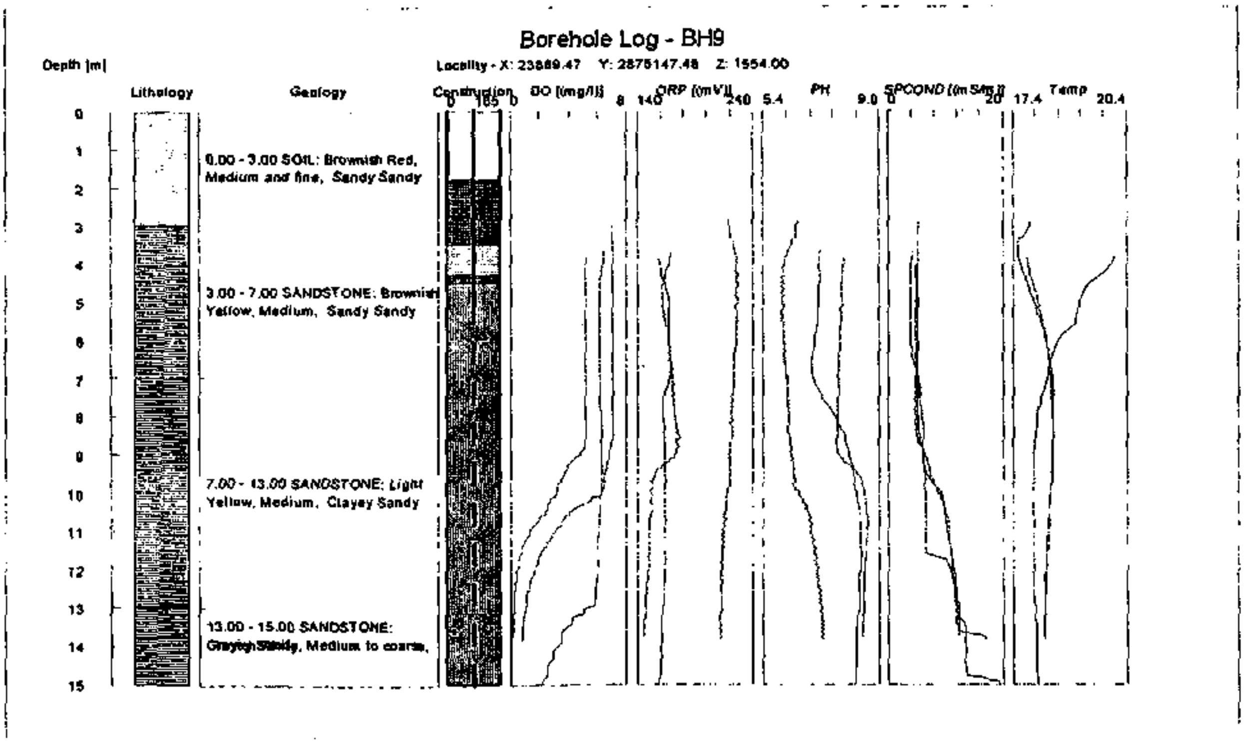


Figure F7. Geological log of borehole BH9 at pivot Major.

Appendix G

Results from pumping test analysis

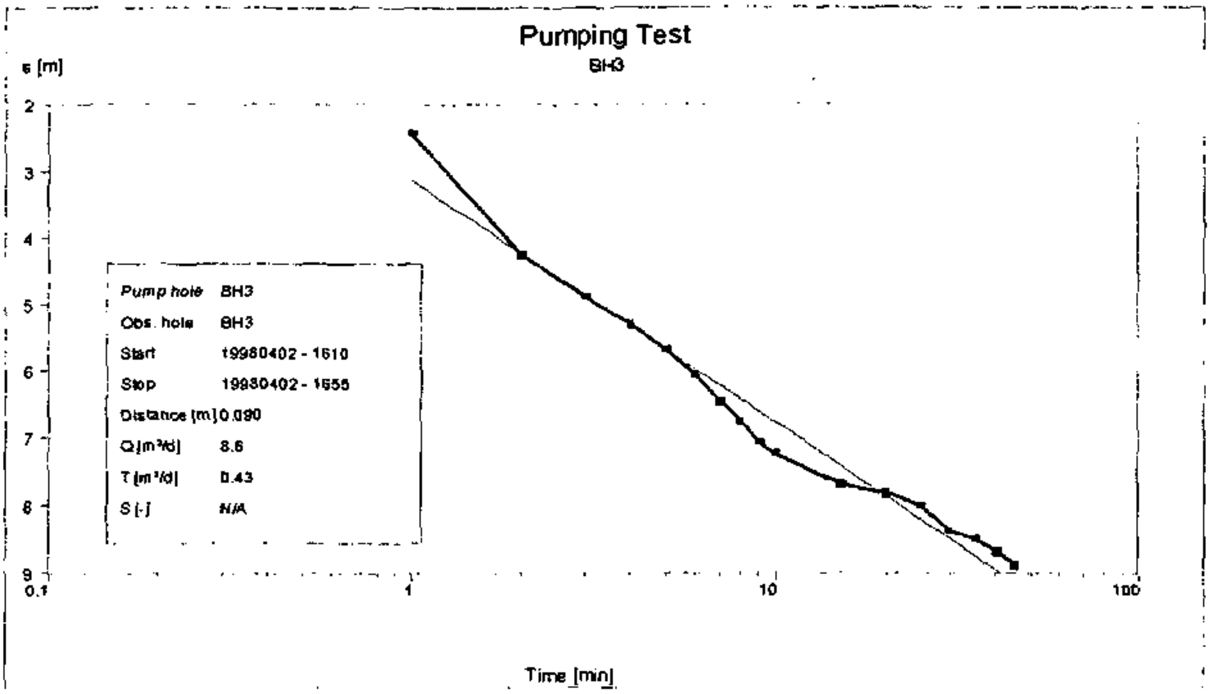


Figure G1. Pumping test curve for groundwater monitoring borehole BH3 at pivot Major.

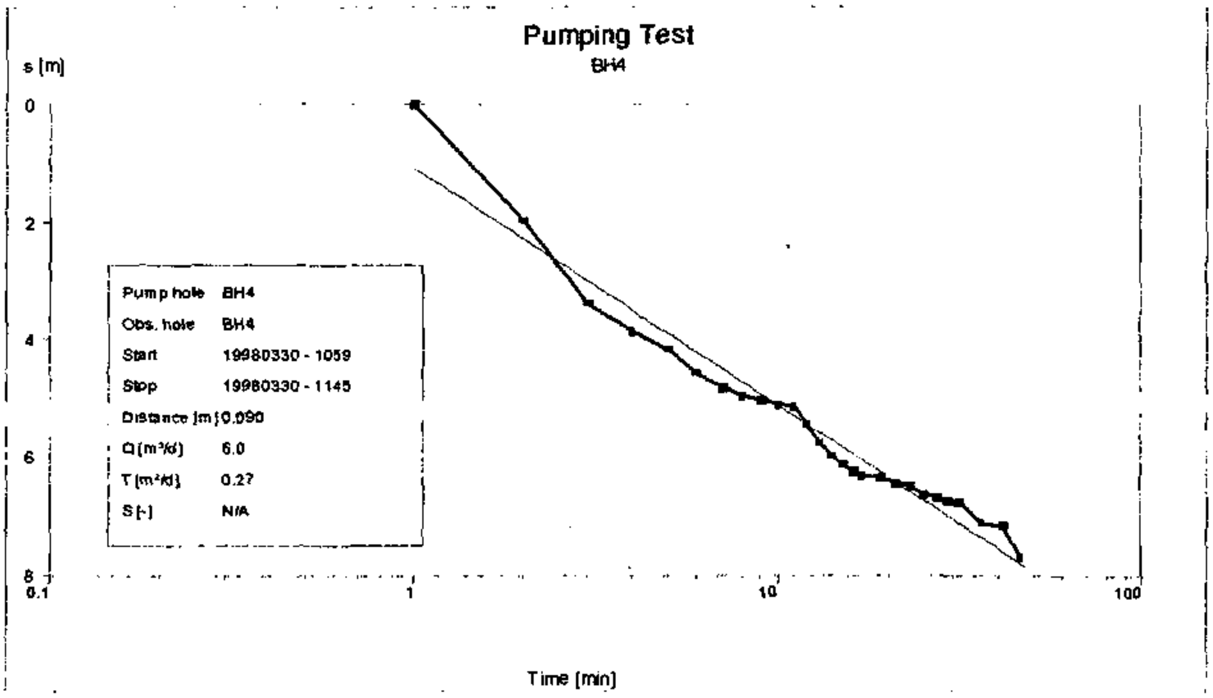


Figure G2. Pumping test curve for groundwater monitoring borehole BH4 at pivot Major.

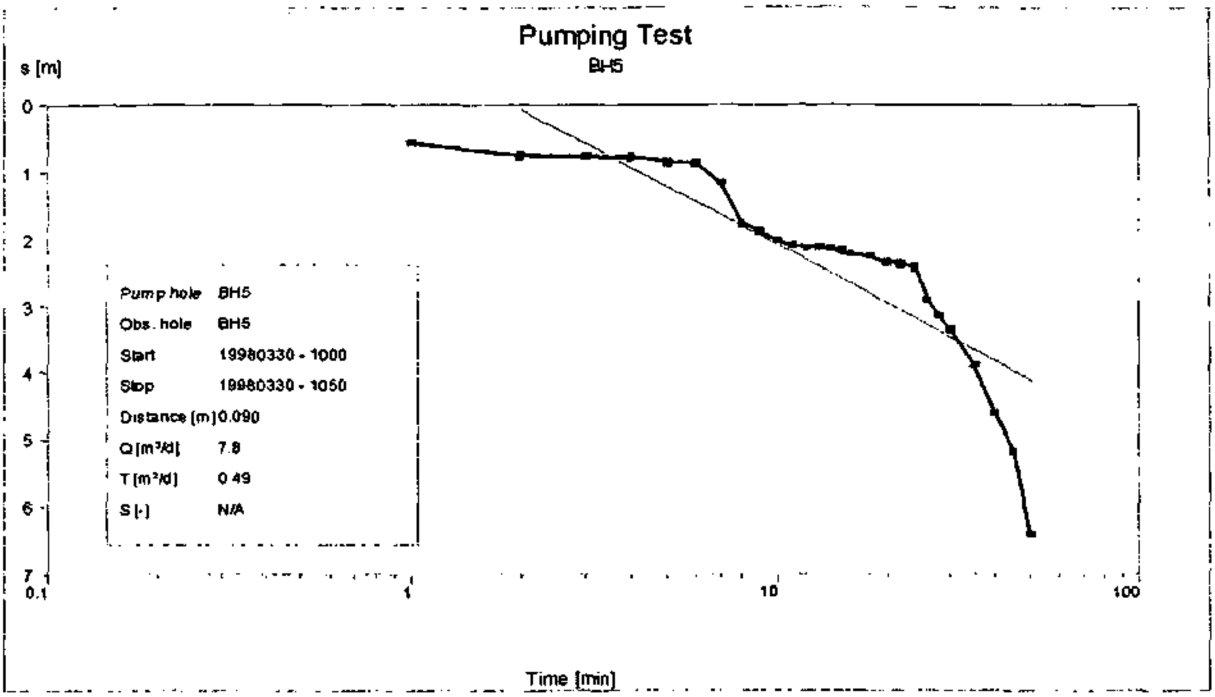


Figure G3. Pumping test curve for groundwater monitoring borehole BH5 at pivot Major.

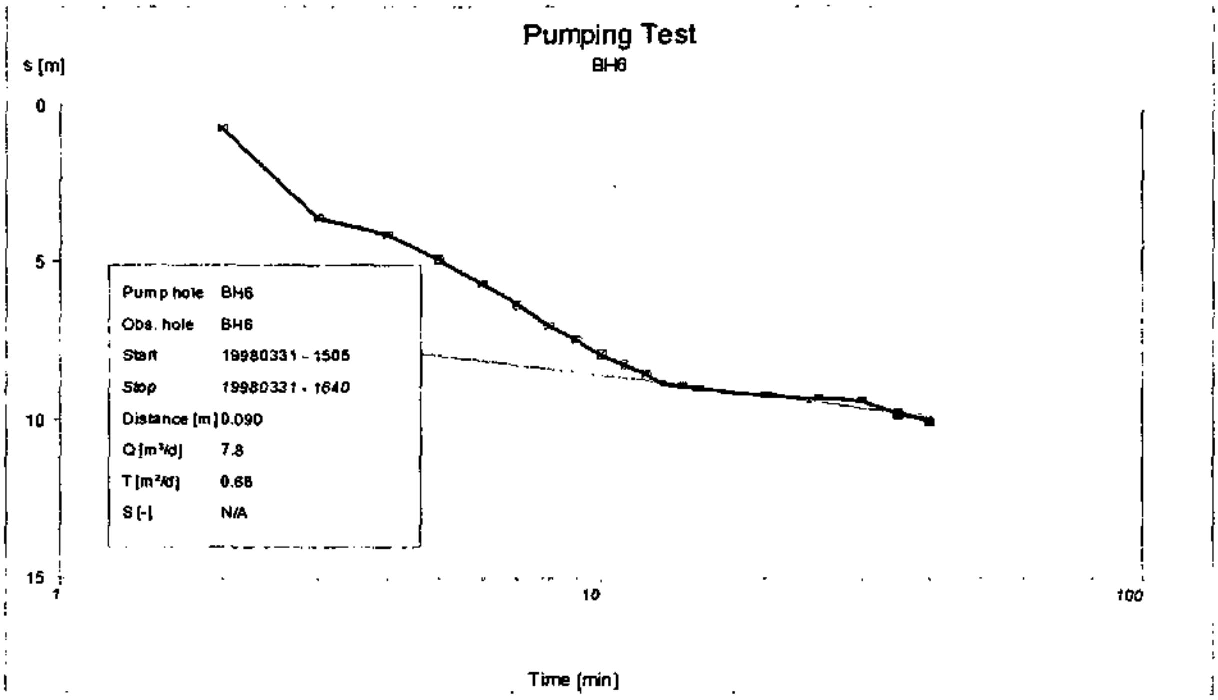


Figure G4. Pumping test curve for groundwater monitoring borehole BH6 at pivot Major.

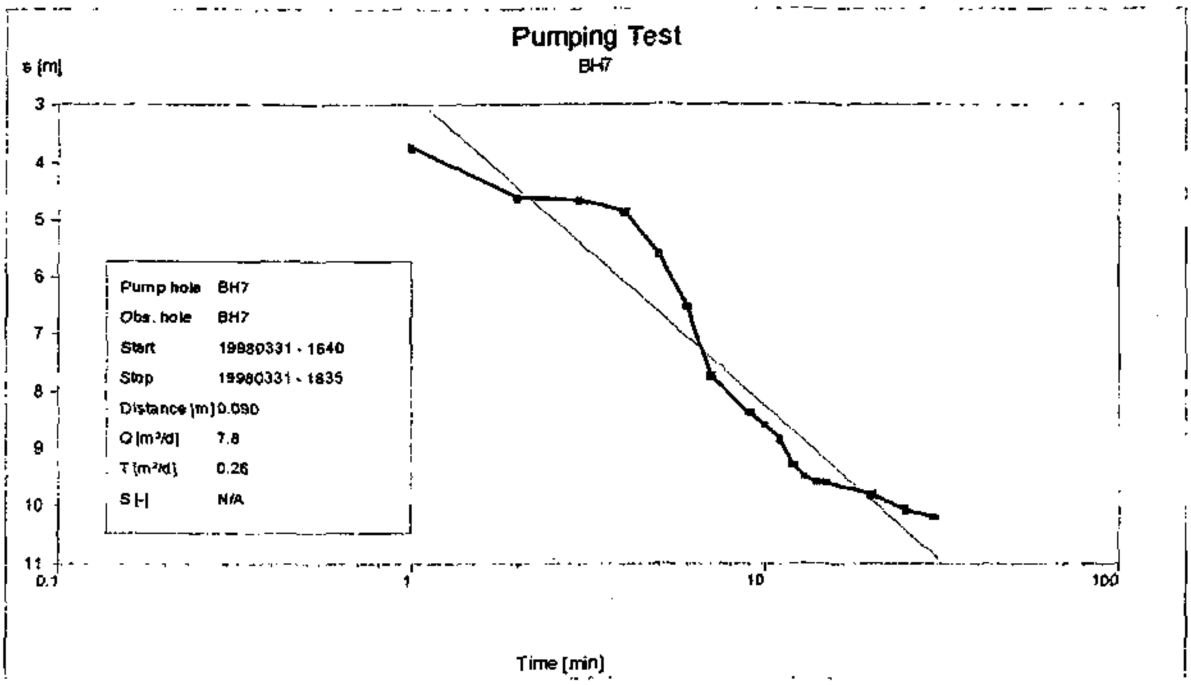


Figure G5. Pumping test curve for groundwater monitoring borehole BH7 at pivot Major.

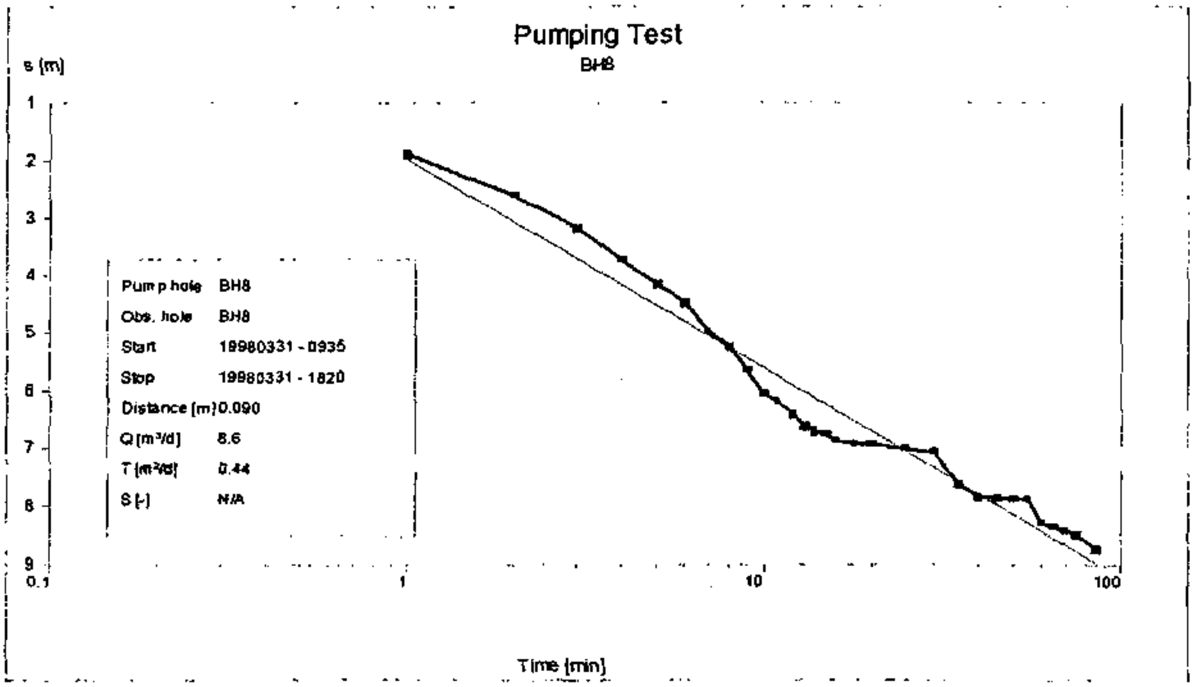


Figure G6. Pumping test curve for groundwater monitoring borehole BH8 at pivot Major.

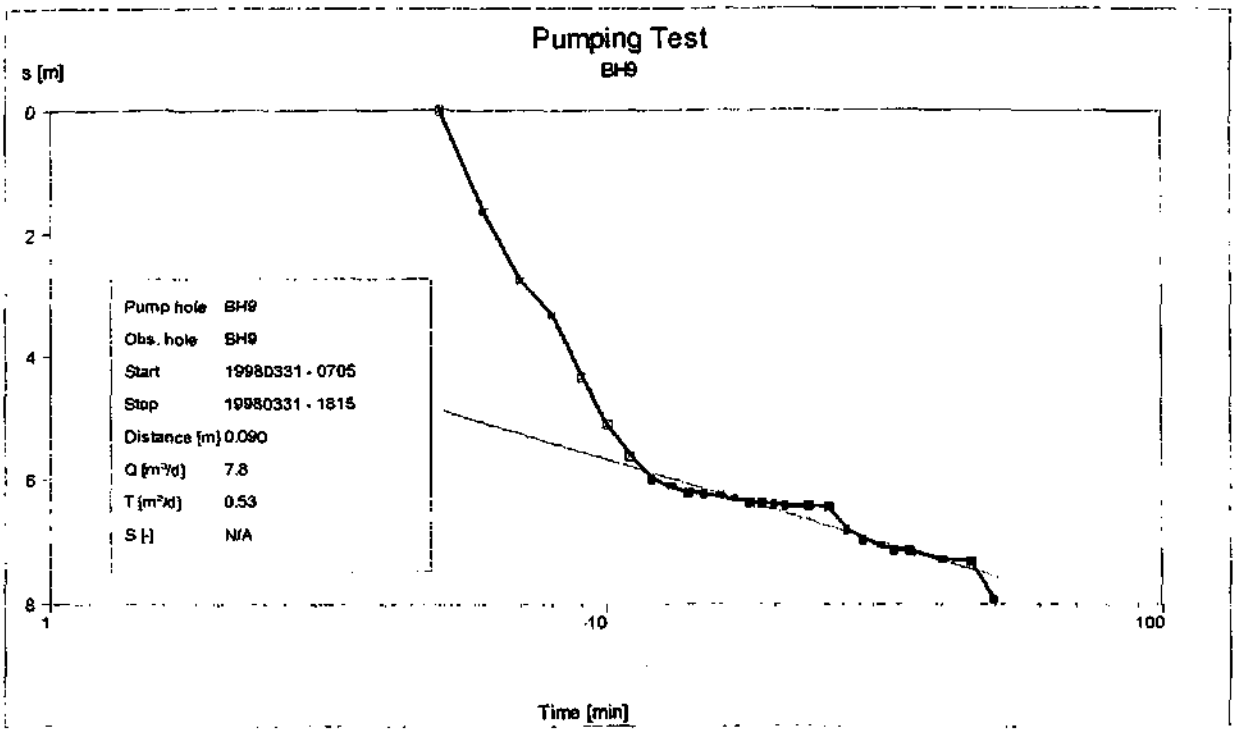


Figure G7. Pumping test curve for groundwater monitoring borehole BH9 at pivot Major.

Appendix H

Solute transport characteristics breakthrough curves

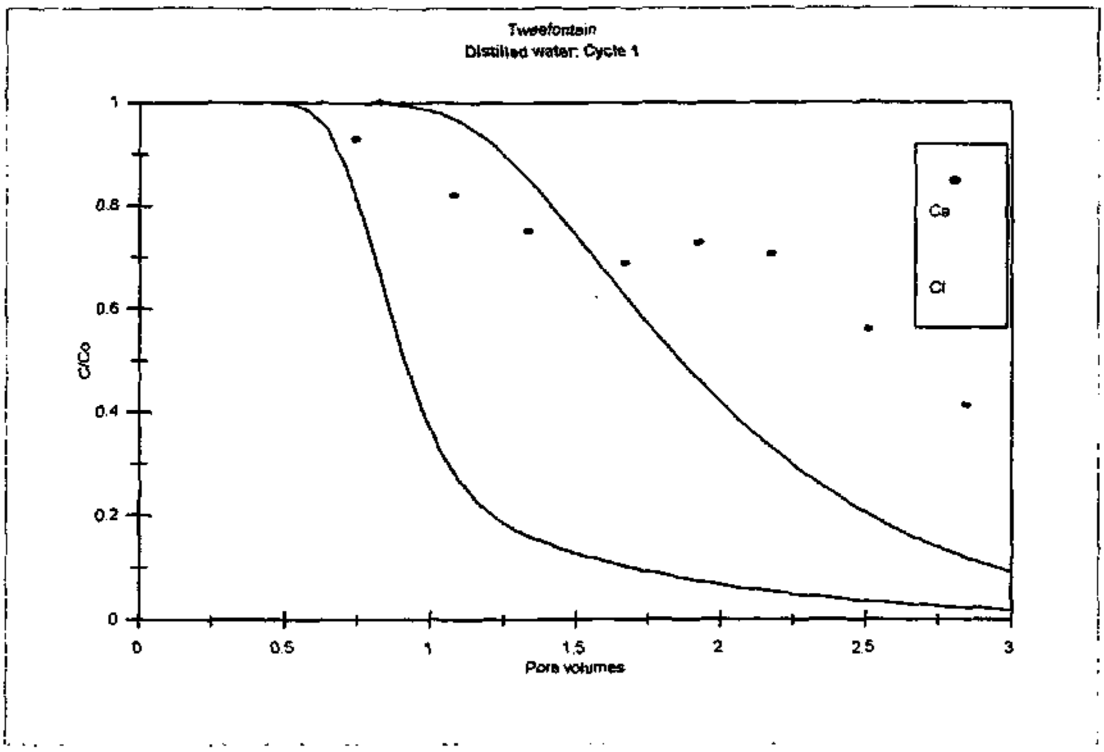


Figure H1. Breakthrough characteristic for distilled water injection of sample from pivot Tweefontein.

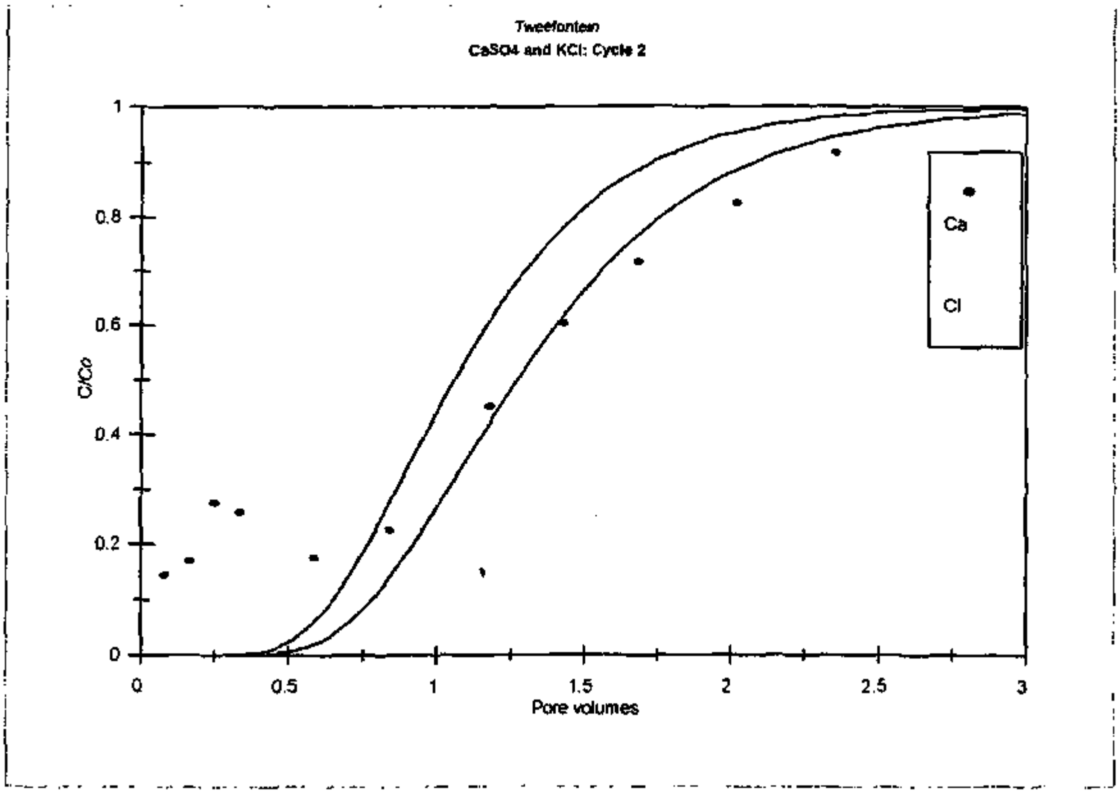


Figure H2. Breakthrough characteristic for $CaSO_4$ and KCl solution injection of sample from pivot Tweefontein.

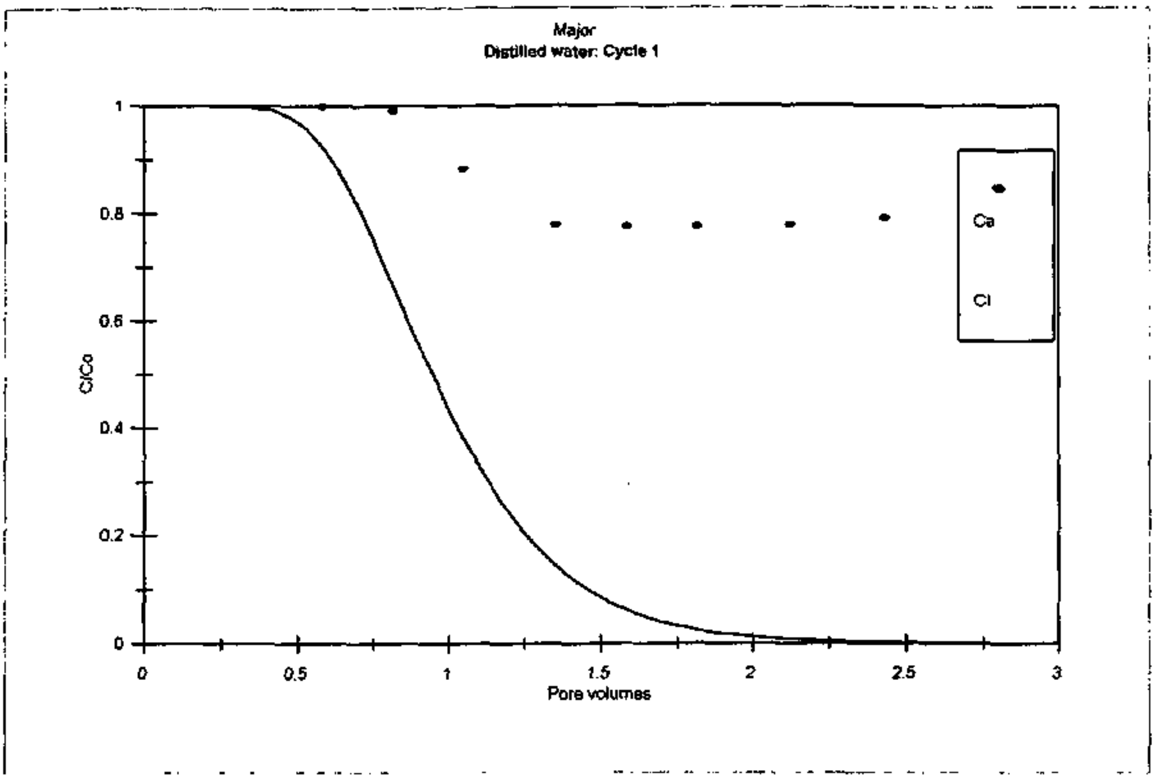


Figure H4. Breakthrough characteristic for distilled water injection of sample from pivot Major.

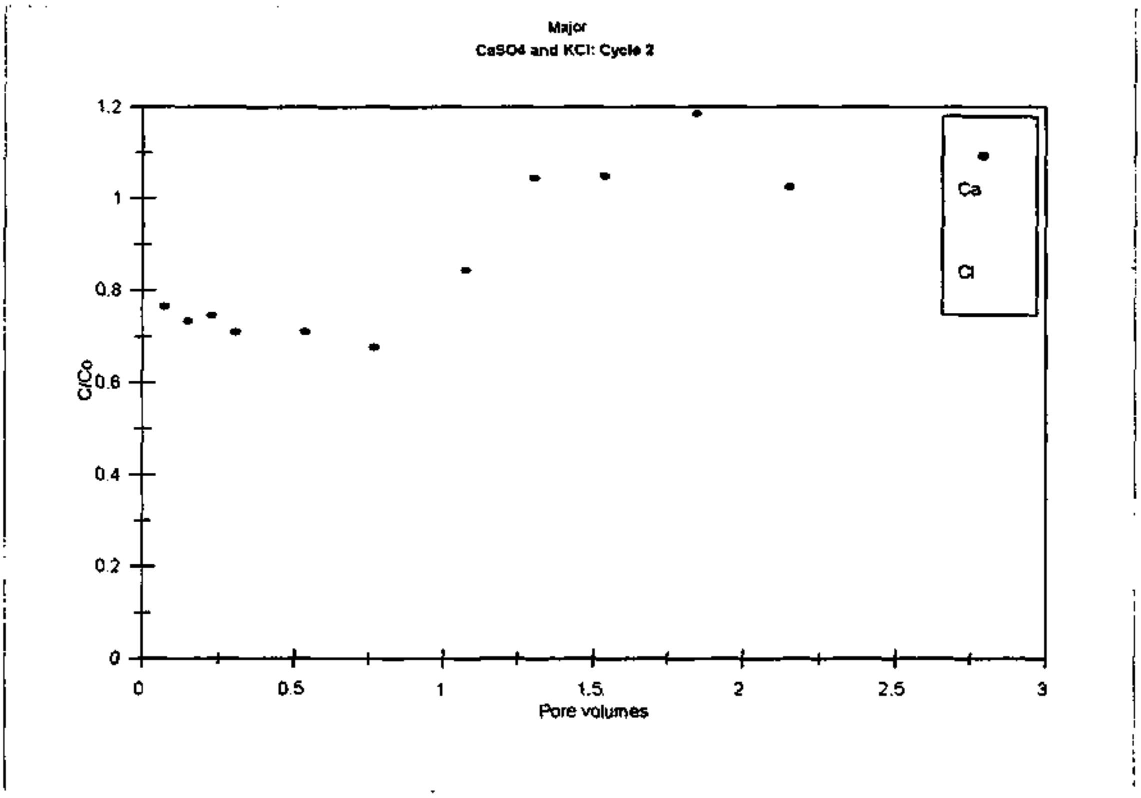


Figure H3. Breakthrough characteristic for $CaSO_4$ and KCl solution injection of sample from pivot Major.

APPENDIX I

Chemistry of soils and regolith irrigated with gypsiferous mine water

Introduction

A characterization of the effects on soil and deep sub-soil chemistry of irrigation with gypsiferous mine water at Kleinkopje was conducted by Ross Campbell and Prof. Martin Fey at the Universities of Cape Town and Stellenbosch. The methods used to analyze deep soil samples and the results of these analyses are presented in this Appendix.

Methods

Soil samples from the areas irrigated to field capacity in pivots Major, Fourth and Tweefontein, as well as samples of non-irrigated soil close to each pivot were examined. Certain sub-samples representing particular depth intervals have been omitted to save analytical time, but these gaps in the data do not appear to mar the clear trends apparent in the majority of results obtained. Samples from the leaching fraction and deficit treatment irrigation areas have not been considered in this report.

Soil passing through a 2 mm sieve has been analysed using the methods discussed below. The following analytical procedures have been performed:

a) Saturated paste extracts

Electrical conductivity of extracts, major cations and anions by ion chromatography, alkalinity of extracts by titration and dissolved organic carbon.

b) pH

Soil pH has been measured in the saturated pastes and in 1:2.5 soil suspensions in water and 1M KCl.

c) Exchangeable cations

Exchangeable acidity by extraction with 1M KCl and titration against 0.01M NaOH. Ammonium acetate extracts analysed by atomic absorption spectroscopy for exchangeable Ca, Mg, Na and K.

d) Colloid mineralogy

Clay fraction mineral identification by X-ray diffractometry (XRD).

e) Textural analysis

Separation and determination of relative proportions of sand, silt and clay by sieving and suspension in sodium hexametaphosphate solution.

f) Organic carbon

Total organic carbon content of the soils by the Walkley-Black dichromate oxidation method.

Major findings

1. Saturated paste extract analyses revealed soluble salt accumulation in the irrigated soils greatly in excess of soils not treated with gypsiferous mine water.
2. In pivot Major, most soluble salts were confined to the upper 1 m, while in pivot Fourth there was a more uniform distribution of salts in the profile, with a slight peak between 1.5 and 2m down in the profile.
3. In pivot Major ammonium acetate extractable cation data (an index of exchangeable cation concentration) revealed a decrease in adsorbed Ca with depth, and a significant increase in adsorbed Mg with depth, with the extractable Mg concentration exceeding that of Ca below 1.2 m.

Results

See the following pages for selected analytical results.

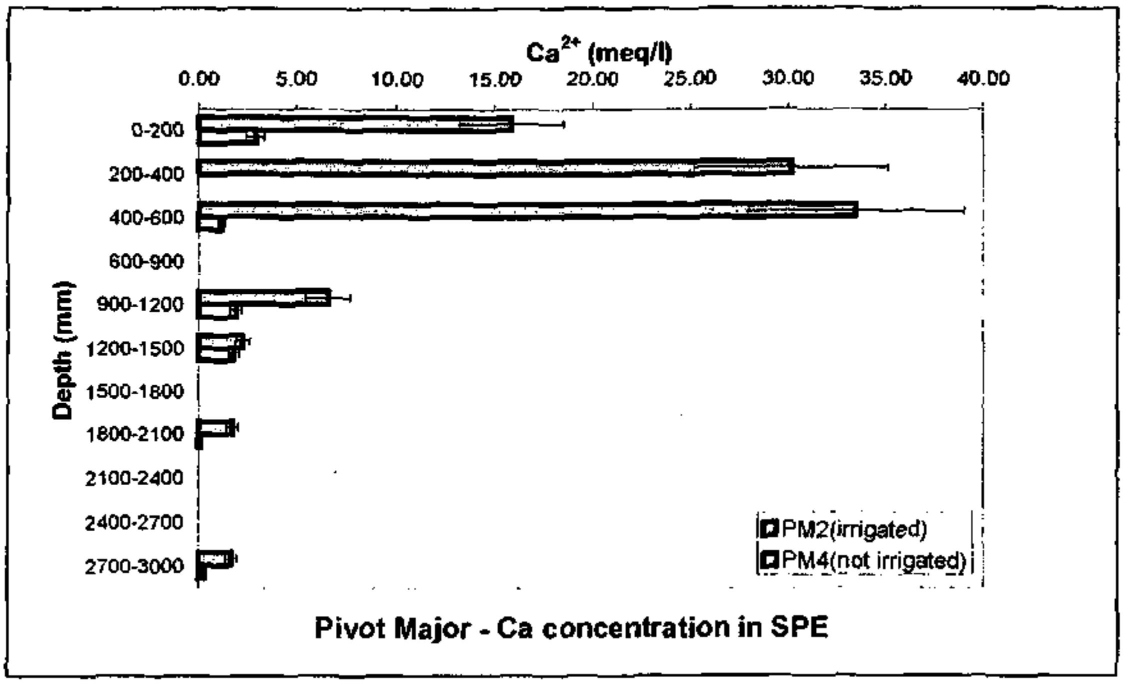


Figure I1. Soluble calcium concentration (meq l^{-1}) of the saturated paste extract (SPE) in the field capacity treatment of pivot Major (PM2) and outside the pivot area (PM4) as a function of depth (mm).

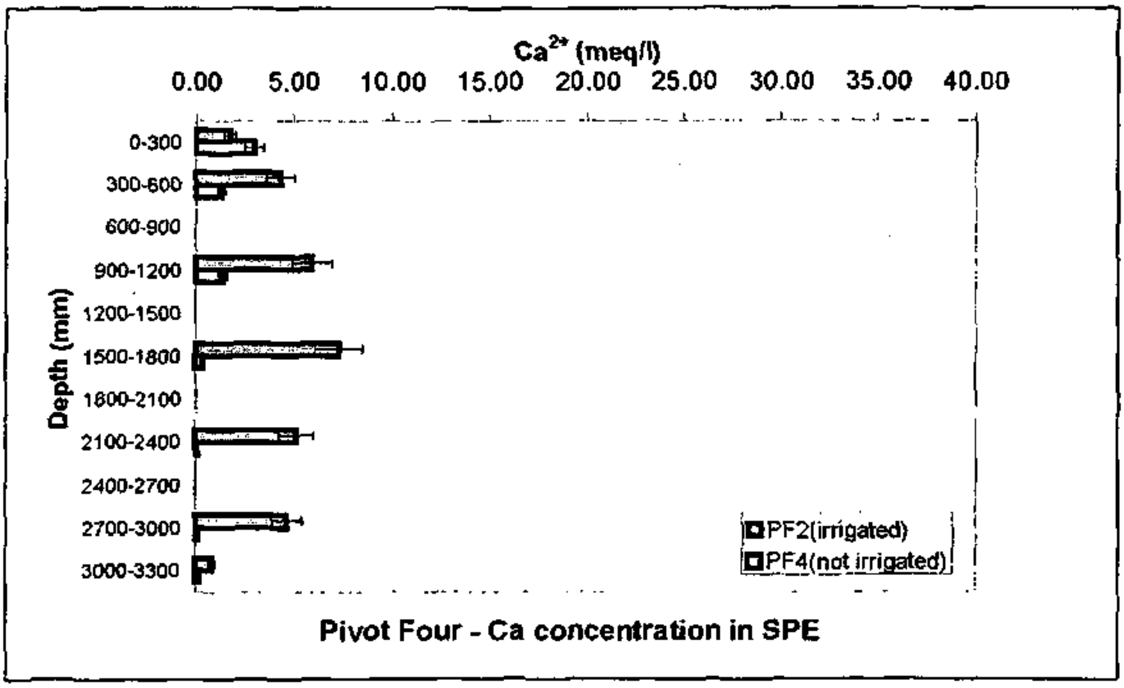


Figure I2. Soluble calcium concentration (meq l^{-1}) of the saturated paste extract (SPE) in the field capacity treatment of pivot Fourth (PF2) and outside the pivot area (PF4) as a function of depth (mm).

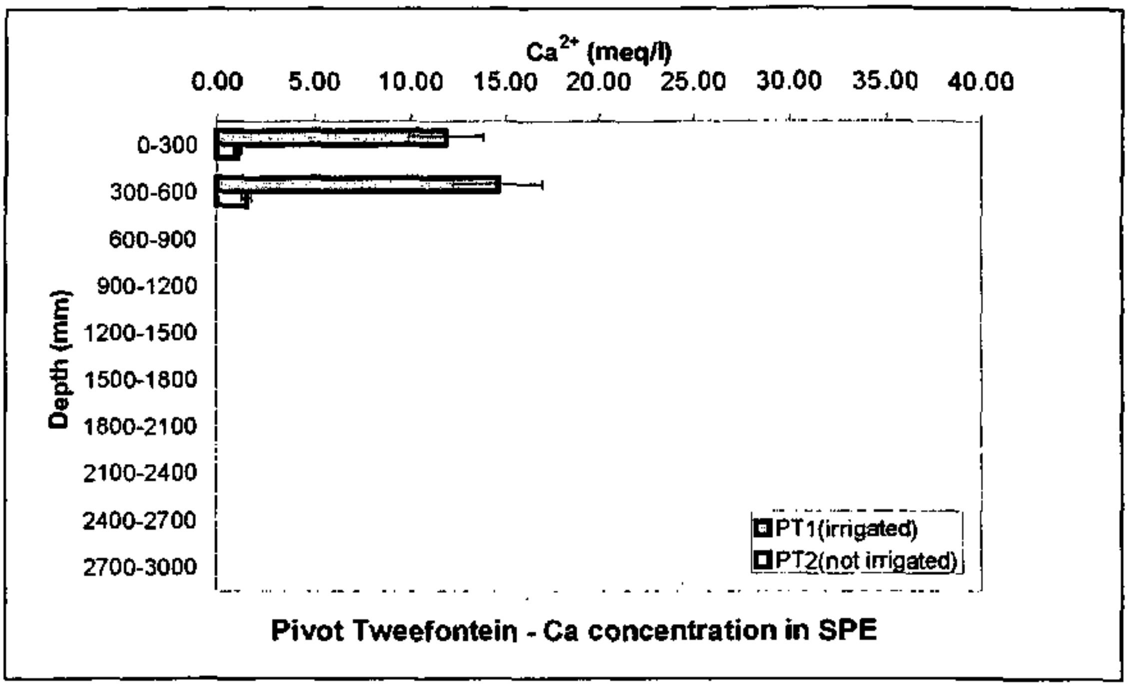


Figure I3. Soluble calcium concentration (meq l^{-1}) of the saturated paste extract (SPE) in the field capacity treatment of pivot Tweefontein (PT2) and outside the pivot area (PT4) as a function of depth (mm).

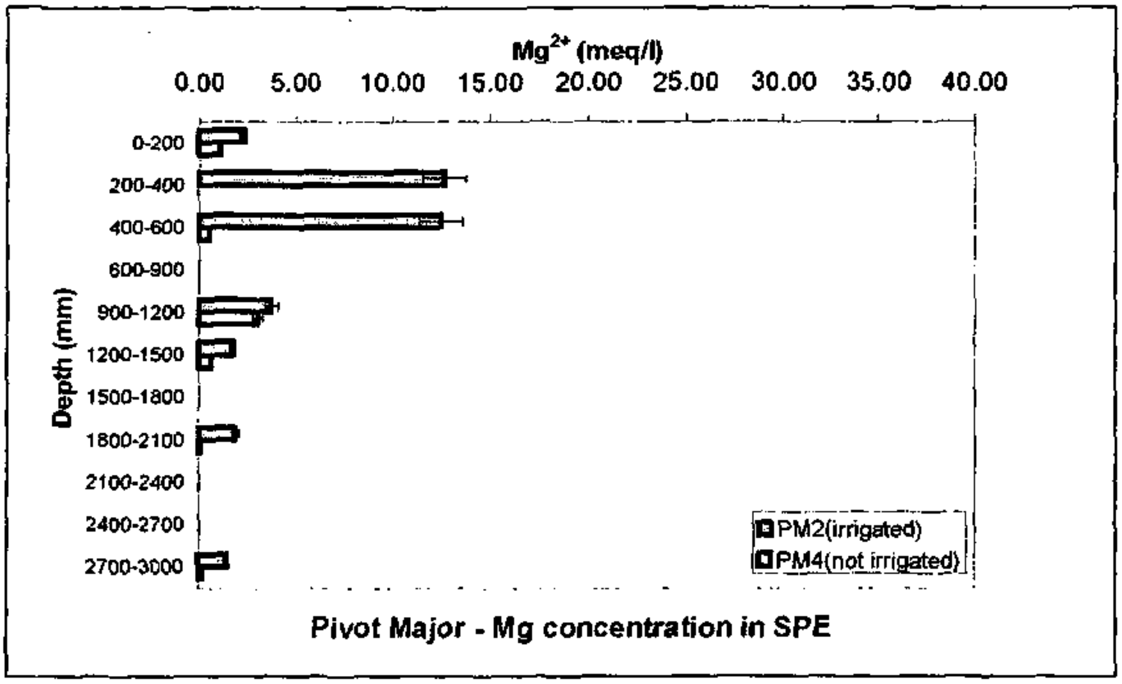


Figure 14. Soluble magnesium concentration (meq l^{-1}) of the saturated paste extract (SPE) in the field capacity treatment of pivot Major (PM2) and outside the pivot area (PM4) as a function of depth (mm).

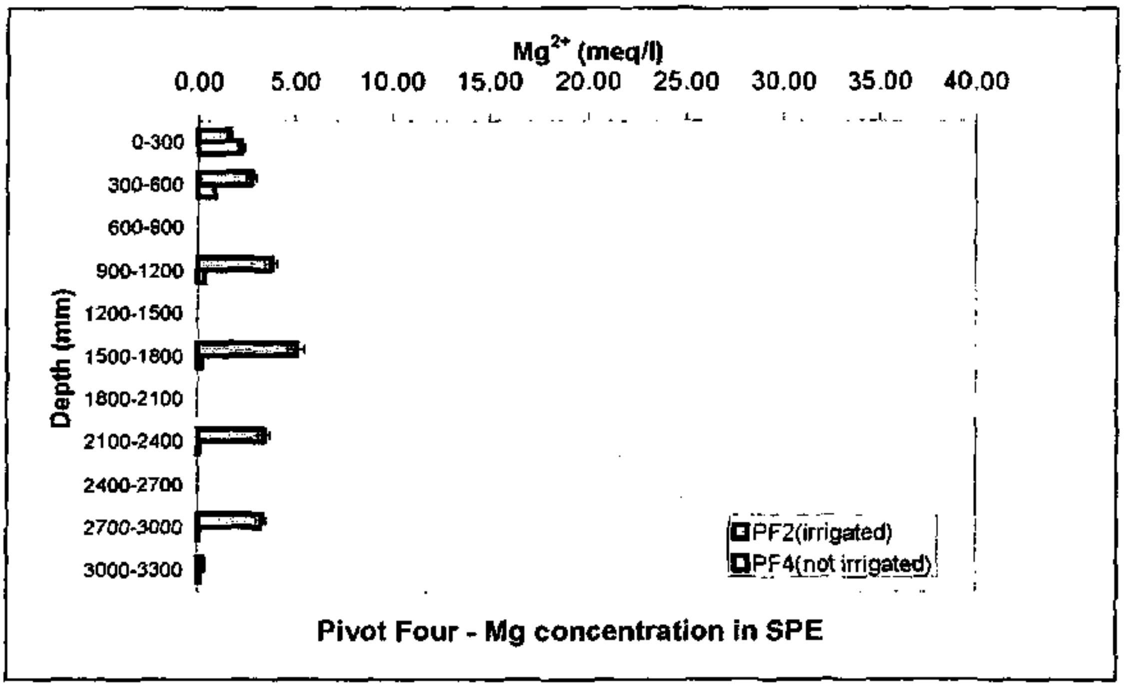


Figure 15. Soluble magnesium concentration (meq l^{-1}) of the saturated paste extract (SPE) in the field capacity treatment of pivot Fourth (PF2) and outside the pivot area (PF4) as a function of depth (mm).

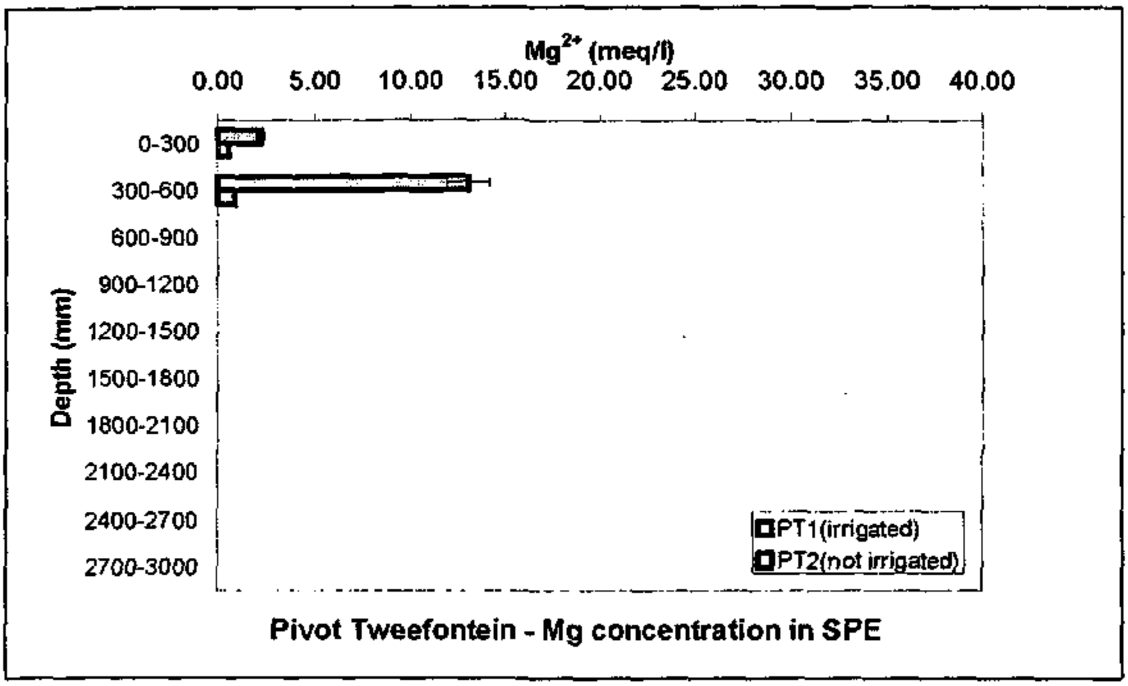


Figure I6. Soluble magnesium concentration (meq l^{-1}) of the saturated paste extract (SPE) in the field capacity treatment of pivot Tweefontein (PT2) and outside the pivot area (PT4) as a function of depth (mm).

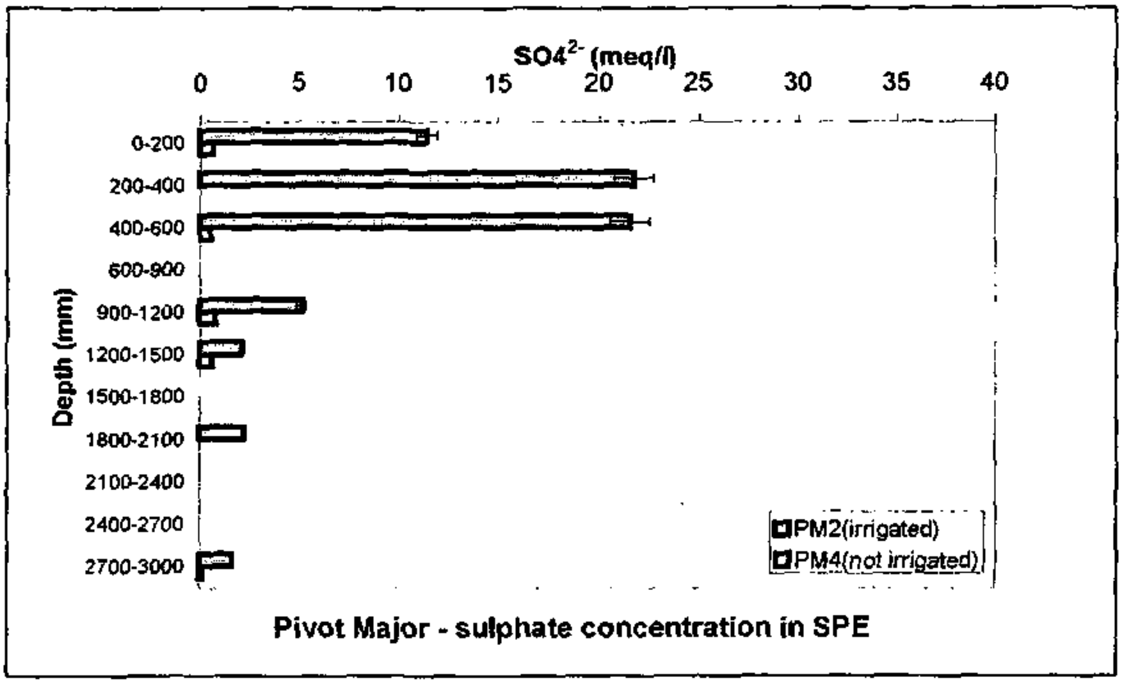


Figure I7. Soluble sulphate concentration (meq l^{-1}) of the saturated paste extract (SPE) in the field capacity treatment of pivot Major (PM2) and outside the pivot area (PM4) as a function of depth (mm).

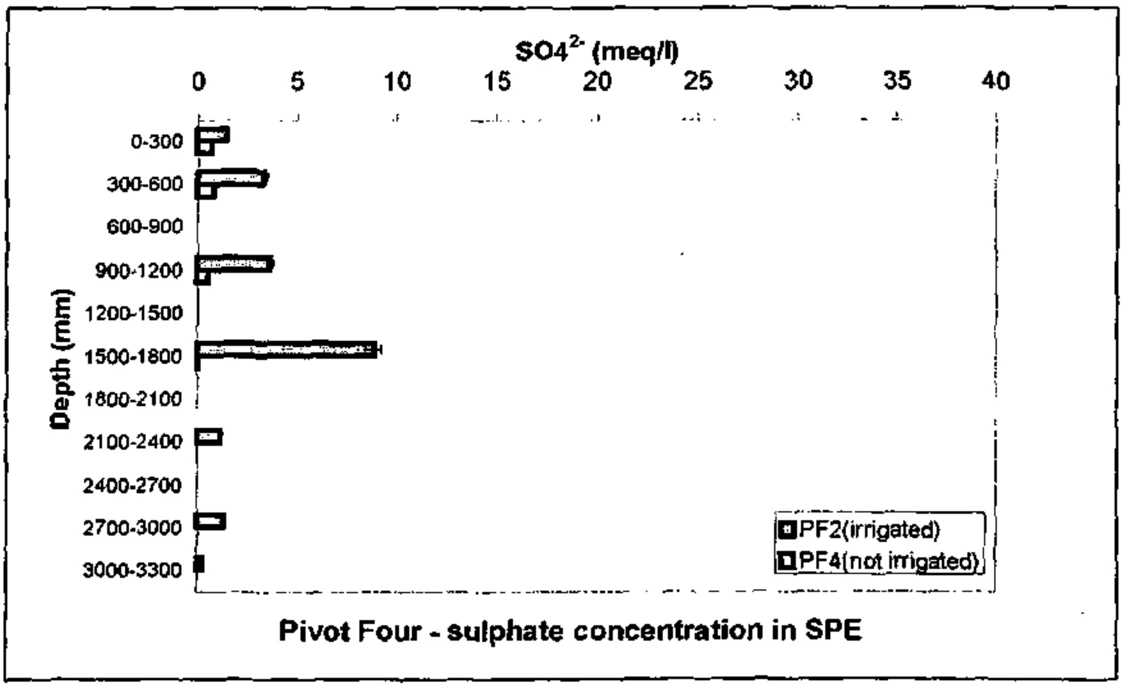


Figure I8. Soluble sulphate concentration (meq l^{-1}) of the saturated paste extract (SPE) in the field capacity treatment of pivot Fourth (PF2) and outside the pivot area (PF4) as a function of depth (mm).

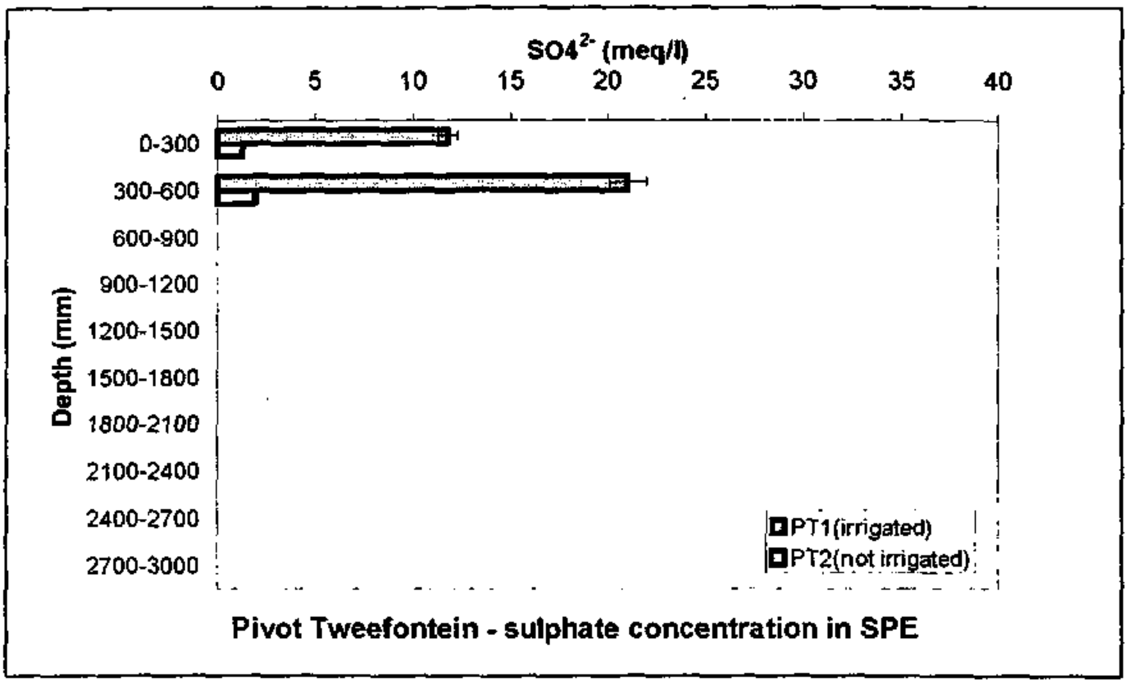


Figure I9. Soluble sulphate concentration (meq l^{-1}) of the saturated paste extract (SPE) in the field capacity treatment of pivot Tweefontein (PT2) and outside the pivot area (PT4) as a function of depth (mm).

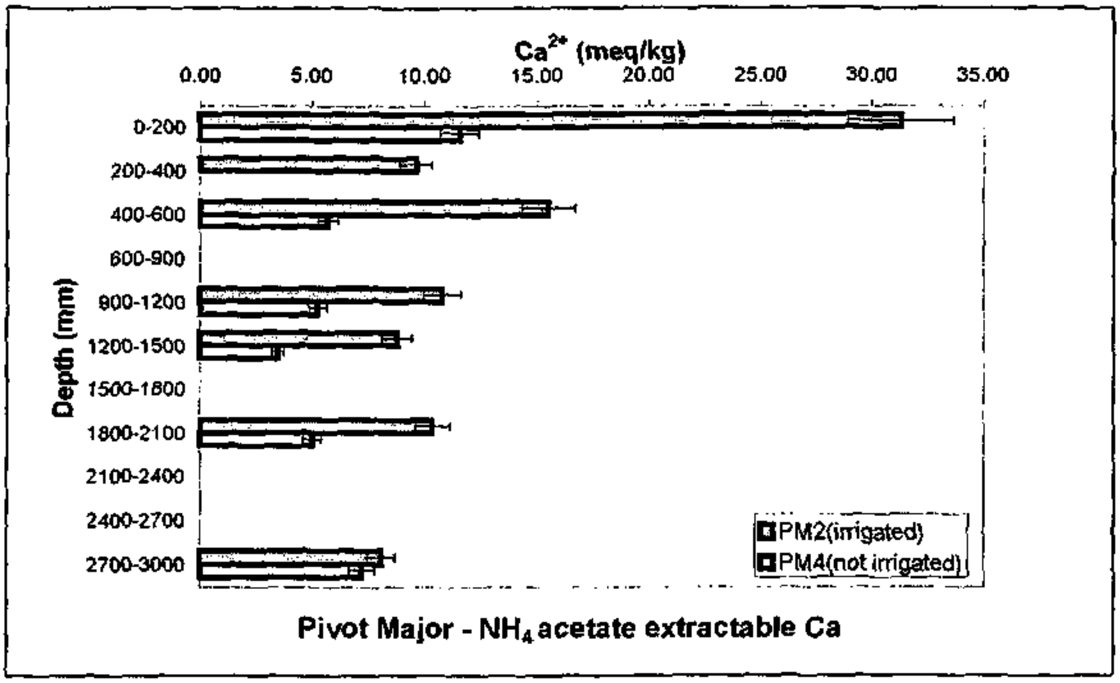


Figure I10. NH$_4$ acetate extractable calcium (meq kg^{-1}) in the field capacity treatment of pivot Major (PM2) and outside the pivot area (PM4) as a function of depth (mm).

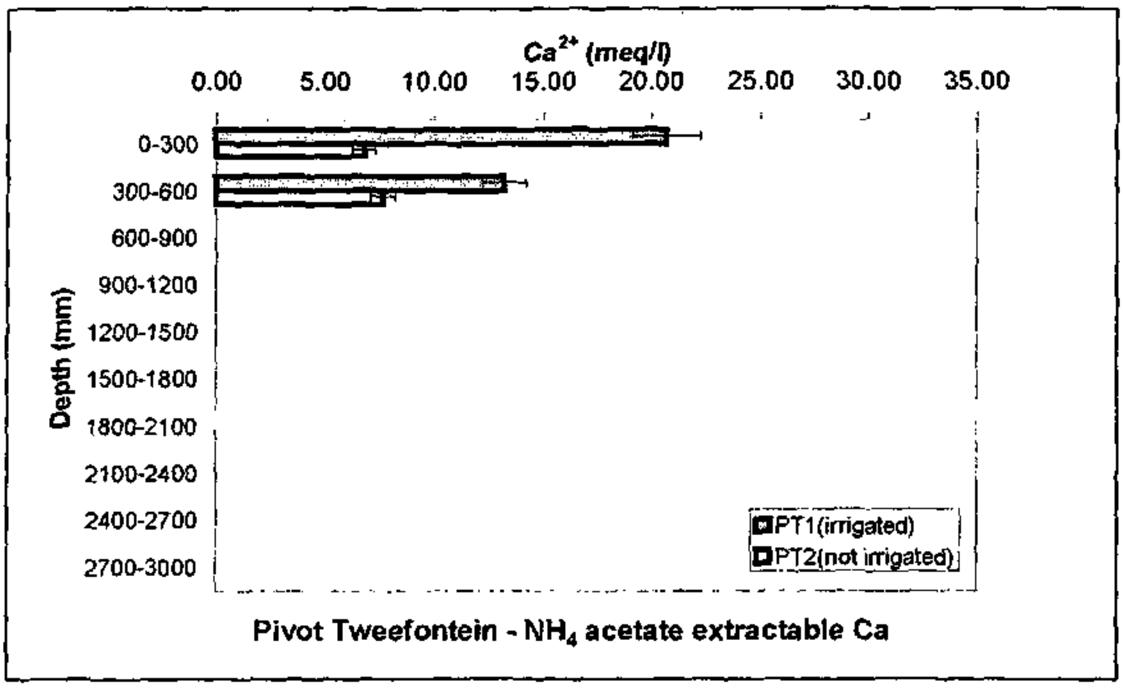


Figure I11. NH$_4$ acetate extractable calcium (meq kg^{-1}) in the field capacity treatment of pivot Tweefontein (PT2) and outside the pivot area (PT4) as a function of depth (mm).

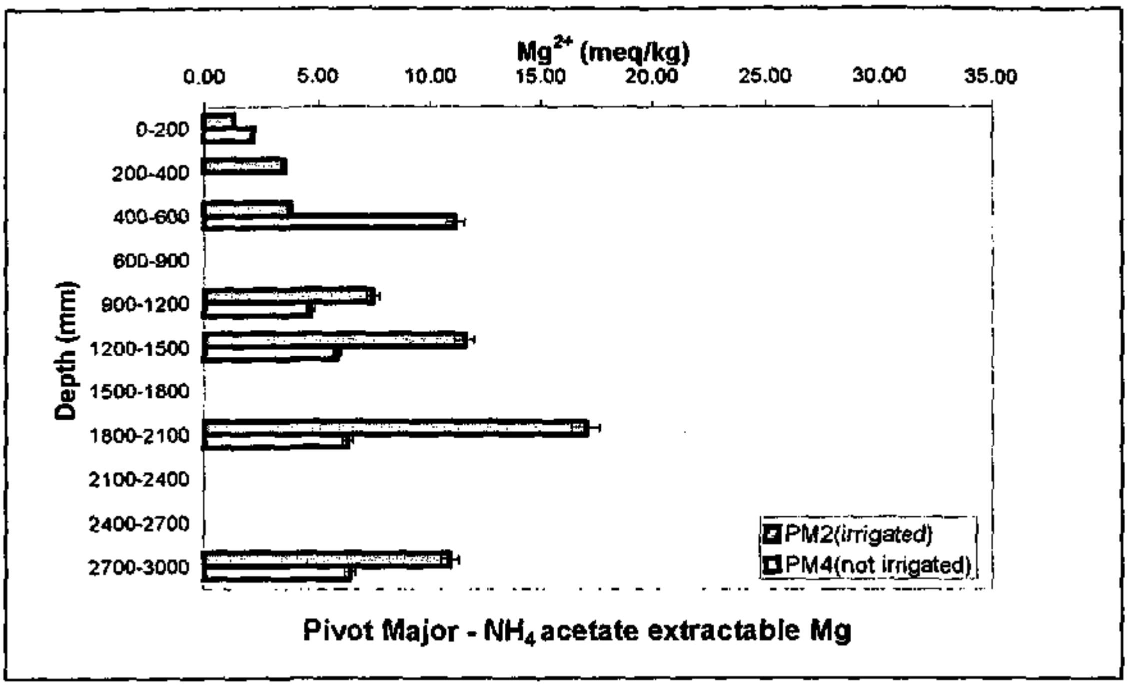


Figure I12. NH_4 acetate extractable magnesium (meq kg^{-1}) in the field capacity treatment of pivot Major (PM2) and outside the pivot area (PM4) as a function of depth (mm).

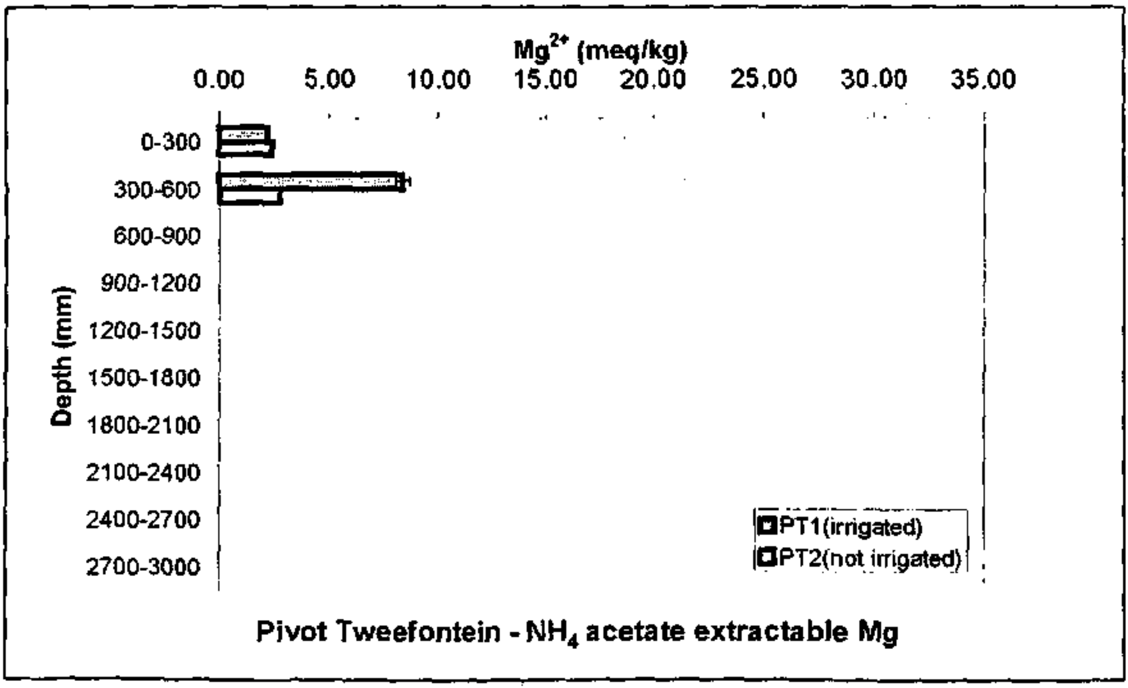


Figure I13. NH_4 acetate extractable magnesium (meq kg^{-1}) in the field capacity treatment of pivot Tweefontein (PT2) and outside the pivot area (PT4) as a function of depth (mm).

Appendix J

Results of chemical analyses of borehole water samples

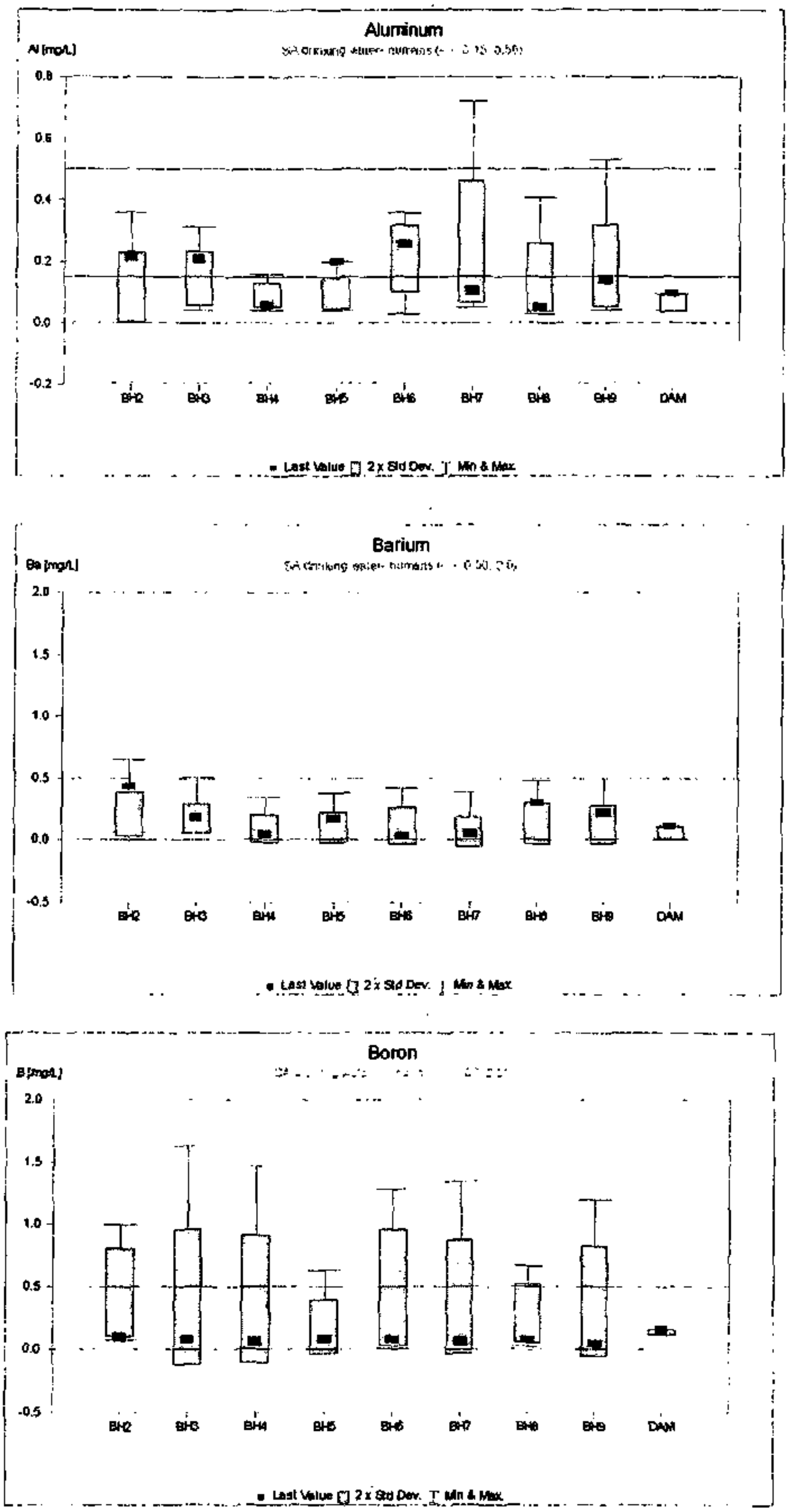


Figure J1. Concentrations of aluminum, barium and boron in boreholes BH2 to BH9 at pivot Major and Jacuzzi dam.

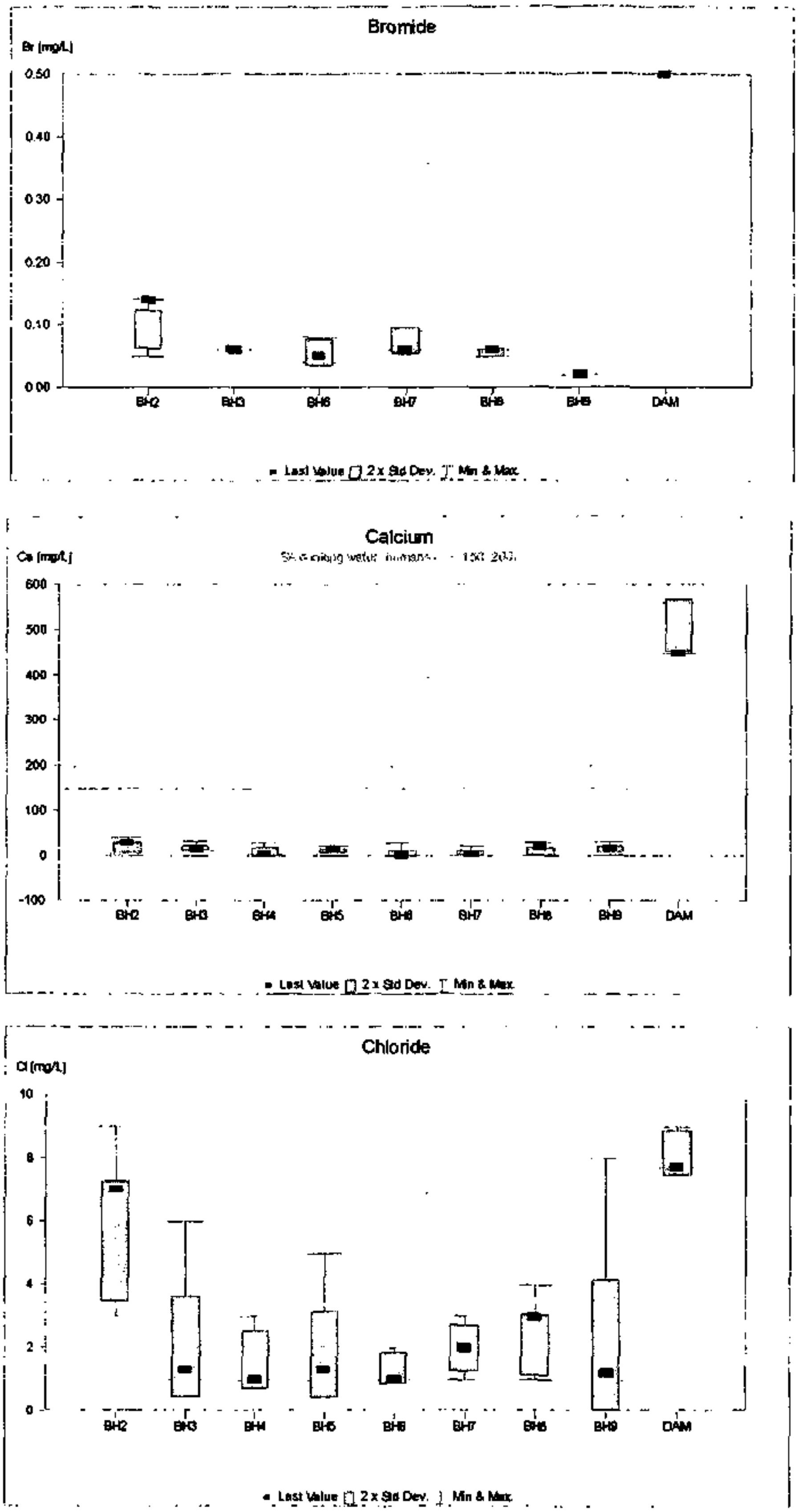


Figure J2. Concentrations of bromide, calcium and chloride in boreholes BH2 to BH9 at pivot Major and Jacuzzi dam.

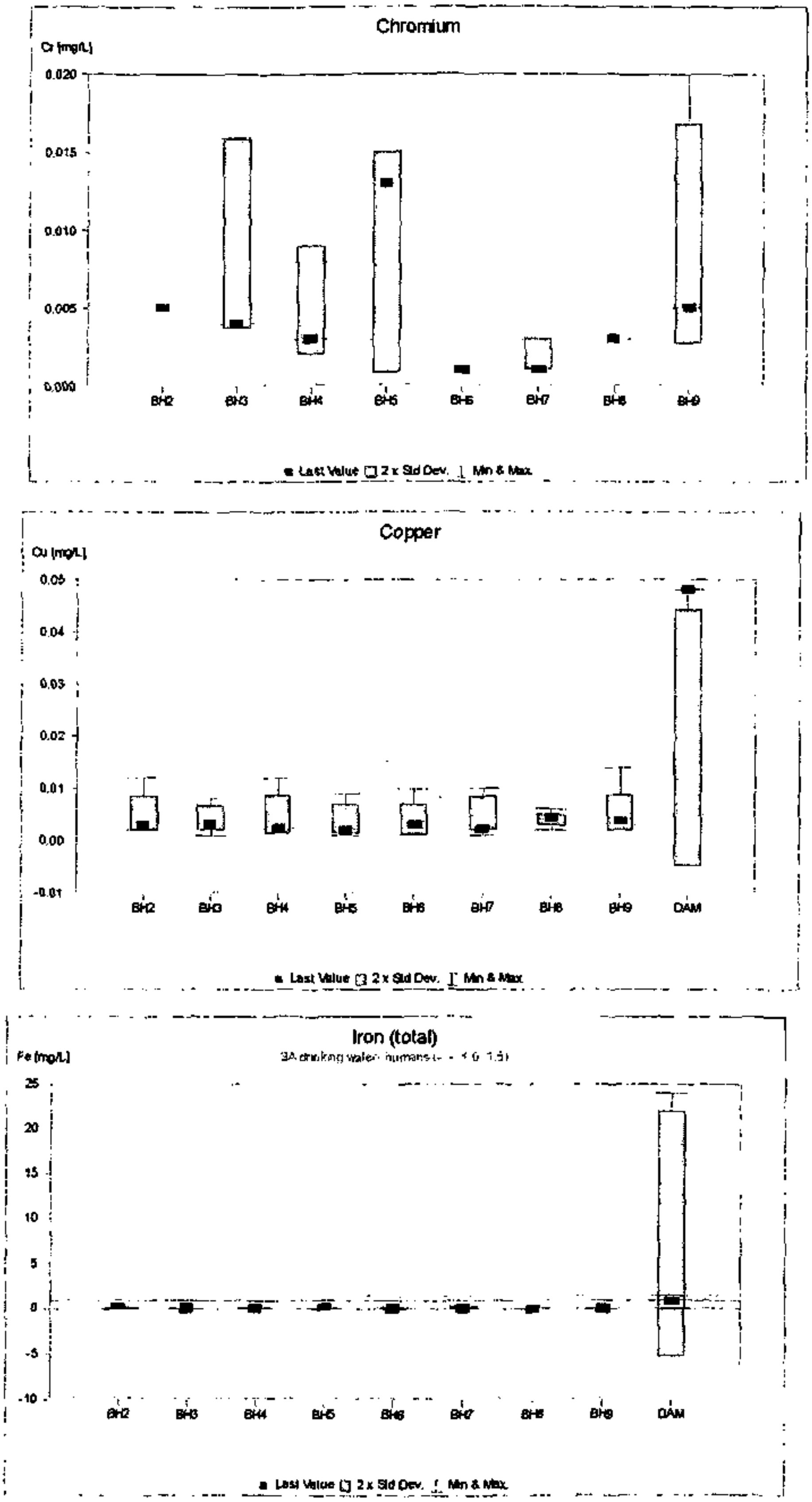


Figure J3. Concentrations of chromium, copper and iron in boreholes BH2 to BH9 at pivot Major and Jacuzzi dam.

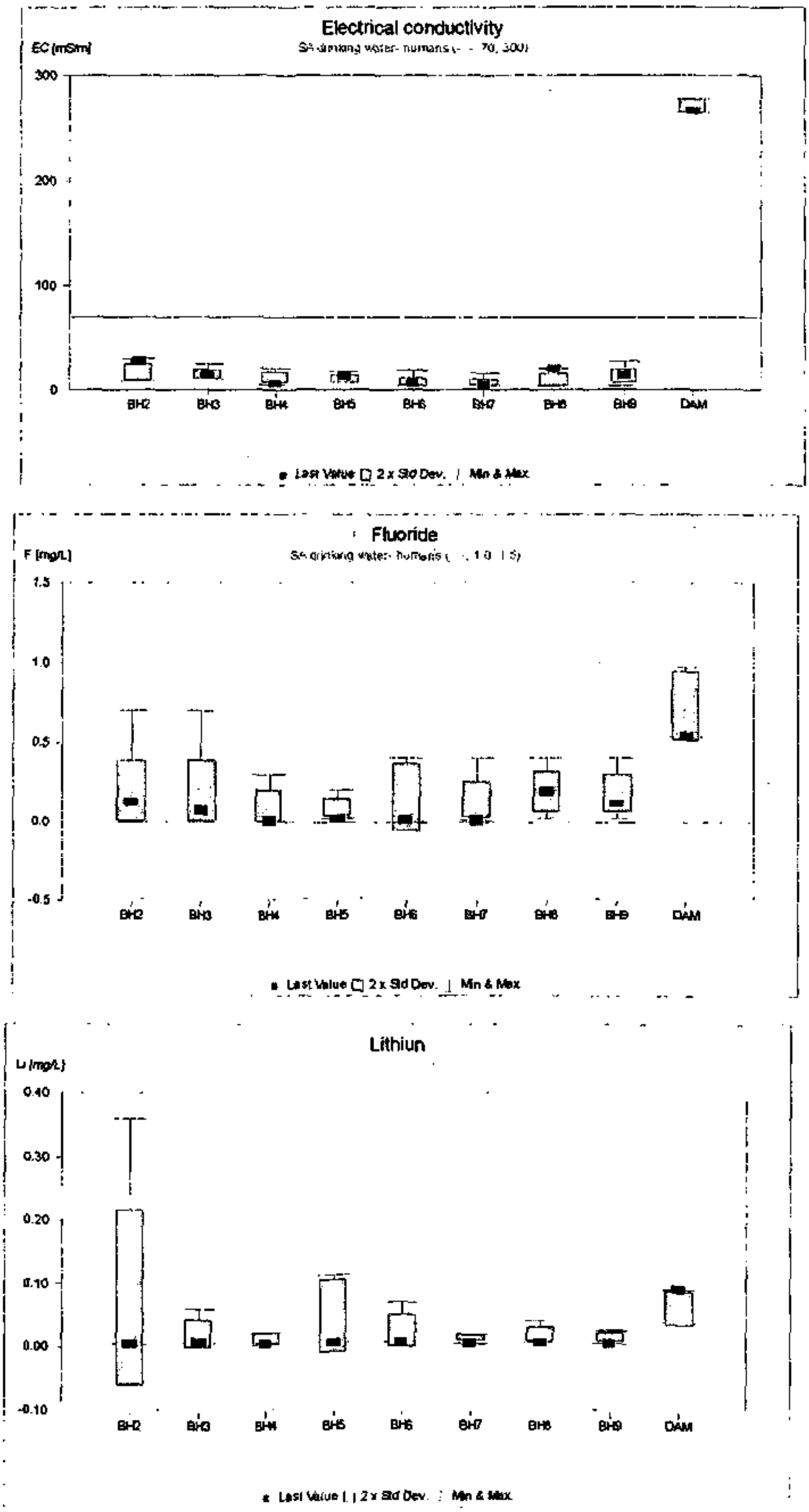


Figure J4. Electrical conductivity and concentrations of fluoride and lithium in boreholes BH2 to BH9 at pivot Major and Jacuzzi dam.

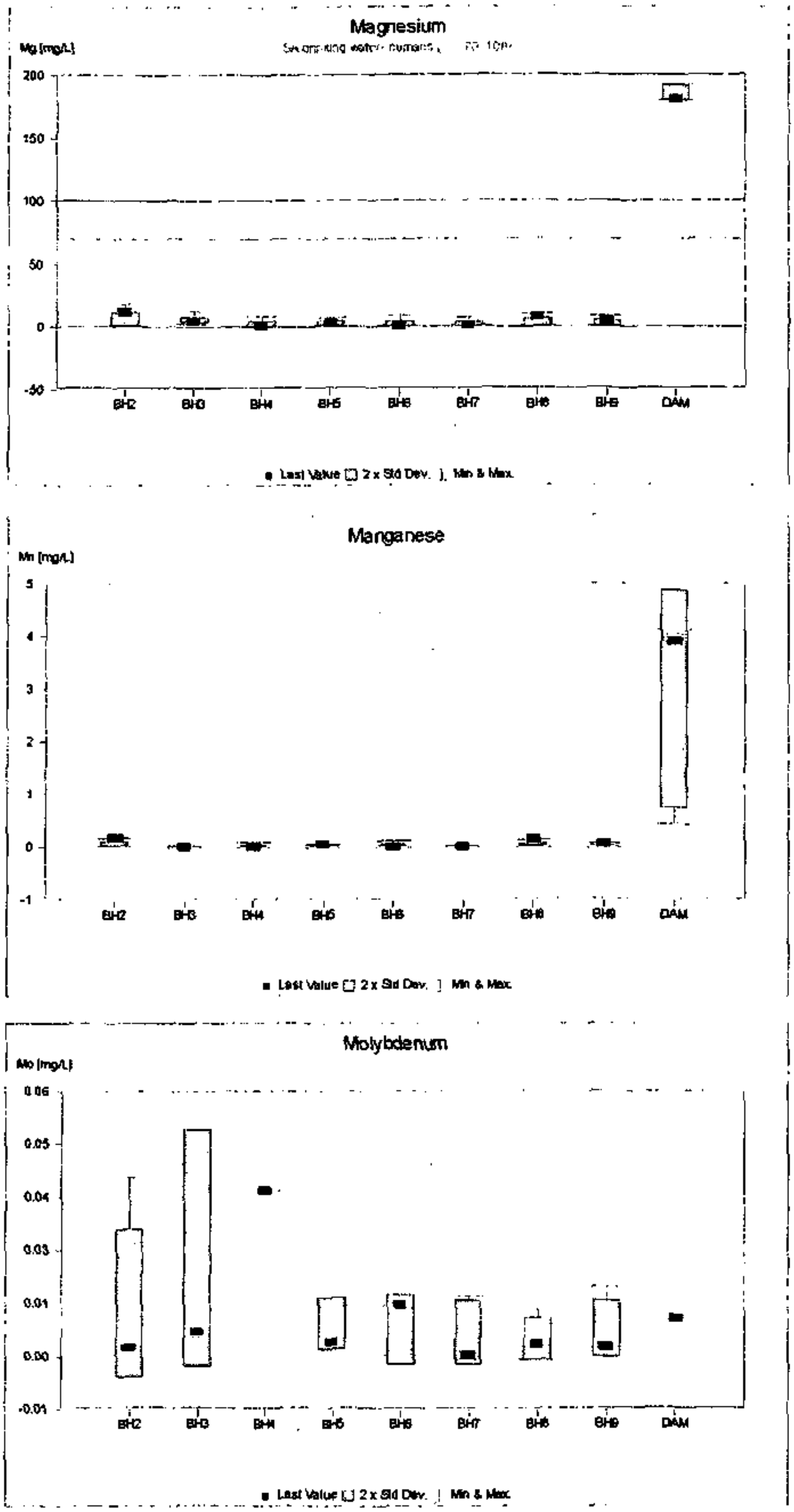


Figure J5. Concentrations of magnesium, manganese and molybdenum in boreholes BH2 *to* BH9 at *pivot* Major and Jacuzzi dam.

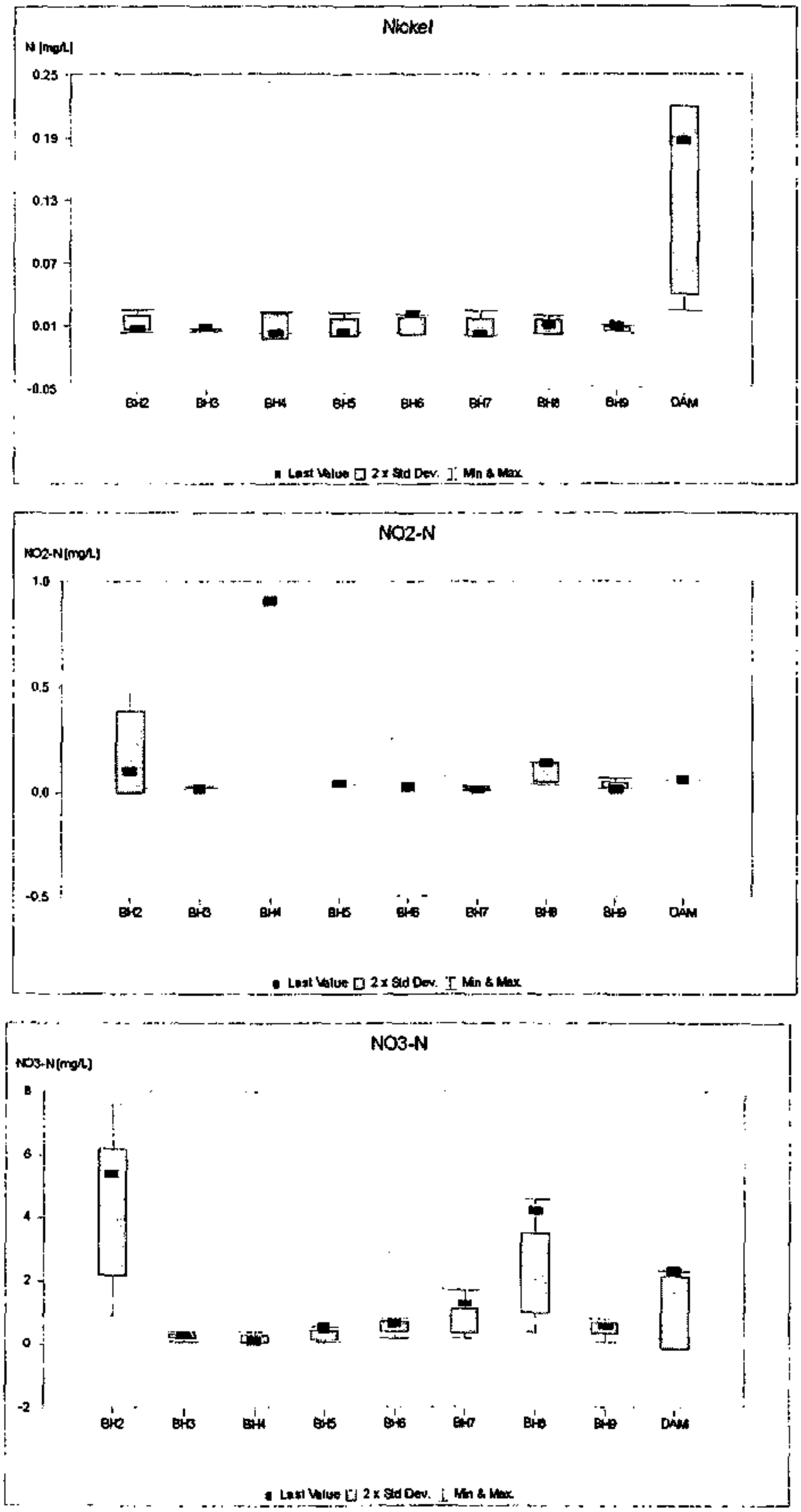


Figure J6. Concentrations of nickel and nitrogen (NO_3 and NO_2) in boreholes BH2 to BH9 at pivot Major and Jacuzzi dam.

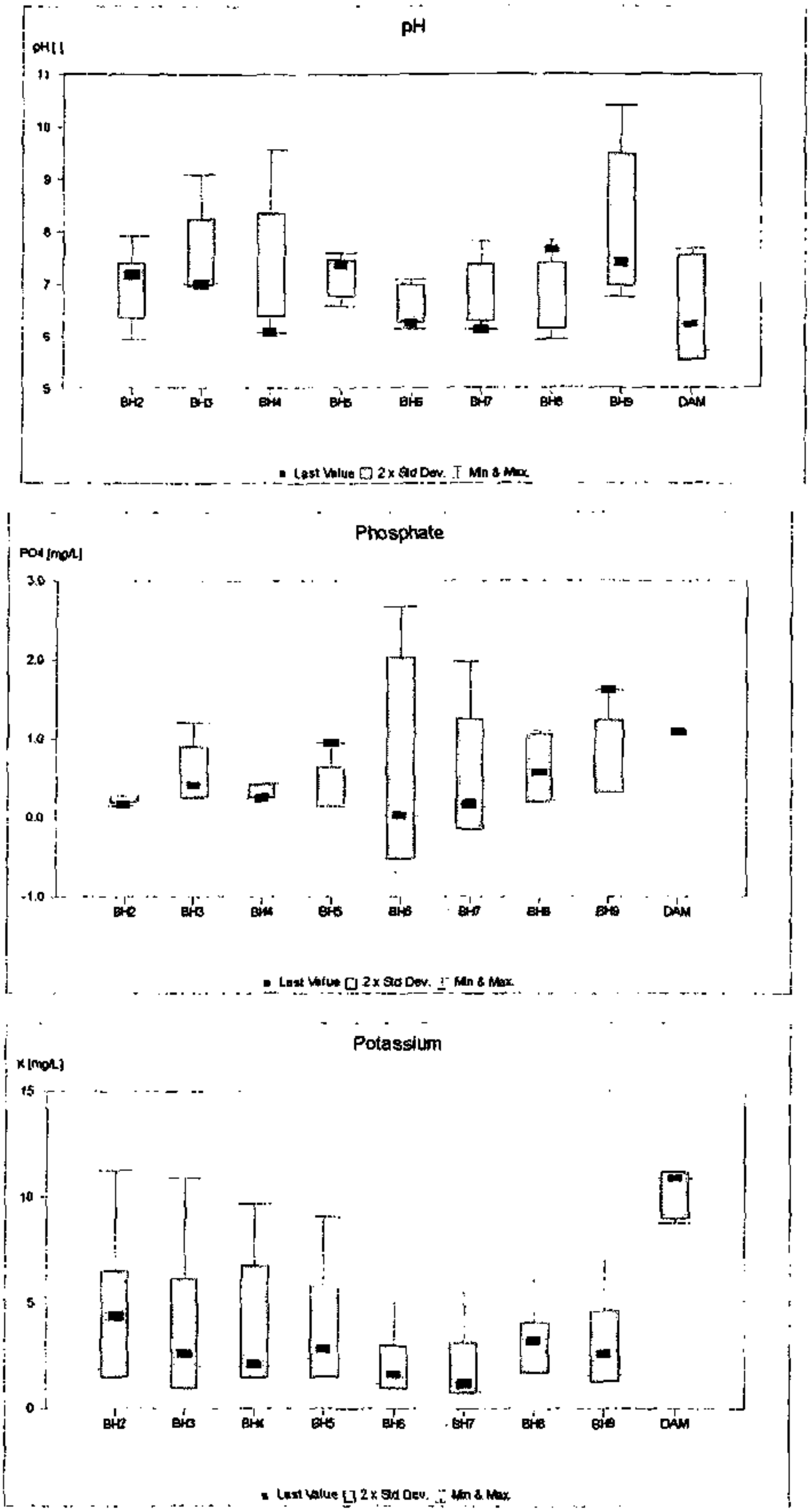


Figure J7. pH and concentrations of phosphate and potassium in boreholes BH2 to BH9 at pivot *Major* and *Jacuzzi* dam.

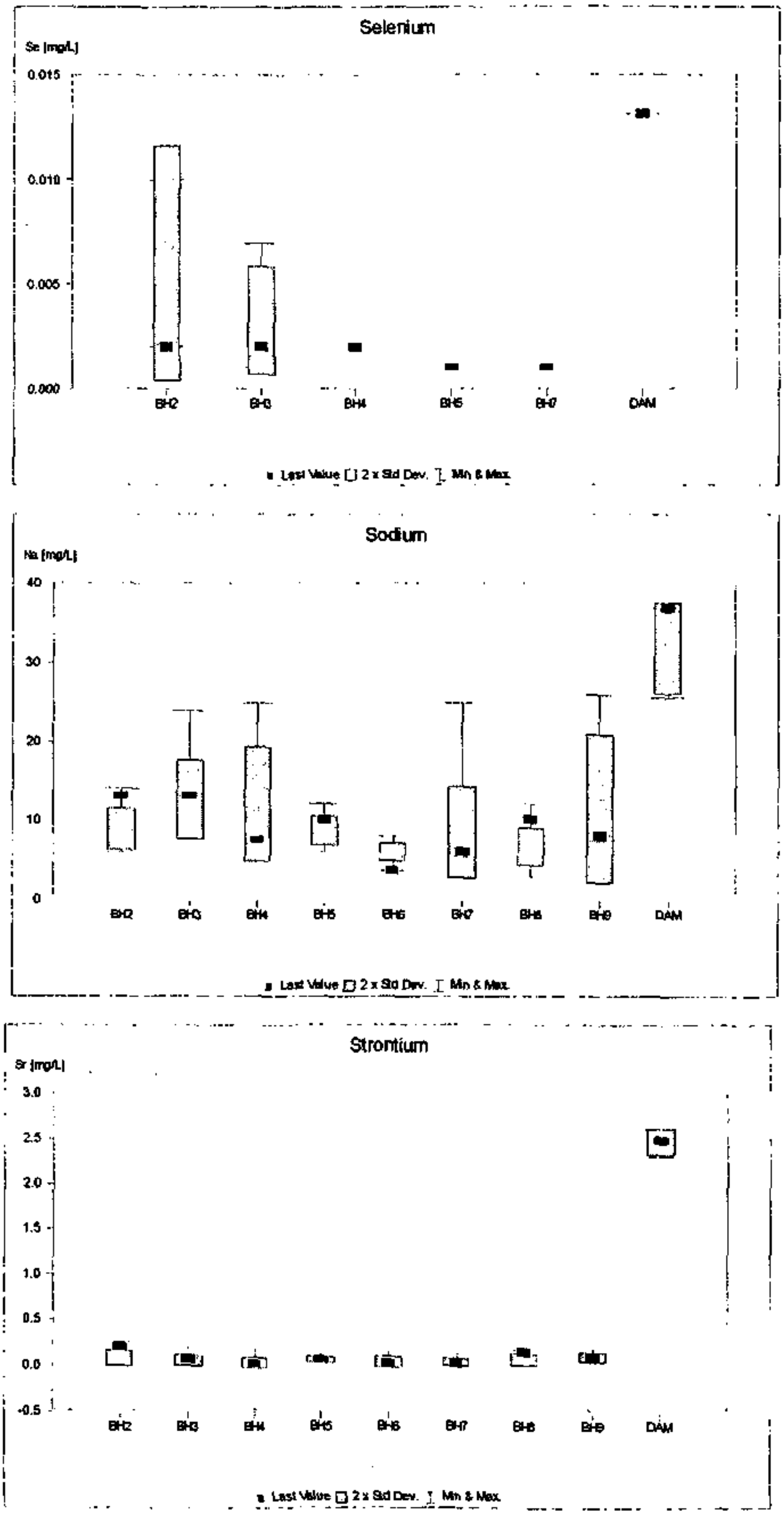


Figure J8. Concentrations of selenium, sodium and strontium in boreholes BH2 to BH9 at pivot Major and Jacuzzi dam.

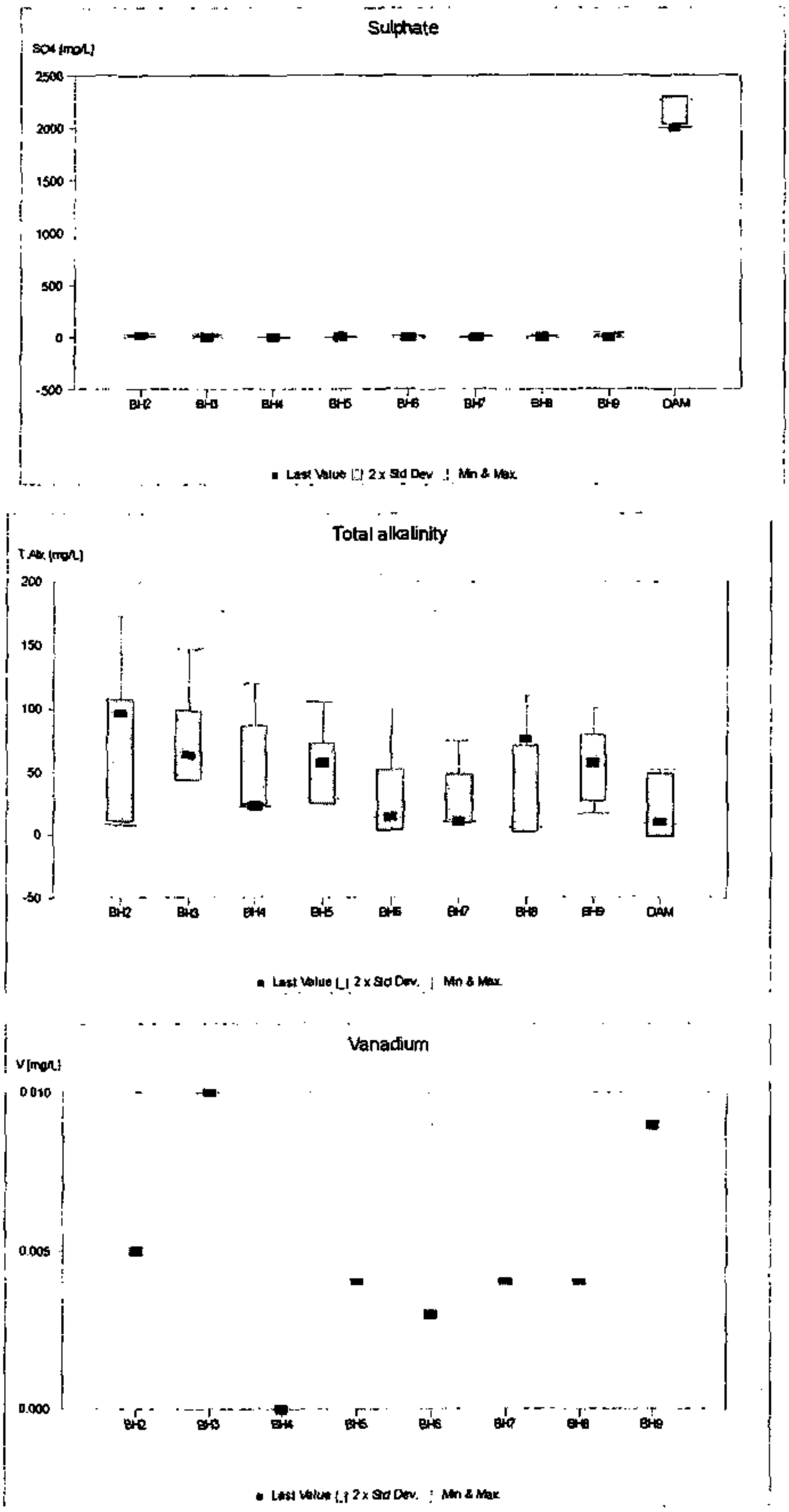
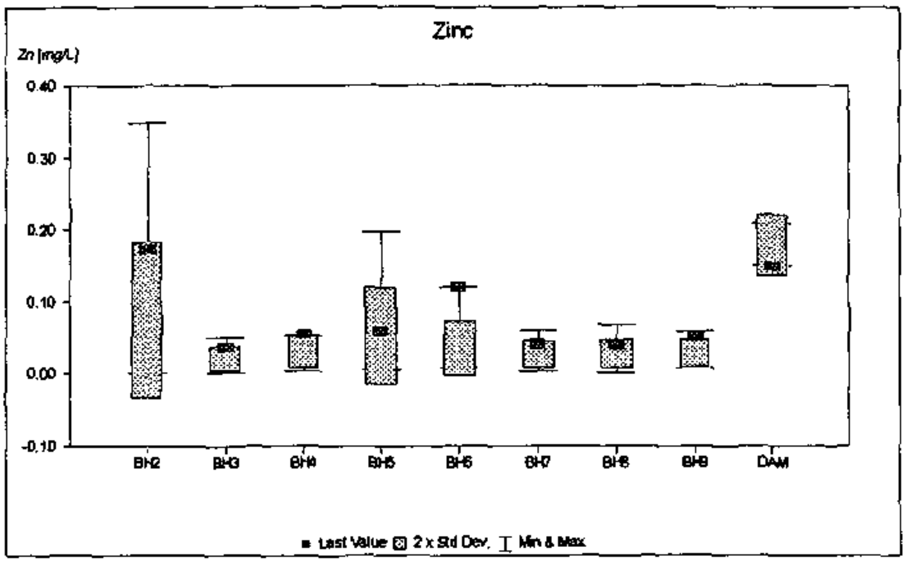


Figure J9. Concentrations of sulphate, total alkalinity and concentrations of vanadium in boreholes BH2 to BH9 at pivot Major and Jacuzzi dam.



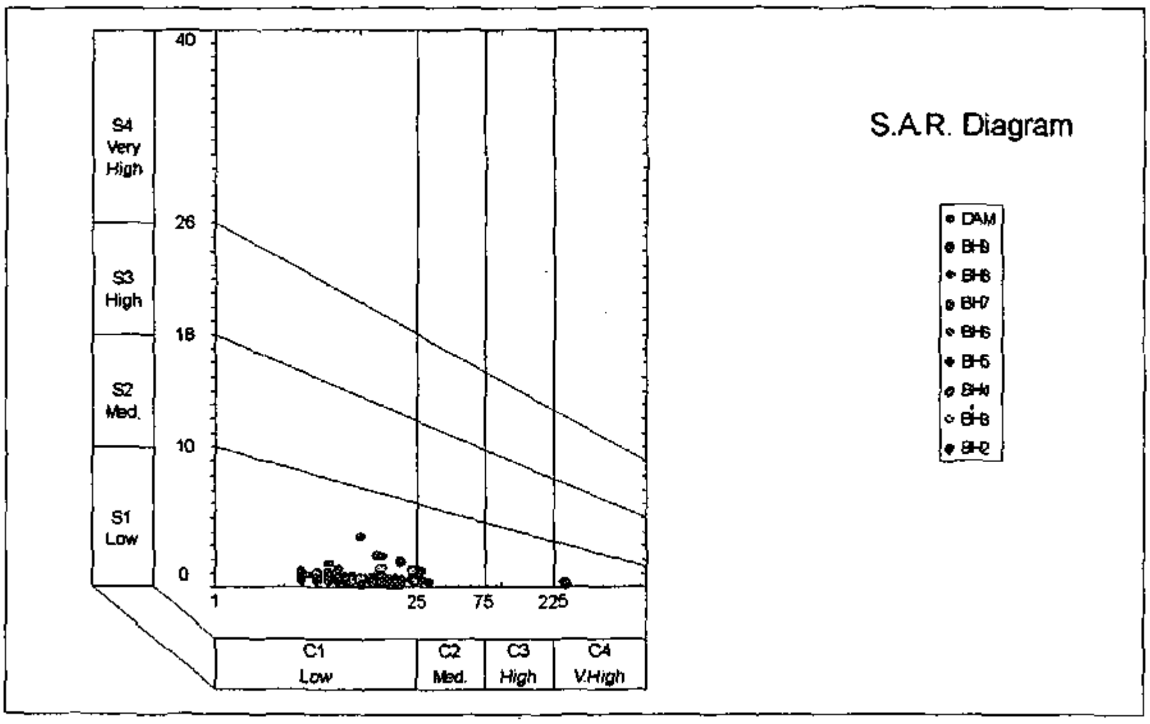


Figure J10. Concentrations of zinc and sodium adsorption ratio diagram for boreholes BH2 to BH9 at pivot Major and Jacuzzi dam.

APPENDIX K

Growth and nutrient composition of *Triticum aestivum* L. as affected by nutritional management under sulphate salinity

Introduction

Accumulation of salts in the root-zone can adversely affect plant growth due to a lowered osmotic potential, caused by the high concentration of soluble ions, specific ion toxicities (Grattan and Grieve, 1994) or nutritional imbalances (Bernstein et al., 1974). Most crop plants have evolved under conditions of low soil salinity and consequently have developed mechanisms for absorbing nutrients in non-saline soil. The utilization of soils containing excessive amounts of Ca, Mg and SO_4 raises the problem of providing growing conditions that will support reasonable plant productivity. Mashali (1996) reported that high concentrations of Ca and SO_4 in the soil solution could decrease the plant uptake of K, Mg, Mn, Fe, Cu, Zn, PO_4 and NO_3 through ion competition and complementary ion effects on nutrient uptake. High concentrations of Ca and Mg in the soil solution may lead to a substantial release of K from the adsorption complex with a possible loss through deep percolation under leaching. Excessive amounts of gypsum in the active root-zone may also affect nutrient availability and uptake by plants (Mashali, 1996). The precipitation of phosphate ions and fixation of micronutrients in an unavailable form seems to be the most compelling problems associated with excessive gypsum in the soil (Panahi and Rowell, 1996; Mashali, 1996; Oyonarte et al., 1996). Excessive gypsum may further cause loss of nutrients through cation and anion interaction effects (Mashali, 1996; Fey et al., 1997).

If salinity causes certain nutritional deficiencies or imbalances, the possibility exists that application of this specific nutrient can alleviate the inhibition of growth by salinity. Several studies have shown that crop growth under NaCl-saline conditions can be sustained and even improved with specific fertilizer application (Papadopoulos and Rendig, 1983; Cordovilla et al., 1995; Khan et al., 1994; Gómez et al., 1996). There is, however, very little systematic information in respect of nutritional management under sulphate-dominated salinity. An attempt to alleviate the effects of salinity on agricultural crops by changing the nutritional regime from that considered appropriate for non-saline conditions would be of great economic importance.

This study was undertaken to determine the effect of calcium and magnesium sulphate salinity on crop growth and yield and compare crop response to SO_4-salinity at differential levels of NO_3, NH_4, P and K in order to give guidelines for the management of crops irrigated with such waters.

Materials and methods

Experimental procedure

The investigation was conducted in solution culture under controlled glasshouse conditions. Wheat (*Triticum aestivum* L.) cv. SST 825 was used as test crop. Seeds were germinated in vermiculite and after 10 days, four sets of five uniform seedlings were transplanted to 11 l of the treatment solutions. The seedlings were supported with foam rubber strips through holes in the lids of the containers. The pots were placed on rotating tables and aerated continuously to ensure uniform radiation on plants. The treatments consisted of a control (full strength modified Hoagland solution no. 2, P supplied at half strength) (Hoagland and Arnon, 1950), one calcium and magnesium sulphate salinized control (K, NO_3 and NH_4 supplied as full strength Hoagland solution no. 2, P supplied at half strength) and nine calcium and magnesium sulphate salinized treatments with differential levels of K (3, 8 and 10 mmol l^{-1}), P (0.25 and 0.75 mmol l^{-1}), NO_3 (7 and 20 mmol l^{-1}) and NH_4 (7 and 9 mmol l^{-1}). The nutrient solutions of the salinized treatments were salinized with approximately 15 mmol l^{-1} Ca, 7 mmol l^{-1} Mg and 22 mmol l^{-1} SO_4 and had a mean EC of 355 mS m^{-1} over the experimental period compared to a mean EC of 175 mS m^{-1} of the control. Other than the nutrient under study, all other nutrients were approximately balanced to give a full strength Hoagland solution. Micronutrients were added as a full Hoagland solution to provide 0.5 mg l^{-1} B (as H_3BO_3), 0.5 mg l^{-1} Mn (as $MnSO_4.4H_2O$), 0.05 mg l^{-1} Zn (as $ZnSO_4.7H_2O$), 0.02 mg l^{-1} Cu (as $CuSO_4.5H_2O$), 0.01 mg l^{-1} Mo (as $NaMoO_4.2H_2O$) and 1 mg l^{-1} Fe (as ferric sodium EDTA). The nutrient solutions were replaced once a week.

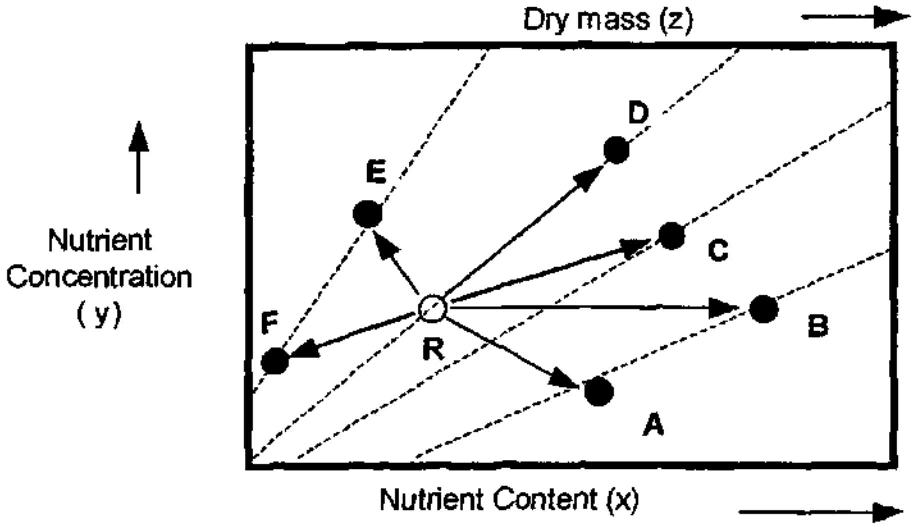
Growth and nutrient concentration measurements

Roots and tops were harvested separately, 28 days after transplanting the seedlings. The plant parts were washed with deionized water, dried at 65°C and weighed. The top dry matter of the replicates for each treatment was then composted, milled and chemically analysed according to the standard procedures as prescribed by ALASA (1998). Nitrogen and P 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 wet-digested using nitric-acid and perchloric acid in a digestion block. These nutrients were analysed by atomic absorption spectroscopy.

Statistical analysis and data interpretation

Dry matter production and leaf nutrient composition data were evaluated statistically by analysis of variance (ANOVA) (Genstat 5 Committee of the Statistics Department, 1993). The Bonferroni multiple comparison test was used to compare treatments when the ANOVA showed significant differences among means. Data of the top dry matter yield and chemical composition were interpreted using a graphical vector nutrient diagnostic technique (Timmer and Stone, 1978; Timmer and Teng, 1999). Its application recognizes and applies the biological principle that growth of plants is dependent on nutrient uptake (or content). The nutrient content in the plant is estimated as the product of the plant nutrient concentration and biomass accumulation. A brief discussion of the method follows.

The relationship between nutrient content and biomass accumulation is examined by comparing growth and nutrient status of plants, differing in productivity with the aid of a nomogram. Biomass (z) is plotted on the upper horizontal axis, plant nutrient content (x) on the lower horizontal axis, and corresponding plant nutrient concentration (y) on the vertical axis (Figure K1). The dashed diagonals are isopleths representing change of y on x where z remains unchanged. When normalized to a specified reference sample (usually the control set to 100%), differences are depicted as vectors because of shifts in both direction and magnitude. Analysis of any set of data is based on vector direction of individual nutrients, identifying occurrence of dilution (A), sufficiency (B), deficiency (C), luxury consumption (D), toxicity (E) and antagonism (F) as illustrated in Figure K1. Each configuration corresponds to a specific phase in dose response curves relating changes [increasing (+), decreasing (-), or none (0)] in plant growth, nutrient content and nutrient concentration to increasing nutrient supply in the growth medium. Vector magnitude reflects the extent or severity of specific diagnoses, and facilitates relative ranking and prioritising.



Vector shift	Change in relative z	x	y	Nutritional effect	Nutrient status	Possible diagnosis
A	+	+	-	*Dilution*	*Non-limiting*	*Growth dilution*
B	+	+	o	Accumulation	Non-limiting	Sufficiency, steady-state
C	+	+	+	Accumulation	Limiting	*Deficiency response*
D	o	+	+	Accumulation	Non-limiting	Luxury consumption
E	-	-, +	+	Concentration	Excess	Toxic accumulation
F	-	-	-	Antagonism	Limiting	Induced deficiency by E

Figure K1. Nutrient vector analysis. Interpretation of directional changes in relative dry mass and nutrient status of plants differing in productivity (modified from Timmer and Teng, 1999).

Results and discussion

High concentrations of sulphate salts were reported to cause disorder symptoms typical to that of salt affected plants, i.e. a reduction in growth rate and a dark green colour of the leaves (Mengel and Kirkby, 1987). The top growth of plants of this experiment grown with high concentrations of calcium and magnesium sulphate were, however, chlorotic when compared to the control plants. The mean root and top dry matter yields (Table K1) revealed that the top growth of the salinized treatment plants was relatively more depressed than the root growth when compared to that of the control. There were no significant differences between treatments at the 5% significance level using the Bonferroni multiple comparison test. This comparison test is, however, very stringent for use in interpreting data from nutrient solution trials. The F-probability value of the analysis of variance indicated that differences between the largest and smallest mean top dry matter yields were significant at the 5% probability level.

Root growth of the 3 and 8 mmol l^{-1} K and 7 mmol l^{-1} NH_4 salinized treatments was better than that of the control. Although the top growth yield of the salinized treatment plants was lower than that of the control, the application of NO_3 at a level 7 mmol l^{-1} lower, and NH_4 and K at respective levels of 6 mmol l^{-1} and 2 mmol l^{-1} higher than the level considered beneficial for non-saline conditions, improved top growth of wheat under sulphate saline conditions. Different levels of P under calcium and magnesium sulphate saline conditions had no effect on top dry matter production. The highest top dry matter yield of the SO_4 salinized treatments was attained with the 7 mmol l^{-1} NH_4 treatment (NO_3:NH_4 ratio 2:1). This is of great significance, since NH_4 concentrations greater than 5 mmol l^{-1} in the growth medium are generally reported to be toxic to crops (Magalhães and Wilcox, 1984; Magalhães et al., 1995). No symptoms of NH_4 toxicity were observed in this experiment, even at the highest NH_4 application level. In addition to this, results obtained by Barnard et al. (1998) and from a pilot test study conducted prior to this experiment explicitly indicated that a NO_3:NH_4 ratio of 2:1, even at low NH_4 concentrations in the growth medium, severely suppressed the growth of wheat under non-saline conditions, while the growth of SO_4 salinized plants was normal.

Table K1. Mean root and top dry matter yields of wheat plants.

Mean dry mass per pot (g)	Treatments (mmol l^{-1})										
	Control	Salinized control	7 NO_3	20 NO_3	7 NH_4	9 NH_4	0.25 P	0.75 P	3 K	8 K	10 K
Roots	1.38	1.23	1.26	1.08	1.46	1.22	1.01	1.04	1.40	1.52	1.30
Tops	6.12	3.85	4.86	4.09	6.01	4.19	3.79	3.86	4.28	5.69	4.29

Root growth $p = 0.167$, c.v. 21.7%; Top growth $p = 0.029$, c.v. 24.8%

The nutrient concentrations in the top growth are given in Table K2. The N concentration in plants decreased with increasing K supply, while it tended to increase with an increased NH_4 concentration in the medium but not with NO_3. Also, at comparable solution N concentrations of 21 mmol l^{-1} (20 mmol l^{-1} as NO_3 and 1 mmol l^{-1} as NH_4) and 21 mmol l^{-1} (14 mmol l^{-1} as NO_3 and 7 mmol l^{-1} as NH_4), tissue N concentrations were higher where the NO_3:NH_4 was 2:1, suggesting that N utilization efficiency was higher with NH_4 than with NO_3. This is presumably due to the lower energy cost of NH_4 uptake, which is a result of active and passive uptake of this cation, and that NH_4 as a cation can follow its electrochemical gradient in wheat seedlings (Botella et al., 1994). It may also be possible that the N utilization efficiency was higher with NH_4 than with NO_3 since high SO_4 concentrations suppressed NO_3 uptake. Ammonium, with respect to NO_3, Cl and SO_4, was further reported to restore the electrical equilibrium that is disturbed by high anion levels (Villora et al., 1998). Although the N concentration of the plants was adequate to high, the N:S ratio in plants of all treatments was below the optimal ratio of 15:1, reported for maximum dry matter production of wheat (Zhao et al., 1997). The plants of the salinized treatments accumulated large concentrations of SO_4 relative to the control plants. Root dry matter yields decreased significantly with increasing concentrations of SO_4 in the top growth of plants, while top growth yields were significantly decreased with increasing Mg and SO_4 concentrations in the top growth. The Mg concentration in plants of all the salinized treatments was, however, lower than 0.5%, which is the concentration above which Mg is reported to be high in wheat (Reuter, 1986). The Ca concentration in plants was within the reported sufficiency range for wheat. Calcium and Mg concentrations decreased with increasing NH_4 supply, while an opposite trend was observed with increasing NO_3 supply. This effect of N forms on Ca and Mg concentrations were consistent with that of Cao and Tibbits (1998). The beneficial effect of an enhanced NH_4 nutrition under SO_4 salinity in this experiment could probably be ascribed to the antagonistic effect of NH_4 on the plant Mg concentrations. This result is in accordance with that of Lasa et al. (2000) who found that the presence of high levels of Mg in a nutrient solution containing 5 mmol l^{-1} NH_4 as the sole N source, resulted in a stimulation of growth and CO_2 assimilation. The highest K and NH_4 treatment levels (10 mmol l^{-1} K and 9 mmol l^{-1} NH_4) produced comparatively lower yields than the 8 mmol l^{-1} K and 7 mmol l^{-1} NH_4 treatments, probably because of inhibited Ca uptake. The poorer Ca status of these treatments can possibly be ascribed to decreasing root-medium pH due to H^+ excretion by roots in exchange for K^+ and NH_4^+ absorption, which in return decreased the availability of Ca.

Use was made of nutrient vector analyses to obtain an integrated picture of changes in plant nutrient concentration, content and dry mass in a single graph and to identify the nutrients that influenced the dry matter yield the most under sulphate saline conditions. All treatments showed a common pattern of the largest downward, left-pointing vectors associated with Fe (Shift F, antagonism in Figure K1), and the largest, upward right pointing vectors associated with Mg (Shift E, concentration in Figure K1). Therefore, only the nutrient vector analysis for the salinized control treatment relative to the non-salinized control, is given in Figure K2.

Table K2. Nutrient concentrations in top growth of wheat.

Treatment (mmol l^{-1})	N	P	K	Ca	Mg	SO_4	Fe	Mn	Cu	Zn
	(%)						(mg kg^{-1})			
Control	4.19	0.86	5.23	0.39	0.13	1.17	47.6	81	10.5	34.5
7 NO_3	4.11	0.93	4.90	0.50	0.34	1.53	59.6	153	15.0	69.0
14 NO_3	5.90	1.12	4.55	0.61	0.39	1.98	28.1	165	13.5	58.5
20 NO_3	3.93	0.83	4.85	0.70	0.43	1.49	56.6	165	12.0	55.5
1 NH_4	5.90	1.12	4.55	0.61	0.39	1.98	28.1	165	13.5	58.5
7 NH_4	5.95	1.06	4.84	0.41	0.32	1.48	28.1	135	16.5	61.5
9 NH_4	6.10	1.16	4.94	0.38	0.29	1.50	92.6	132	18.0	69.0
0.25 P	5.70	0.88	5.20	0.67	0.44	1.99	25.1	194	16.5	84.0
0.5 P	5.90	1.12	4.55	0.61	0.39	1.98	28.1	165	13.5	58.5
0.75 P	4.18	0.98	5.18	0.62	0.42	1.69	20.6	210	18.0	84.0
3 K	5.95	1.13	5.27	0.71	0.41	1.86	65.6	171	13.5	79.5
6 K	5.90	1.12	4.55	0.61	0.39	1.98	28.1	165	13.5	58.5
8 K	4.08	0.82	5.12	0.64	0.39	2.00	50.6	177	15.0	69.0
10 K	3.45	0.65	4.97	0.57	0.38	2.00	32.6	179	15.0	73.5

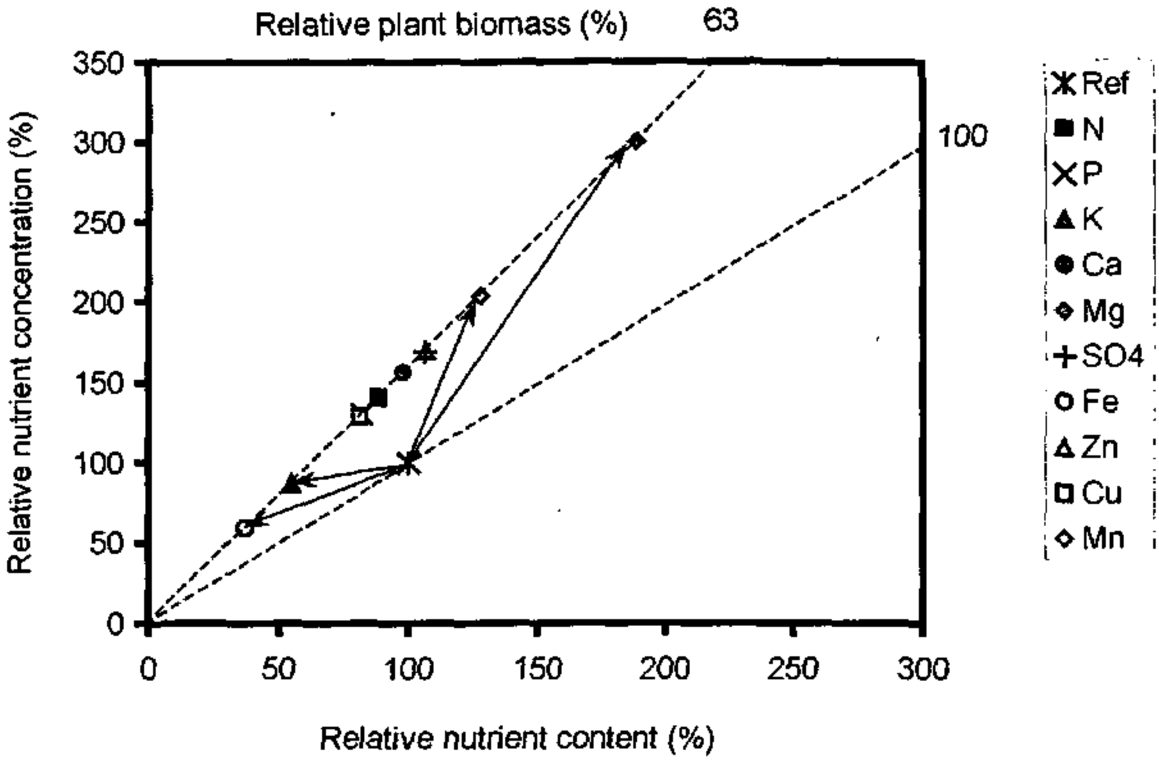


Figure K2. Relative response in nutrient concentration, content and dry mass of the sulphate salinized control treatment.

The largest downward, left pointing vectors were associated with Fe and K, and the largest, upward pointing vectors associated with Mg and Mn. Available literature suggests that the interactions between Mg and Fe, Mn and Fe, and Mg and K are antagonistic (Dangarwala, 1992; Ananthanarayana and Hanumantharaju, 1992). The Fe:Mn concentration ratio of the plants of the salinized control treatment was 0.2, while the reported critical ratio is in the order of 6.5 (Dangarwala, 1992). The chlorotic appearance of the salinized treatments can most probably be attributed to a Fe deficiency induced by Mg and/or Mn. The K concentration in plants increased with an increasing NH_4 concentration in the nutrient medium. Although a positive interaction was reported to exist between N and K uptake - Mengel (1976) stated that it was unlikely that NH_4^+ and K^+ compete for selective binding sites in the absorption process - the K concentration in the plants of the NH_4 treatments was still low in comparison to the control and most of the other salinized treatments. The K concentration in plants was poorly related with dry matter yield, but the K content increased with increasing top dry matter yield.

Further analysis of nutrient concentrations in plants of the salinized treatments relative to nutrient supply revealed that the Cu and Zn concentrations increased while the Mn concentration decreased in plants with increasing NH_4 supply. With the exception of the Mn concentration in plants of the control treatment, the plants of the 7 and 9 mmol l^{-1} NH_4 treatments had the lowest Mn status. The Mn concentration in plants further significantly increased with increasing plant Mg concentration. In contradiction to this, several reports have shown that the Mn concentration in plants was decreased with an increasing Mg supply and concentration in plants (Mengel and Kirkby, 1987; Huang and Redmann, 1995). The P concentration in plants decreased with an increasing K supply and was the lowest for the 10 mmol l^{-1} K treatment. This value was, however, still higher than the upper critical literature norm.

Conclusions

High concentrations of calcium and magnesium sulphate in the nutrient solution suppressed growth of wheat plants. Decreases in yield were associated with significant increases in plant concentrations of SO_4 and Mg. Nutrient vector analysis revealed that high concentrations of calcium and magnesium sulphate in the growth medium decreased Fe and K uptake, while increasing Mg and Mn uptake the most.

The application of NO_3 at a level 7 mmol l^{-1} lower, and NH_4 and K at respective levels of 6 mmol l^{-1} and 2 mmol l^{-1} higher than the level considered beneficial for non-saline conditions, improved top growth of wheat under sulphate saline conditions.

The unexpected beneficial effect of an enhanced NH_4 nutrition under SO_4 salinity can probably be ascribed to the antagonistic effect of NH_4 on the plant Mg and Mn concentrations and/or to NH_4 being a supplementary N source when large SO_4 concentrations suppressed NO_3 uptake, since N utilization efficiency was higher with NH_4 than with NO_3 at similar solution concentrations. In practice this could mean that the inclusion of NH_4-fertilizers in a NO_3:NH_4 ratio of 2:1, could be advantageous when irrigating wheat with water containing high levels of Ca and Mg sulphate. Care should, however, be exercised that large application levels of NH_4-fertilizers does not suppress Ca uptake by plants.

The results obtained from the solution culture trial must be interpreted with caution, since the effect of sulphate salinity on nutrient availability and uptake may differ in the field, particularly for P and K, since their concentrations are controlled by the solid phase and are difficult to measure or predict. Confirmation of the results obtained should thus be sought in field trials.

APPENDIX L

Herbicide effects

Introduction

Herbicides are widely used to control weeds in crop production, particularly in large-scale farming. They are the most practical way of coping with weeds at this level of farming, and probably at all levels of crop production (Akobundu, 1987, Ashton and Crafts, 1981, Klingman et al., 1982). The behaviour of herbicides in the soil and in the plant is influenced by soil factors, type of herbicide, environmental factors and plant species. The combined effect of these factors will determine the fate of a herbicide in the environment (Walker, 1994; Akobundu, 1987; Weaver and Reinhardt, 1998). Of particular importance is how potential interactions could influence the following important criteria for herbicide performance: weed control efficacy, the tolerance of crop species, and the potential for herbicides to leach to groundwater.

The soil solution characteristics, in addition to pH and soil colloids, govern to a large extent herbicide behaviour (Walker, 1994). Clay et al. (1995) reported the effects of fertilizer application on herbicide activity or efficacy. Application of ammonia fertilizer to the soil increased soil pH and dissolved organic carbon. This reduced atrazine adsorption and resulted in increased atrazine in the soil solution. The principle behind this is that some herbicides compete with charged electrolytes for adsorption sites on the soil colloids. The replacing power of cations on clay and humus generally follows the order $C^+ < C^{2+} < C^{3+}$ (Brady, 1974). The divalent ions are more competitive and more strongly adsorbed than monovalent ions.

Simazine and atrazine adsorption was reportedly influenced by high electrolyte concentrations. Hurle and Freed (1972) ascribed stronger herbicide adsorption in the presence of high levels of electrolytes to depressed herbicide solubility. Dao and Lavy (1978) reported that atrazine adsorption increased as KCl and NH_4Cl concentrations increased in the soil solution. Clay et al. (1995) found interaction between ammonia and atrazine. Ammonia-based fertilizers increase pH, and at high pH, atrazine sorption is decreased. This results in high atrazine in the soil solution, thus increasing the possibility of atrazine leaching, as well as the risk to sensitive follow-up crops. Changes in soil pH influence the behaviour of herbicides. Chemical hydrolysis is pH-dependent for most herbicides. The atrazine molecule is stable under neutral pH conditions, but rapid chemical hydrolysis occurs under highly acid or alkaline conditions (Armstrong et al., 1967).

Herbicide interaction with mine water is very possible due to the high concentration of electrolytes in this water. The quality of water used as a solvent in herbicide application is known to influence the efficacy of certain herbicides. This kind of interaction could lead to:

- Increased herbicide leaching with the end result of groundwater contamination and poor weed control due to reduced herbicide activity in the root-zone,
- Increased herbicide concentration in the soil solution which may result in crop injury and reduced selectivity,
- Stronger adsorption of herbicides on soil colloids, resulting in inadequate weed control, and increased persistence which could promote environmental pollution and/or cause damage to follow-up crops.

Objectives

The objectives of this preliminary investigation were to determine the influence of mine water on the three important performance criteria for herbicides, namely:

- Weed control efficacy;

- Herbicide selectivity; and
- Herbicide persistence and mobility in soil (incorporates risks of environmental pollution).

In addressing the above issues it first needed to be determined whether the quality of water used for preparing tank mixtures for herbicide spraying affects the integrity, and thus, the potential biological activity of herbicides. Chemical analyses of selected herbicides in a tank mixture were done by gas chromatography (GC) analysis.

In a parallel investigation, bioassays were conducted in a greenhouse in order to assess whether the biological activity of the selected herbicides is affected by the presence of gypsum in soil.

Chemical analyses

Effect of mine water on herbicide stability in a tank mixture

Experiments were conducted to determine the stability of herbicides in a tank mixture where mine water was used as a carrier. Two sources of water were used to make a herbicide tank mix (Table L1). Two herbicides, atrazine and 2,4-D, were mixed with each of the water types and also with distilled water which was used as a control. Samples were atrazine + Jacuzzi water, atrazine + Tweefontein water, atrazine + distilled water, 2,4-D + Jacuzzi water, 2,4-D + Tweefontein water and 2,4-D + distilled water. Atrazine and 2,4-D were applied at the rate of 1625 g ha^{-1} and 960 g ha^{-1} (active ingredients) respectively. The herbicide tank-mix was left to stand for 3 h before freezing it. After freezing the samples for seven days, they were taken for chemical analyses at the Pesticide Dynamics Division, Plant Protection Research Institute, ARC.

Table L1. Chemical composition of mine water used in the herbicide tank mixture.

Water source	$CaSO_4.2H_2O$ (g 5 l^{-1})	$MgSO_4$ (g 5 l^{-1})	NaCl (g 5 l^{-1})
Jacuzzi	11.88	4.2	0.58
Tweefontein	9.38	4.8	0.59

Quantitative results

Preliminary quantitative results are presented in Table L2. Generally, the residue levels measured were lower than expected if compared with concentrations made up for both compounds. Amongst the three mixtures of each herbicide, the highest residues were found in the distilled water (control) and the lowest in the Jacuzzi water. Where 2,4-D was added, the decrease in concentration, from the control, was 8 % for the Tweefontein water and 24% for the Jacuzzi water. Where atrazine was added, a much more severe effect was found. In the Tweefontein water, atrazine concentrations decreased by 77% from the control, while in the Jacuzzi water atrazine residues were reduced by 90%.

The results indicate that there is rapid transformation of the herbicides in the mine water, with atrazine having a higher inactivation rate. This suggests that the electrolytes found in the mine water interact with herbicide molecules to rapidly transform them. This could mean that mine water may not be a suitable carrier for herbicide spraying.

Table L2. Quantitative results of the mine water herbicide tank-mix.

Water source	Atrazine (mg l^{-1})	2,4-D (mg l^{-1})
Distilled water	1602.7	528.9
Tweefontein	356.0	486.4
Jacuzzi	113.9	403.5

Qualitative results (mass spectra)

Atrazine

The retention times of the control sample (distilled water) was the same as for the standard. However, a slight shift in retention times was found with both the Tweefontein and Jacuzzi samples. A retention time shift of 4 and 5 seconds of a minute was found for the Tweefontein and Jacuzzi samples respectively.

The mass spectra were the same for all samples with the exception of Jacuzzi sample where many peaks were observed in the spectrum as compared to the standard and library spectrum.

The spectrum fit as compared to the library spectrum for atrazine was 98% for all samples, again with the exception of the Jacuzzi where only 90% fit was rendered.

Although the retention time shift found with atrazine is slight, the data indicate that the Tweefontein and Jacuzzi water may exert an effect on the adsorption characteristics of the atrazine molecule. This is not completely unexpected, as one would expect dissolved salts to have an effect on the polarity of the compound. This would mean that in the field, there is a possibility that soil retention would decrease and so leaching could increase, reducing the efficacy of the herbicides because the herbicide will not stay long enough in the topsoil layer to be absorbed by plants. Leaching would also lead to groundwater contamination. It is imperative that the biological activity of the herbicide transformation products be assessed also.

Bioassays

Effect of gypsum added to soil on the biological activity of selected herbicides

The bioassay principle is that the growth response of a sensitive organism (plant species) towards a chemical (herbicide) is indicative of the biological activity of that compound. Bioassaying is a powerful tool for assessing the influence of various environmental factors on herbicide performance. The biological activity of atrazine and metolachlor was investigated in separate pot experiments conducted in a greenhouse. Dose response curves for the parameters dry matter yield and visual injury rating were obtained with a herbicide concentration range involving 10 rates. For each herbicide the experiment was repeated in order to obtain dose response curves that show high definition across the concentration range, i.e. in order to avoid too low or too high herbicide activity across major portions of the concentration range. The test species for atrazine and metolachlor were wheat and sorghum, respectively. Selection of test species was based on high sensitivity of that species to low levels of the particular herbicide. Selection was done in preliminary experiments. The soil factor investigated consisted of two levels, namely gypsum added to the soil used, or not. Growth responses of the test species were expressed as percentage reduction in growth from the controls (zero herbicide).

Results and discussion

Data for percentage growth reduction (=herbicide biological activity) are given in Tables L3 and L4 for atrazine and metolachlor, respectively.

Table L3. Effect of gypsum in soil on the biological activity of atrazine across 10 herbicide concentrations.

Soil	% Growth reduction
+ gypsum	72.4 a
- gypsum	63.8 b

Table L4. Effect of gypsum in soil on the biological activity of metolachlor across 10 herbicide concentrations.

Soil	% Growth reduction
+ gypsum	26.1 b
- gypsum	71.2 a

The biological activity of atrazine was significantly increased in the presence of gypsum, whilst the activity of metolachlor was significantly reduced by the same treatment. The magnitude of activity change was far greater in the case of metolachlor than for atrazine, and in the case of the latter herbicide the activity difference probably does not hold any practical consequences in terms of herbicide efficacy, selectivity or persistence. In contrast, the performance of metolachlor was dramatically affected, and this has important practical consequences. Reduction of metolachlor activity in the presence of gypsum implies that weed control by the herbicide will be poor on soils irrigated with water containing high levels of calcium sulphate. In the case of metolachlor, the finding does not suggest that selectivity of the herbicide towards the crop would be a concern. The effect on herbicide selectivity is also not an issue in the case of the atrazine, because of the inherent high tolerance of the main crop in which it is used, namely maize.

Further research will be aimed at determining what effects, if any, the presence of calcium sulphate and other salts would have on the leaching potential and persistence of the herbicides. Should persistence and/or leaching of the herbicides be increased in the presence of salts associated with mine water, there is a real risk of contamination of groundwater in particular. Confirmation of effects on herbicide integrity in spray tank mixtures prepared with contaminated water is needed, and the relationships with the biological activity of those herbicides need to be established also.

APPENDIX M

Theory of the finite-difference water balance and convection/dispersion solute redistribution used in the SWB model

Introduction

These theoretical notes were compiled by Prof J.G. Annandale (Dept. Plant Production and Soil Science, University of Pretoria) and Dr K.L. Bristow (CSIRO Land and Water, Townsville, Australia).

Water and vapour flux with the Richards' equation

The continuity equation states that the change in storage of water in a control volume (CV) equals the difference between water and vapour flux into and out of the CV. This is described by the Richards' equation given below and includes changes in storage due to a water source and/or sink, in this case evaporation, transpiration, deep drainage and infiltration.

$$\rho_w \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K \frac{\partial \psi}{\partial z}\right] - g \frac{\partial K}{\partial z} + S \tag{1}$$

where

ρ_w - Density of water (1000 kg m^{-3})
θ - Volumetric water content (m^3 water m^{-3} soil)
t - Time (s)
z - Vertical distance (m)
K - Hydraulic conductivity (kg s m^{-3})
ψ - Matric potential (J kg^{-1})
g - Gravitational acceleration (9.8 m s^{-2})
S - Source/sink of water (kg m^{-3} s^{-1})

The first term on the right is matric potential induced vapour and liquid transport. The conductivity term should include a vapour term but we will explicitly calculate vapour flux instead. Vapour flux at the surface is, of course, evaporation. Linked thermally induced vapour flux, as well as osmotic potential effects on vapour flux are not taken into account. The effect of osmotic potential on vapour gradients should be included in our highly saline system. The second term on the right is gravity induced water flux.

Transient water and solute flux problems can't be solved analytically for physically realistic field situations, and for this reason a numerical approach is followed. Nodes are placed at textural discontinuities so as to enable the simulation of water flux with the matric flux potential (Campbell, 1985) as driving force in layered profiles. This approach has been shown to work efficiently by Ross and Bristow (1990) and Annandale (1991). Soil layers are referenced by the node at the top of the layer, and each node is in the centre of a control volume to which the mass balance equations are applied. Each layer is therefore divided into an upper and a lower portion, with the upper half of layer i and the lower half of layer i-1 forming control volume i, CV(i). The nodal set-up illustrating soil layers and control volumes is presented in Figure M1. Note that the thickness of the first layer is imposed and equal to 1 cm. The properties of the soil layers are deduced from the same input file as that given for the cascading model. The correspondence between the soil layers defined in the cascading model and those defined in the finite-difference model are also shown in Figure M1. Each control volume is assumed to have a uniform matric potential and solute concentration. The physical properties of the upper and lower halves of control volumes can, however, differ, so water contents, bulk densities, hydraulic conductivities and water release characteristics may be different for the two halves. The subscripts *u* and *l* denote the upper and lower halves of each layer. Depth z and all vectors are chosen positive downwards. A backward difference or fully implicit form in time is used. All quantities given are for time j+1, unless specified otherwise by a second superscript (e.g. $\theta_u^{i,j}$ is the water content of the upper half of layer i at time jδt). A description of the functions used to describe the hydraulic properties is first given, followed by the discretized version of the terms in the Richards' equation.

Hydraulic properties

It is essential that the model be able to estimate matric potential from water content and *vice versa*, i.e. a water retention function is required. Functions available in the literature include the unsmoothed Brooks-Corey function (Brooks and Corey, 1964, 1966), which reduces to the Campbell functions (Campbell, 1974, 1985) if the residual water content is taken as zero, the smoothed Brooks-Corey function (Hutson and Cass, 1987) and the van Genuchten (1980) function.

The smoothed Brooks-Corey function is used in this model. It is given by:

$$\theta = \theta_s \left[\frac{\psi}{\psi_e}\right]^{-1/b}, \quad \psi \le \psi_i \qquad (2)$$

$$\theta = \theta_s (1 - c\psi^2), \quad \psi_i < \psi < 0 \qquad (3)$$

$$\theta = \theta_s, \quad 0 \le \psi \qquad (4)$$

with ψ_e the air entry potential (J kg^{-1}), b the slope of a log-log water retention function, ψ_i a threshold water potential, where

$$\psi_i = \psi_e a^{-b} \qquad (5)$$

$$a = 2b / (1+2b) \qquad (6)$$

$$c = (1-a)/\psi_i^2 \qquad (7)$$

The derivatives needed for the Newton-Raphson solution (as discussed later) are

$$\frac{\partial\theta}{\partial\psi} = \frac{-\theta}{b\psi}, \quad \psi \le \psi_i \qquad (8)$$

$$\frac{\partial\theta}{\partial\psi} = -2c\theta_s\psi, \quad \psi_i < \psi < 0 \qquad (9)$$

$$\frac{\partial\theta}{\partial\psi} = 0, \quad 0 \le \psi \qquad (10)$$

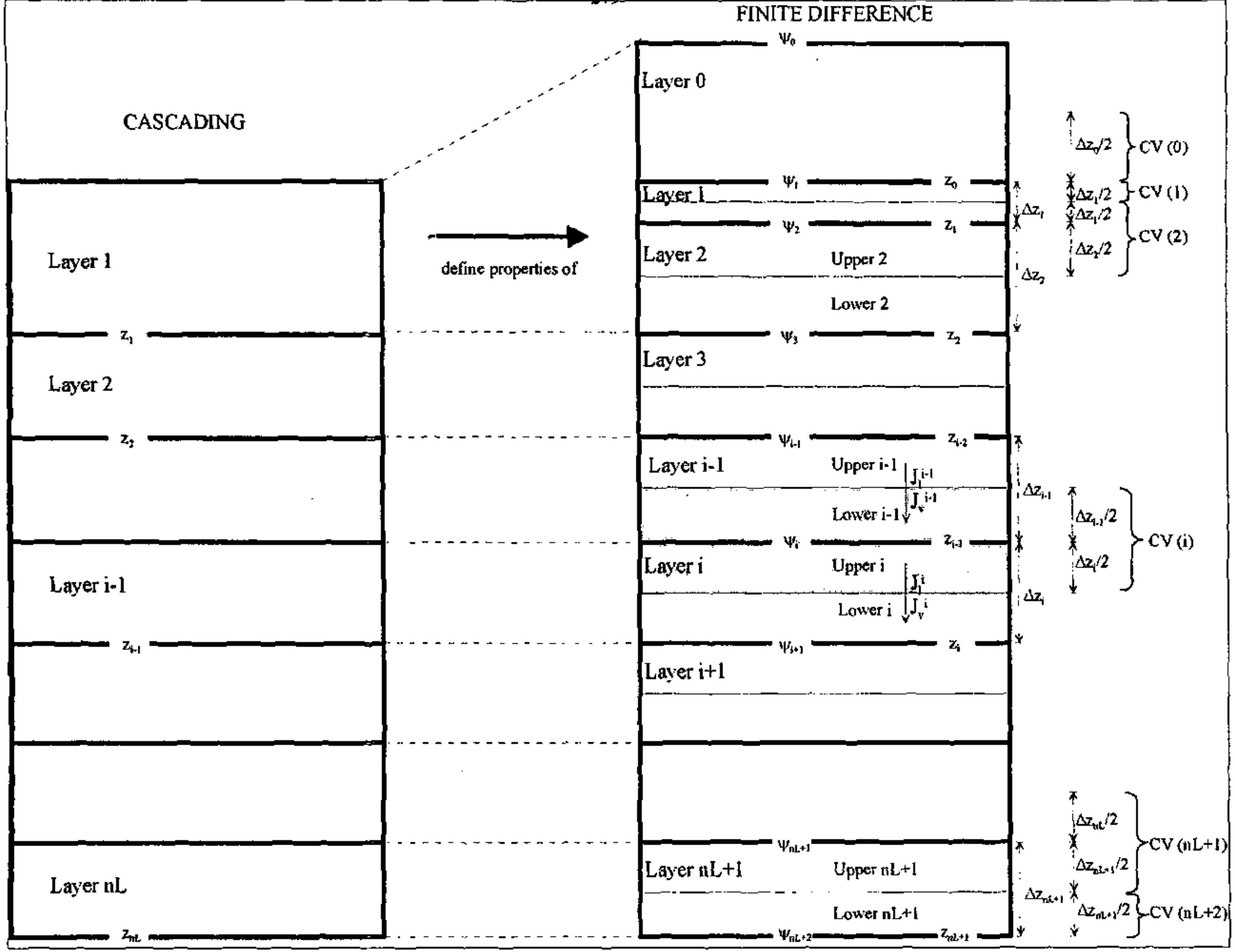


Figure M1. Nodal set-up showing upper and lower halves of layers, layer thicknesses (Δz), control volumes and fluxes of vapour (J_v) and liquid (J_l) between control volumes.

It is also essential to know the hydraulic conductivity associated with a particular matric potential. Again several models exist including Mualem (1976), Brooks and Corey (1964, 1966), Campbell (1974, 1985), van Genuchten (1980) and van Genuchten and Nielsen (1985). These are summarized by Verburg et al. (1996). The Campbell (1985) functions are presently used in SWB:

$$K = K_s \left[\frac{\psi_e}{\psi} \right]^n, \quad \psi < \psi_e \tag{11}$$

$$K = K_s, \quad \psi_e \le \psi \tag{12}$$

with K_s the saturated hydraulic conductivity and

$$n = 2 + 3/b \tag{13}$$

The derivatives of the hydraulic conductivity functions are

$$\frac{\partial K}{\partial \psi} = \frac{-nK}{\psi}, \quad \psi < \psi_e \tag{14}$$

$$\frac{\partial K}{\partial \psi} = 0, \quad \psi_e \le \psi \tag{15}$$

We are expecting gypsum precipitation to affect hydraulic conductivity and this will need to be taken into account. Verburg et al. (1996) use several different hydraulic conductivity functions in their model SWIM v. 2.1. This is a very flexible tool as their model is therefore not bound to one type of hydraulic conductivity function, which may not describe the particular situation very well. Another feature of SWIM is that for numerical efficiency it builds a hydraulic properties look-up table, which includes water retention and hydraulic conductivities at various potentials, as well as their derivatives needed for the Newton-Raphson solution. The discretized version of the terms in the Richards' equation follow.

Change in water storage

$$\Delta S^i = \rho_w \left[\frac{\left(\theta_u^i - \theta_u^{i,j}\right)\left(z_{i+1} - z_i\right) + \left(\theta_l^{i-1} - \theta_l^{i-1,j}\right)\left(z_i - z_{i-1}\right)}{2\,\Delta t} \right] \tag{16}$$

The control volume change in storage ΔS is in kg m^{-2} s^{-1}, the superscript j refers to the previous time step whilst j+1 is the current time step, with *u* denoting the upper and *l* the lower half of a soil layer. Layer depth is denoted by *z* (m) and Δt is the time step (s). A gain in water by the control volume is indicated by a positive sign for ΔS.

Liquid water flux

The water flux density J_l *is given by*

$$J_l = -K(\psi)\left(\frac{\partial \psi}{\partial z} - 1\right) \tag{17}$$

We consider the liquid fluxes J_l^i between nodes (or control volumes) i and i+1, and J_l^{i-1} between nodes i-1 and i

$$J_l^i = \frac{\phi_u^i - \phi_l^i}{\Delta z_i} + g\left[\sigma K_u^i + (1-\sigma)K_l^i\right] \tag{18}$$

$$J_l^{i-1} = \frac{\phi_u^{i-1} - \phi_l^{i-1}}{\Delta z_{i-1}} + g\left[\sigma K_u^{i-1} + (1-\sigma)K_l^{i-1}\right] \tag{19}$$

where ϕ is the matric flux potential (kg m^{-1} s^{-1}), which is defined by Campbell (1985) as

$$\phi = \int_{-\infty}^{\psi} K \, d\psi \tag{20}$$

and is used to reduce some of the non-linearity of Eq. (1). The layer thickness is Δz and σ is a space weighting factor for gravity flow, which can vary between 0 and 1. Full upstream weighting occurs when $\sigma = 1$, but central space weighting $\sigma = 0.5$ tends to give smaller numerical errors than full upstream weighting (Ross, 1990).

Liquid flux at the surface is, of course, infiltration, and a flux upper boundary condition is calculated by dividing precipitation (*Precip*) by the time step, so that

$$J_l^0 = \frac{Precip}{\Delta t} \tag{21}$$

Vapour flux

Isothermal vapour flux is described by Fick's law and given by Campbell (1985) as

$$J_v = -D_v \frac{\partial c_v}{\partial z} \tag{22}$$

where D_v is vapour diffusivity in soil (m^2 s^{-1}) and c_v is the vapour concentration in the soil atmosphere (kg m^{-3}). Vapour diffusivity in soil is affected by tortuosity τ and gas filled porosity $\varnothing_g$, and can be estimated using the vapour diffusivity in air D_{vo} (2.4 x 10^{-5} m^2 s^{-1}) as follows:

$$D_v = \tau \varnothing_g D_{vo} \tag{23}$$

with the tortuosity factor determined after Millington and Quirk (1961)

$$\tau = \frac{\theta^{7/3}}{\theta_s^2} \tag{24}$$

and gas filled porosity calculated using the saturated volumetric water content θ_s

$$\varnothing_g = \theta_s - \theta \tag{25}$$

and

$$\theta_s = 1 - \frac{\rho_b}{\rho_s} \tag{26}$$

with ρ_b the dry bulk soil density and ρ_s the particle density assumed to be 2.65 Mg m^{-3}. The vapour concentration can be written as

$$c_v = h_r\, c_v' \tag{27}$$

where h_r is the fractional relative humidity and c_v' the saturation vapour concentration which is 0.017 kg m^{-3} at 293 K. We are dealing with isothermal conditions so

$$\frac{\partial c_v}{\partial z} = c_v' \frac{\partial h_r}{\partial z} \tag{28}$$

Relative humidity can be described as a function of water potential

$$h_r = \exp\frac{M_w \psi}{RT} \tag{29}$$

The discretized vapour flux equation can therefore be given by

$$J_v^i = -k_v^i \left(h_{i+1} - h_i\right) \tag{30}$$

with the transfer coefficient k_v^i equal to

$$k_v^i = \tau\ D_{vo}\ c_v' \frac{\left(\theta_s^i - \theta^i\right)}{\Delta z_i} \tag{31}$$

where θ_s^i is the average saturated water content of layer i, and θ_i is the average water content of layer i from time $j\delta t$ to time $(j+1)\ \delta t$ and is calculated with

$$\theta^i = \frac{\theta_u^i + \theta_u^{i,j} + \theta_l^i + \theta_l^{i,j}}{4} \tag{32}$$

The vapour flux between nodes i and i-1 can be determined similarly. Vapour flux at the surface is evaporation and this is estimated from atmospheric humidity h_a and potential evaporation E_p (kg m^{-2} s^{-1}). The evaporation process is limited by either atmospheric evaporative demand or supply of water to the evaporating surface. Only during demand limited periods therefore, when the soil surface is wet, will the accuracy of the estimate of potential evaporation and atmospheric humidity be important. Evaporation is modelled by Campbell (1985) as

$$J_v^0 = E_p \frac{h_s - h_a}{1 - h_a} \tag{33}$$

where h_s is the humidity of the surface.

Transpiration

The only sink term is transpiration, which is modelled using the dimensionless water uptake solution of Campbell and Norman (1998). A root water uptake coefficient r_{uk} (kg s m^{-4}) is determined for each control volume, and root water uptake R_u (kg m^{-2} s^{-1}) is calculated using the gradient in water potential between the soil and xylem ψ_x (J kg^{-1}).

$$R_u^{\ i} = -r_{uk}^{\ i} \left(\psi_x - \psi_i\right) \tag{34}$$

Mass balance

Water needs to be conserved by the model and the mass balance error *MBE* (kg m^{-2} s^{-1}) is given by

$$MBE^i = \Delta S^i - J_l^{i-1} + J_l^i - J_v^{i-1} + J_v^i + R_u^i \tag{35}$$

The aim is to find the matric potentials of each control volume that will cause the mass balance error to be negligible, less than some predetermined error limit arbitrarily chosen as 1 x 10^{-7} kg m^{-2} s^{-1} or 0.0086 mm d^{-1} in this model.

Numerical solution

Even though matric flux potential helps linearize the flow equation, this is still non-linear so the solution method chosen needs to be able to solve non-linear equations. The Newton-Raphson iterative method as described by Campbell (1985) is used, and this involves determining the derivatives of the mass balance equation for CV(i) with respect to the potentials at nodes i-1, i and i+1 for the present time step. These derivatives form the coefficient matrix of the solution, which is symmetrical and tri-diagonal. The Thomas algorithm is then used to find a new set of potentials that better satisfy the condition for mass balance. This simultaneous equation solution procedure is repeated until the accepted tolerance level is achieved. The derivatives of the components of the mass balance equation follow.

Storage

$$\begin{aligned}\frac{\partial \Delta S^i}{\partial \psi_i} &= \frac{\partial}{\partial \psi_i}\left(\rho_w\left[\frac{\left(\theta_u^i - \theta_u^{i,j}\right)\left(z_{i+1} - z_i\right) + \left(\theta_l^{i-1} - \theta_l^{i-1,j}\right)\left(z_i - z_{i-1}\right)}{2\Delta t}\right]\right)\\ &= \frac{\rho_w}{2\Delta t}\left[\frac{\partial \theta_u^i}{\partial \psi_i}\Delta z_i + \frac{\partial \theta_l^{i-1}}{\partial \psi_i}\Delta z_{i-1}\right]\end{aligned} \tag{36}$$

The determination of the differential water capacities $\partial\theta/\partial\psi$ is discussed in the hydraulic properties section.

Transpiration or root water uptake

$$\frac{\partial R_u^i}{\partial \psi_i} = \frac{\partial}{\partial \psi_i}\left[-r_{uk}^i\left(\psi_x - \psi_i\right)\right] = r_{uk}^i \tag{37}$$

Liquid fluxes

$$\frac{\partial J_l^i}{\partial \psi_i} = \frac{\partial}{\partial \psi_i}\left[\frac{\phi_u^i - \phi_l^i}{\Delta z_i} + g\left[\sigma K_u^i + (1-\sigma)K_l^i\right]\right] = \frac{K_u^i}{\Delta z_i} + g\sigma\frac{\partial K_u^i}{\partial \psi_i} \tag{38}$$

$$\frac{\partial J_l^i}{\partial \psi_{i+1}} = \frac{\partial}{\partial \psi_{i+1}}\left[\frac{\phi_u^i - \phi_l^i}{\Delta z_i} + g\left[\sigma K_u^i + (1-\sigma)K_l^i\right]\right] = \frac{-K_l^i}{\Delta z_i} + g(1-\sigma)\frac{\partial K_l^i}{\partial \psi_{i+1}} \tag{39}$$

$$\frac{\partial J_l^{i-1}}{\partial \psi_i} = \frac{\partial}{\partial \psi_i}\left[\frac{\phi_u^{i-1} - \phi_l^{i-1}}{\Delta z_{i-1}} + g\left[\sigma K_u^{i-1} + (1-\sigma)K_l^{i-1}\right]\right] \quad = \quad \frac{-K_l^{i-1}}{\Delta z_{i-1}} + g(1-\sigma)\frac{\partial K_l^{i-1}}{\partial \psi_i} \qquad (40)$$

$$\frac{\partial J_l^{i-1}}{\partial \psi_{i-1}} = \frac{\partial}{\partial \psi_{i-1}}\left[\frac{\phi_u^{i-1} - \phi_l^{i-1}}{\Delta z_{i-1}} + g\left[\sigma K_u^{i-1} + (1-\sigma)K_l^{i-1}\right]\right] \quad = \quad \frac{K_u^{i-1}}{\Delta z_{i-1}} + g\sigma\,\frac{\partial K_u^{i-1}}{\partial \psi_{i-1}} \qquad (41)$$

The determination of the slope of the hydraulic conductivity function with respect to matric potential $\partial K / \partial \psi$ is discussed in the section on hydraulic properties.

Vapour fluxes

$$\frac{\partial J_v^i}{\partial \psi_i} = \frac{\partial}{\partial \psi_i}\left[-k_v^i\left(h_{i+1} - h_i\right)\right] = \frac{M_w}{RT}h_i k_v^i \qquad (42)$$

$$\frac{\partial J_v^i}{\partial \psi_{i+1}} = \frac{\partial}{\partial \psi_{i+1}}\left[-k_v^i\left(h_{i+1} - h_i\right)\right] = -\frac{M_w}{RT}h_{i+1} k_v^i \qquad (43)$$

$$\frac{\partial J_v^{i-1}}{\partial \psi_i} = \frac{\partial}{\partial \psi_i}\left[-k_v^{i-1}\left(h_i - h_{i-1}\right)\right] = -\frac{M_w}{RT}h_i k_v^{i-1} \qquad (44)$$

$$\frac{\partial J_v^{i-1}}{\partial \psi_{i-1}} = \frac{\partial}{\partial \psi_{i-1}}\left[-k_v^{i-1}\left(h_i - h_{i-1}\right)\right] = \frac{M_w}{RT}h_{i-1} k_v^{i-1} \qquad (45)$$

Finally, the coefficients of the tri-diagonal matrix are

$$a_i = \frac{\partial MBE^i}{\partial \psi_{i-1}} = -\frac{\partial J_l^{i-1}}{\partial \psi_{i-1}} + \frac{\partial J_l^i}{\partial \psi_{i-1}} - \frac{\partial J_v^{i-1}}{\partial \psi_{i-1}} + \frac{\partial J_v^i}{\partial \psi_{i-1}} = -\frac{K_u^{i-1}}{\Delta z_{i-1}} - g\sigma\frac{\partial K_u^{i-1}}{\partial \psi_{i-1}} - \frac{M_w}{RT}h_{i-1}k_v^{i-1} \qquad (46)$$

$$\begin{aligned} b_i = \frac{\partial MBE^i}{\partial \psi_i} &= -\frac{\partial J_l^{i-1}}{\partial \psi_i} + \frac{\partial J_l^i}{\partial \psi_i} - \frac{\partial J_v^{i-1}}{\partial \psi_i} + \frac{\partial J_v^i}{\partial \psi_i} + \frac{\partial R_u^i}{\partial \psi_i} + \frac{\partial \Delta S^i}{\partial \psi_i} \\ &= \frac{K_l^{i-1}}{\Delta z_{i-1}} + \frac{K_u^i}{\Delta z_i} - g(1-\sigma)\frac{\partial K_l^{i-1}}{\partial \psi_i} + g\sigma\frac{\partial K_u^i}{\partial \psi_i} + \frac{M_w}{RT}h_i k_v^i + \frac{M_w}{RT}h_i k_v^{i-1} \qquad (47) \\ &+ r_{uk}^i + \frac{\rho_w}{2\Delta t}\left[\frac{\partial \theta_u^i}{\partial \psi_i}\Delta z_i + \frac{\partial \theta_l^{i-1}}{\partial \psi_i}\Delta z_{i-1}\right] \end{aligned}$$

$$c_i = \frac{\partial MBE^i}{\partial \psi_{i+1}} = -\frac{\partial J_l^{i-1}}{\partial \psi_{i+1}} + \frac{\partial J_l^i}{\partial \psi_{i+1}} - \frac{\partial J_v^{i-1}}{\partial \psi_{i+1}} + \frac{\partial J_v^i}{\partial \psi_{i+1}} = -\frac{K_l^i}{\Delta z_i} + g(1-\sigma)\frac{\partial K_l^i}{\partial \psi_{i+1}} - \frac{M_w}{RT}h_{i+1}k_v^i \qquad (48)$$

and the Thomas algorithm is used to find a new set of potentials that better satisfy the condition for mass balance.

Other processes simulated in SWIM that have not been incorporated into SWB at this stage are:

1. Macro-pore flow,
2. Hysteresis, and
3. Surface sealing.

Solute flux with the convective-dispersive equation

Once the water fluxes are known, solute flux can be calculated, followed by chemical equilibrium with precipitation-dissolution and cation exchange (Dudley et al., 1981).

Solutes are moved by mass flow or convection, as well as by diffusion in response to concentration gradients. The convection-dispersion equation (CDE), ignoring dissolution-precipitation and cation exchange, is given by Campbell (1985) as

$$\theta \frac{\partial C}{\partial t} = \frac{\partial}{\partial z}\left[\rho_w D(\theta, J_l) \frac{\partial C}{\partial z}\right] + J_l \frac{\partial C}{\partial z} \qquad (49)$$

with

C - Solute concentration in the soil solution (mol l^{-1}), and

D - Combined diffusion and dispersion coefficient ($m^2\ s^{-1}$)

The term on the left represents a change in storage of chemicals in solution. A term for exchangeable ions and precipitation-dissolution could be added, as in the model UNSATCHEM of Simunek et al. (1996). It was decided not to include these two additional terms in the CDE as they make the equation extremely non-linear and therefore more difficult to solve. Instead the approach of Robbins (1991) and Dudley et al. (1981) was followed, where solutes in solution are moved first, after which chemical equilibrium with precipitation and cation exchange are calculated.

The second term on the right is convective solute flux or mass flow.

The first term on the right-hand side of Eq. (49) is solute flux due to diffusion and hydrodynamic dispersion. Molecular diffusion is described by Fick's law and is driven by concentration gradients. Hydrodynamic dispersion results from the effect of differing water velocities, both between different sized pores and within individual pores. This tends to smear the solute front as it moves through soil, much like diffusion does. Although this is strictly speaking a component of mass flow, it is often lumped together with diffusion, and is usually more important than diffusion.

The combined dispersion and diffusion coefficient therefore has two parts to it, one for molecular diffusion and one for hydrodynamic dispersion (Verburg et al., 1996).

$$D = \tau D_o + \varepsilon |v|^n \qquad (50)$$

with the tortuosity factor (Eq. 24) determined after Millington and Quirk (1961).

D_o is an ionic or molecular diffusion coefficient in free water.

ε is the dispersivity of the medium ($m^2\ s^{-1}$) and can be determined from breakthrough curves.

v is pore water velocity jl/θ ($m\ s^{-1}$) and n is an empirical constant, which is also determined from breakthrough curves.

The numerical solution followed is similar to the one for heat flux of Campbell (1985). The mass balance equation (Eq 49) is discretized and solved for the new concentrations of each control volume. This needs to be done independently for each ion or molecule considered, in this case Ca, Mg, Na, K, Cl and SO_4. HCO_3 and CO_3 concentrations are estimated without including them in the solute flux procedure.

The discretized CDE follows:

Change in solute storage

$$\Delta S = \frac{\theta_{i\,avg}\left(c_i^{j+1} - c_i^j\right)\left(z_{i+1} - z_{i-1}\right)}{2\,\Delta t} \tag{51}$$

where $\theta_{i\,avg}$ is the average water content of the upper and lower halves of CV_i for both the old and new time steps.

Diffusion and hydrodynamic dispersion

Diffusive and dispersive solute fluxes between control volumes i-1 and i (jsd_{i-1}) and between nodes i and i+1 (jsd_i) follow:

$$jsd_{i-1} = \frac{\rho_w D_{i-1}\left(C_{i\,avg} - C_{i-1\,avg}\right)}{\Delta z_{i-1}} \tag{52}$$

$$jsd_i = \frac{\rho_w D_i\left(C_{i+1\,avg} - C_{i\,avg}\right)}{\Delta z_i} \tag{53}$$

with D_i the combined diffusion dispersion coefficient for layer i and C_{avg} the time weighted average concentration of a particular solute.

$$C_{avg} = \eta C^{j+1} + (1-\eta) C^j \tag{54}$$

An explicit solution for solute concentration is obtained if the forward difference method is adopted (η=0). If η=0.5 is chosen it is referred to as a time-centred or Crank-Nicholson solution. SWIM uses a backward difference procedure i.e. η=1.

The best choice for time weighting depends on numerical stability and accuracy. A small value for η may cause oscillation, whilst large values will always give stable solutions but perhaps not enough solute will be transferred in a time-step. For heat flow problems Campbell (1985) feels the best accuracy is obtained with η around 0.4, whilst best stability is obtained with η=1. A typical compromise is 0.6.

Convective solute flux

Mass solute fluxes between control volumes i-1 and i (jsm_{i-1}) and between nodes i and i+1 (jsm_i) follow:

$$jsm_{i-1} = jl_{i-1}\left(\delta_{i-1} C_{i-1\,avg} - \varepsilon_{i-1} C_{i\,avg}\right) \tag{55}$$

$$jsm_i = jl_i\left(\delta_i C_{i\,avg} - \varepsilon_i C_{i+1\,avg}\right) \tag{56}$$

δ and ε are space weighting factors and can vary between 0 and 1 ($\delta + \varepsilon = 1$). According to Verburg et al. (1996), it seems to be best to choose central space weighting until oscillations begin at which time one should switch to upstream weighting (0 and 1) depending on the flux direction. SWB presently uses full upstream weighting.

Solute mass balance

The mass of each solute needs to be conserved and each control volumes mass balance error can be calculated as:

$$MBE_i = \Delta S_{solute} - jsd_{i-1} + jsd_i - jsm_{i-1} + jsm_i \tag{57}$$

The mass balance equation is then fully expanded so as to get all the previous time-step concentrations on the one side, and all the new or present time-step concentrations on the other. The new concentrations are then solved for simultaneously using the Thomas algorithm. The terms of the coefficient matrix A(I), B(I) and C(I), as well as the expression containing the previous time-step's concentrations D(I) follow:

$$A(I)\,C_{i-1}^{j+1} = \eta\left(\frac{\rho_w D_{i-1}}{\Delta z_{i-1}} - jl_{i-1}\,\delta_{i-1}\right)C_{i-1}^{j+1} \tag{58}$$

$$B(I)C_i^{j+1} = \left[\frac{\theta_{i\,avg}\,(z_{i+1} - z_{i-1})}{2\,\Delta t} - \eta\left(\frac{\rho_w D_{i-1}}{\Delta z_{i-1}} + \frac{\rho_w D_i}{\Delta z_i} - jl_{i-1}\varepsilon_{i-1} - jl_i\delta_i\right)\right]C_i^{j+1} \tag{59}$$

$$C(I)\,C_{i+1}^{j+1} = \eta\left(\frac{\rho_w D_i}{\Delta z_i} - jl_i\,\varepsilon_i\right)C_{i+1}^{j+1} \tag{60}$$

$$\begin{aligned} D(I) = (1-\eta)&\left[jl_{i-1}\,\delta_{i-1} - \frac{\rho_w D_{i-1}}{\Delta z_{i-1}}\right]C_{i-1}^{j} \\ &+\left[\frac{\theta_{i\,avg}\,(z_{i+1} - z_{i-1})}{2\,\Delta t} + (1-\eta)\left(\frac{\rho_w D_{i-1}}{\Delta z_{i-1}} + \frac{\rho_w D_i}{\Delta z_i} - jl_{i-1}\varepsilon_{i-1}\right)\right]C_i^{j} \\ &+ (1-\eta)\left[jl_i\,\varepsilon_i - \frac{\rho_w D_i}{\Delta z_i}\right]C_{i+1}^{j} \end{aligned} \tag{61}$$

Boundary conditions

The upper boundary condition is an infiltration flux density.

$$jl_0 = \frac{-\mathrm{Precip}}{\Delta t} \tag{62}$$

This will carry solute into the soil if the concentration at the aerial node C(0) is set to the concentration of the infiltrating water. A term needs to be added to the D(I) value to take into account that the concentrations at the very top and bottom of the profile are not taken into account with the matrix inversion. At the top of the profile D(1) becomes:

$$D(1) = D'(1) - A(1)C_0^{j+1} \tag{63}$$

where D'(1) is the D(1) value calculated using Eq. (61). Solute concentration at node 0 is only non-zero during infiltration with water containing solutes.

At the bottom of the profile D(NrOfLayersFD) becomes:

$$D(NrOfLayersFD) = D'(NrOfLayersFD) - C(NrOfLayersFD)C_{NrOfLayersFD+1}^{j+1} \tag{64}$$

A zero gradient for solute concentration is chosen for this model, so lower solute concentration is set equal to the concentration of the node above it for the previous time step.

APPENDIX N

Model validation

In this Appendix, additional validation data for the SWB model are presented for wheat grown during the winter 1999 season at pivot Fourth and for different irrigation treatments (Appendix A, Table A8, replication 2).

Soil water balance and crop growth simulations are shown in Figures N1 to N4 (field capacity and deficit irrigation treatments). Model predictions were reasonable compared to field measurements.

Simulations of soil water redistribution compared generally well to data measured with heat dissipation sensors for different irrigation treatments and soil depths. The comparisons are shown in Figures N5 to N10. It is not clear why the sensors dried out in the field capacity treatment in the middle of the season, especially the sensor installed at 26 cm soil depth (Figure N6), as this was not the case for the leaching fraction (Figure N5) and deficit irrigation treatment (Figure N7). This resulted in very low (negative) readings of soil matric potential. Possible causes are incorrect placement of the sensors, which caused loss of contact between the soil and the ceramic matrix of the sensors as the soil was drying, or unusually high root density and water uptake at the site where the sensors were installed.

The model also gave good predictions of the redistribution of single ionic species in the soil profile. Examples are shown for the major ionic species in irrigation water (calcium, magnesium and sulphate) and the leaching fraction treatment in Figures N11 to N13.

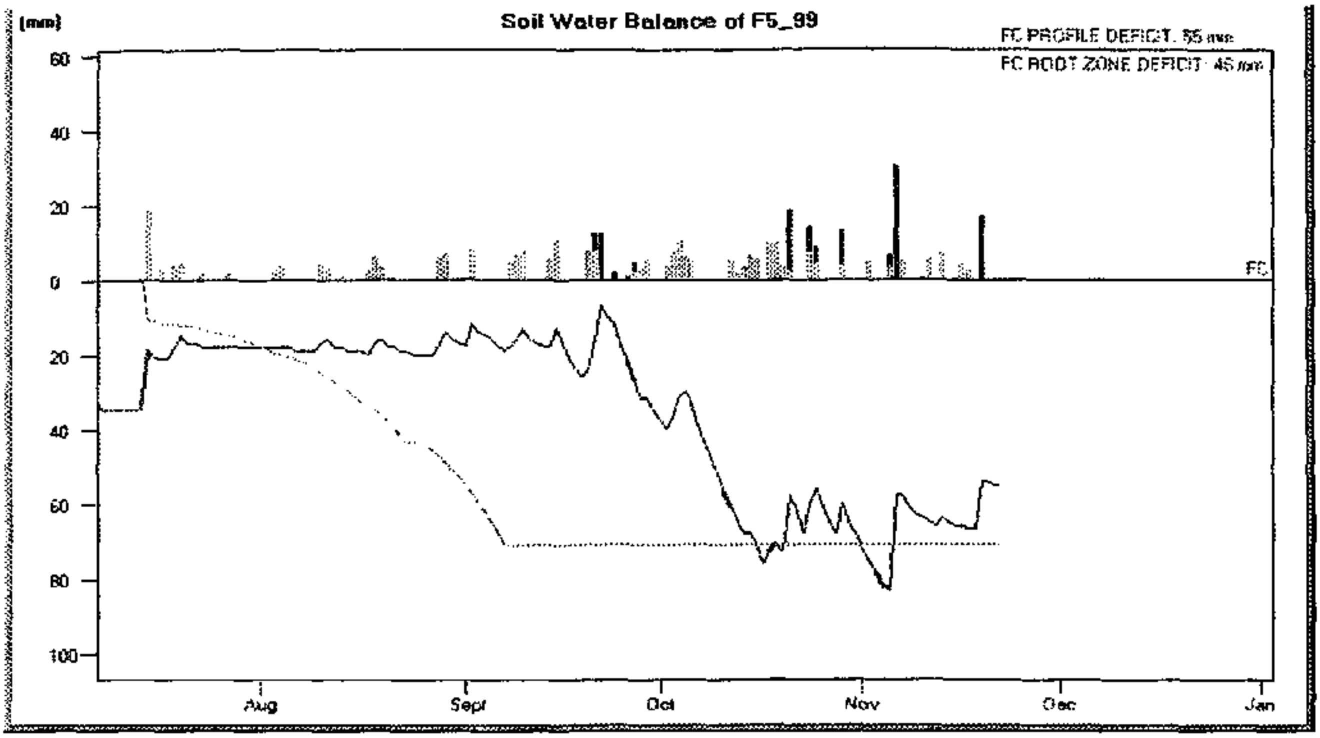


Figure N1. Soil water balance summary graph (wheat crop, winter 1999 season, pivot Fourth, field capacity treatment, replication 2).

Legend:

- Irrigation (*blue, empty histograms*) and *rainfall* (*red, filled histograms*) input data in the top part of the graph.
- Simulated soil water deficit to field capacity (blue/red bold line) and allowable depletion level (grey, thin line) in the bottom part of the graph.
- Simulated profile soil water deficit as well as root-zone deficit to field capacity at the end of the simulation in the top right corner of the graph.
- The horizontal (blue) line on the graph indicates the field capacity level (FC).

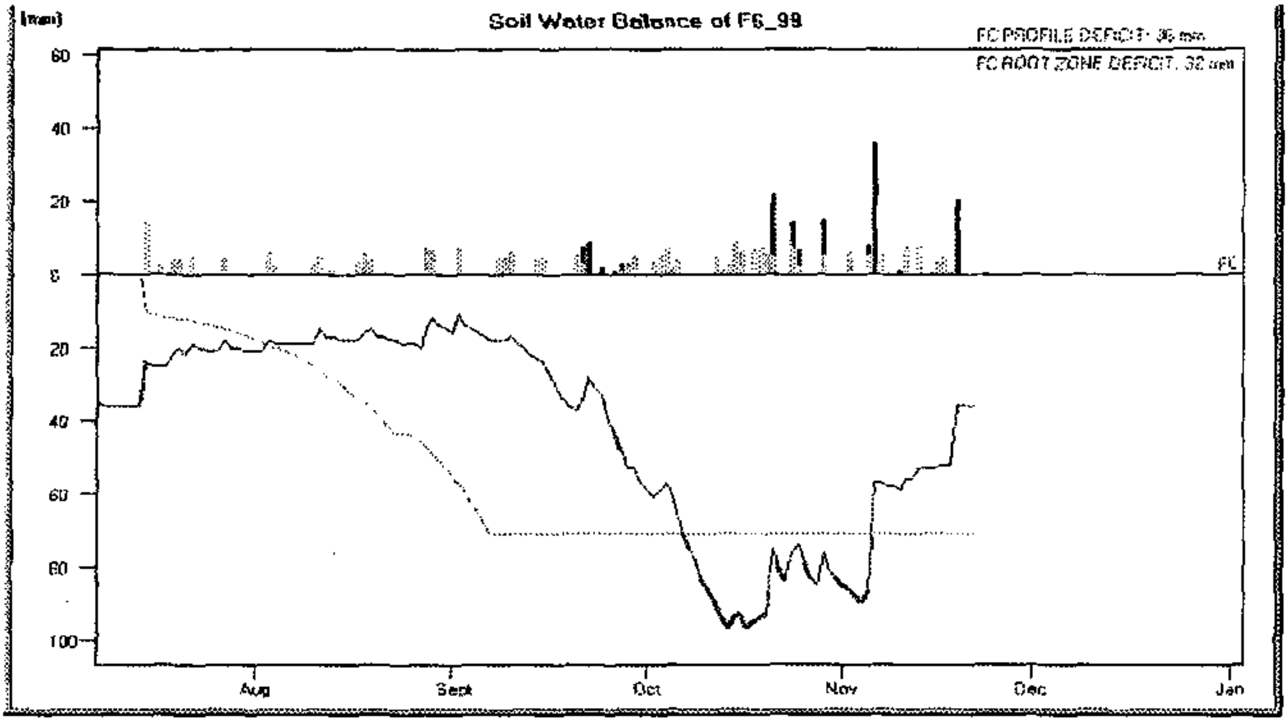


Figure N2. Soil water balance summary graph (wheat crop, winter 1999 season, pivot Fourth, deficit irrigation treatment, replication 2).

Legend:

- Irrigation (blue, empty histograms) and rainfall (red, filled histograms) input data in the top part of the graph.
- *Simulated soil water deficit to field capacity (blue/red bold line) and allowable* depletion level (grey, thin line) in the bottom part of the graph.
- *Simulated profile soil water deficit as well as root-zone deficit to field capacity* at the end of the simulation in the top right corner of the graph.
- The horizontal (blue) line on the graph indicates the field capacity level (FC).

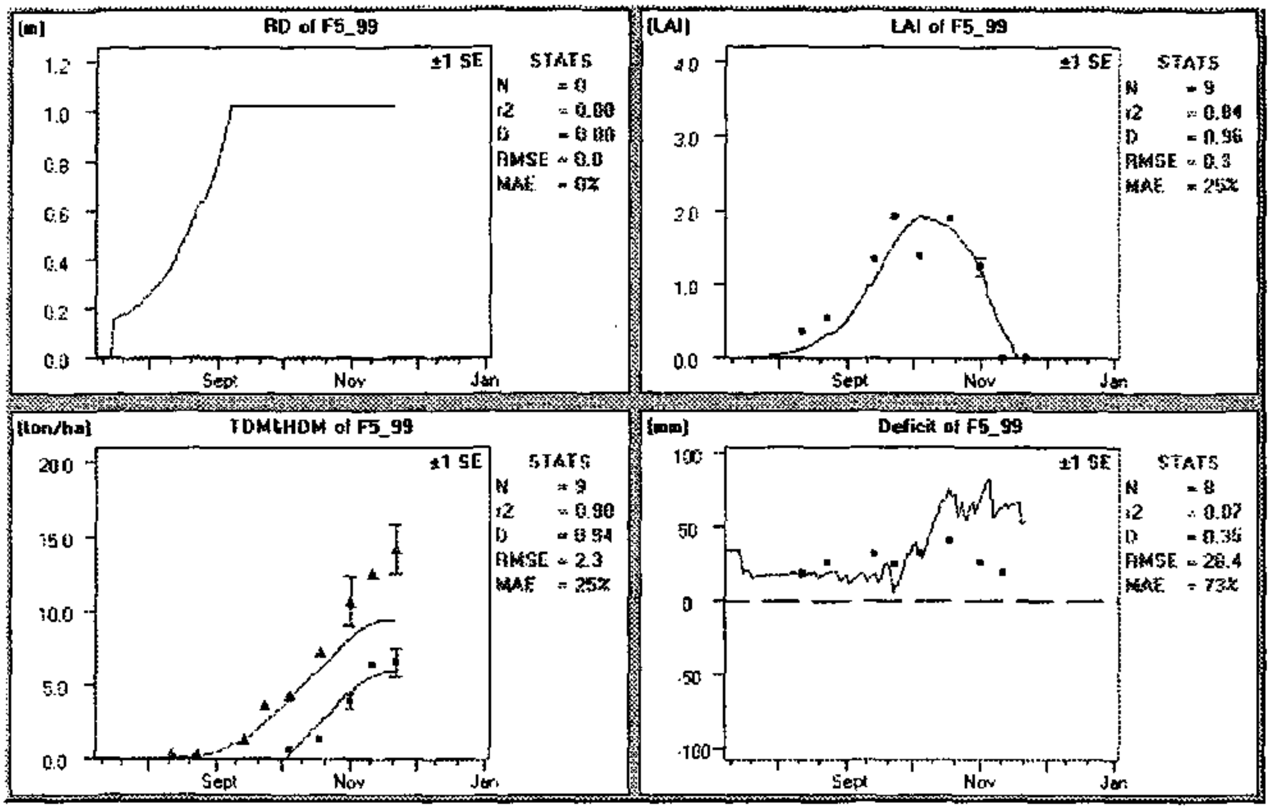


Figure N3. Simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), top and harvestable dry matter (TDM & HDM), as well as soil water deficit to field capacity (wheat crop, winter 1999 season, pivot Fourth, field capacity treatment, replication 2). The parameters of the statistical analysis are:

i) Number of observations (N);
ii) *Coefficient of determination* (*r^2*);
iii) Index of agreement of Willmott (1982) (D);
iv) Root mean square error (RMSE);
v) Mean absolute error (MAE); and
vi) Vertical bars are ± 1 standard error of the measurements.

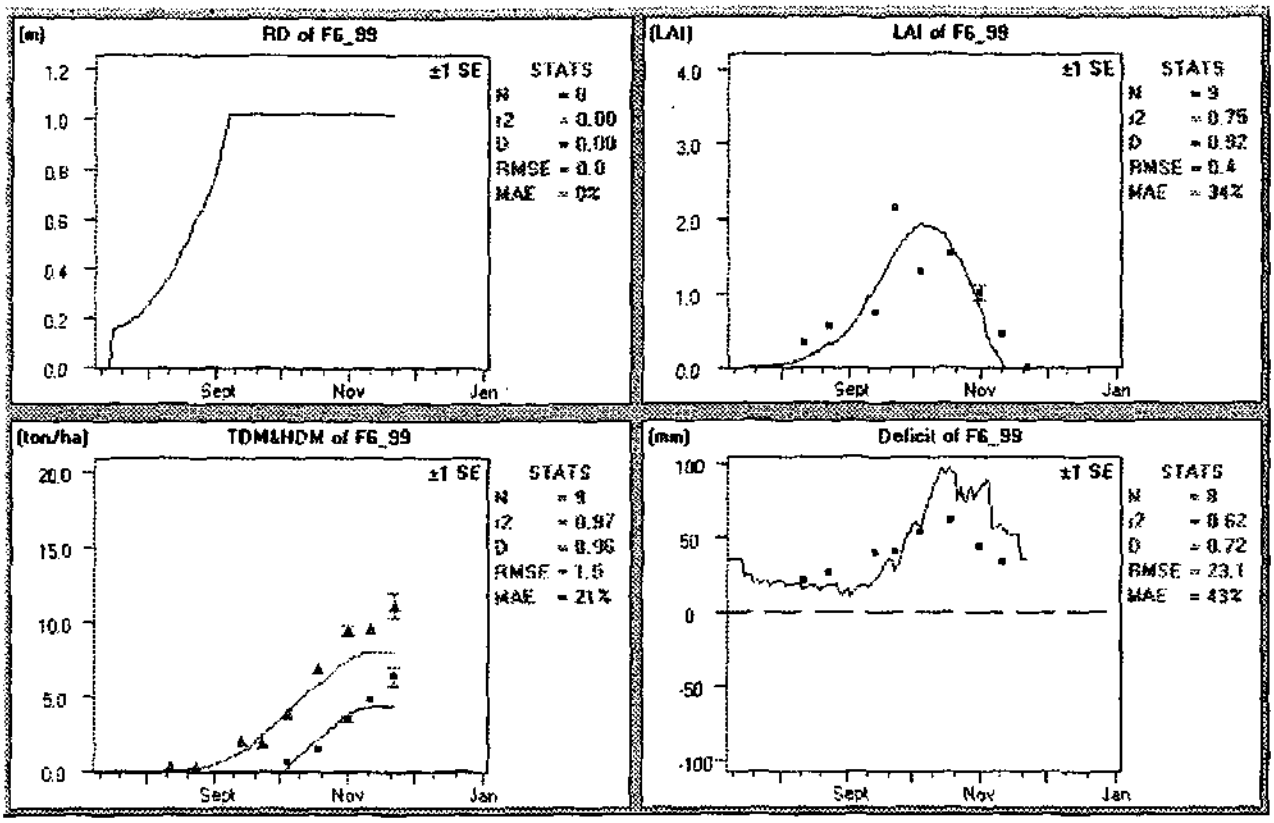


Figure N4. Simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), top and harvestable dry matter (TDM & HDM), as well as soil water deficit to field capacity (wheat crop, winter 1999 season, pivot Fourth, deficit irrigation treatment, replication 2). The parameters of the statistical analysis are:

i) Number of observations (N);
ii) Coefficient of determination (r^2);
iii) Index of agreement of Willmott (1982) (D);
iv) Root mean square error (RMSE);
v) Mean absolute error (MAE); and
vi) Vertical bars are ± 1 standard error of the measurements.

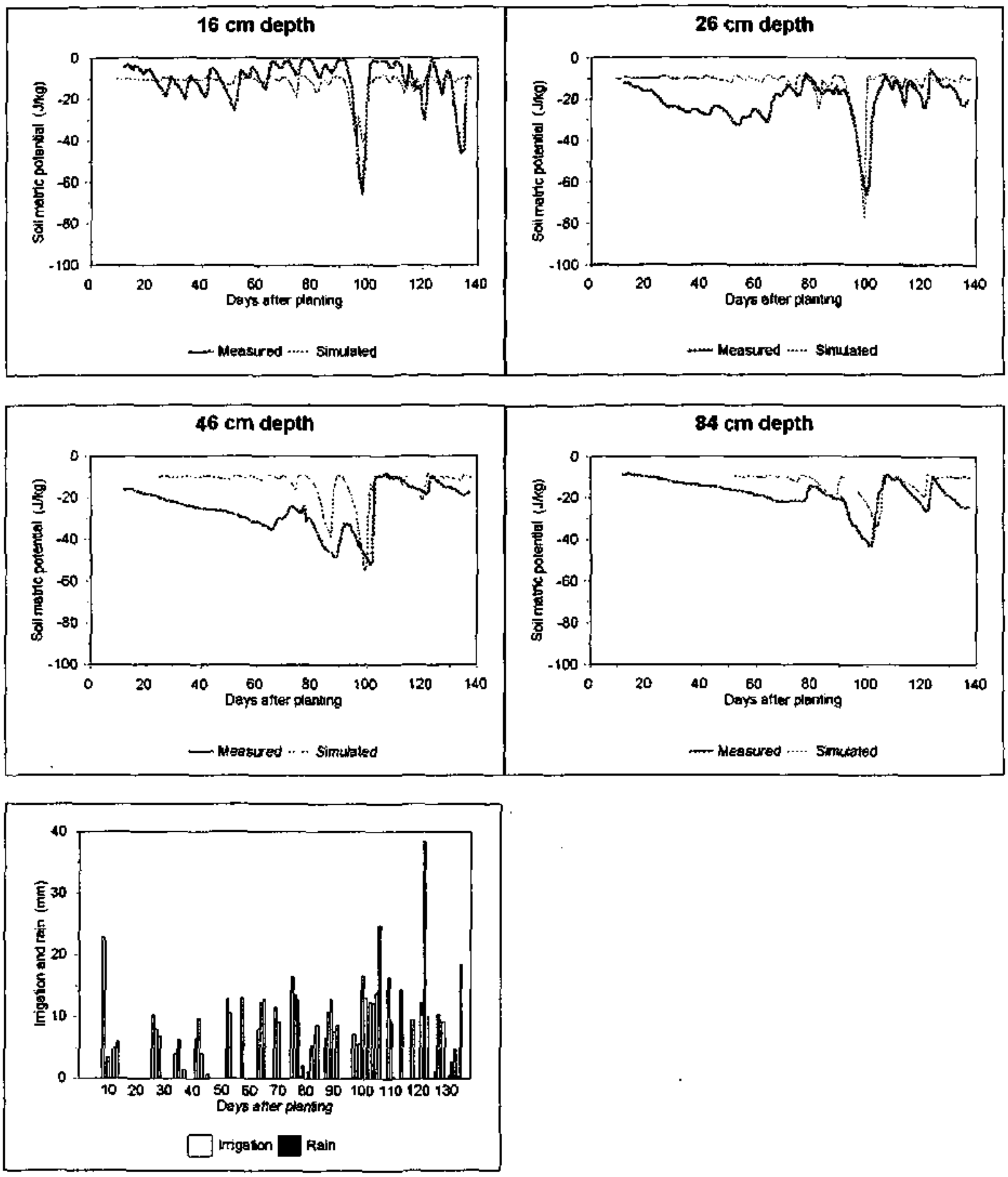


Figure N5. Measured and simulated soil matric potential with the cascading water balance model at different depths in the soil profile, as well as irrigation and rainfall (wheat crop, winter 1999 season, pivot Fourth, leaching fraction treatment, replication 2).

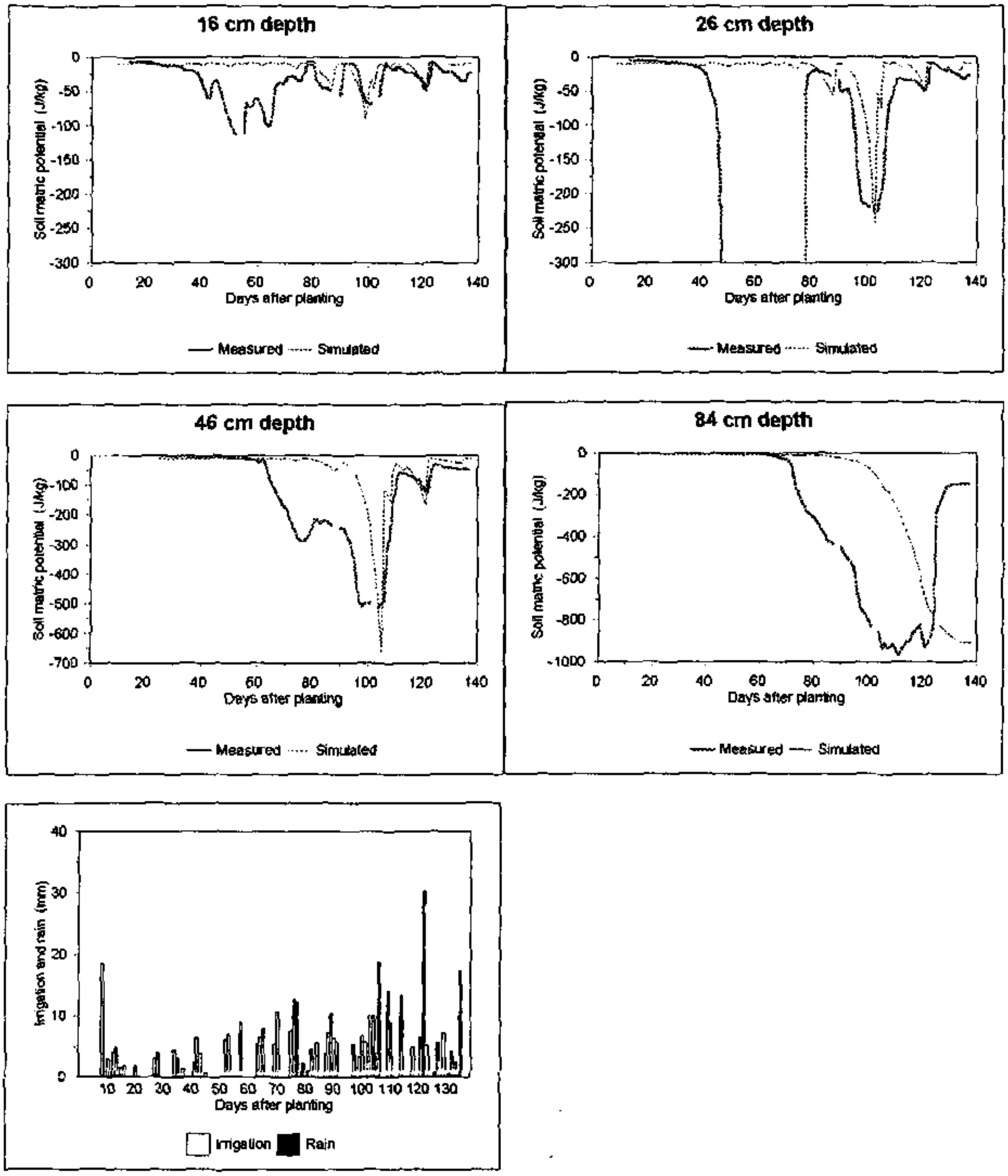


Figure N6. Measured and simulated soil matric potential with the cascading water balance model at different depths in the soil profile, as well as irrigation and rainfall (wheat crop, winter 1999 season, pivot Fourth, field capacity treatment, replication 2).

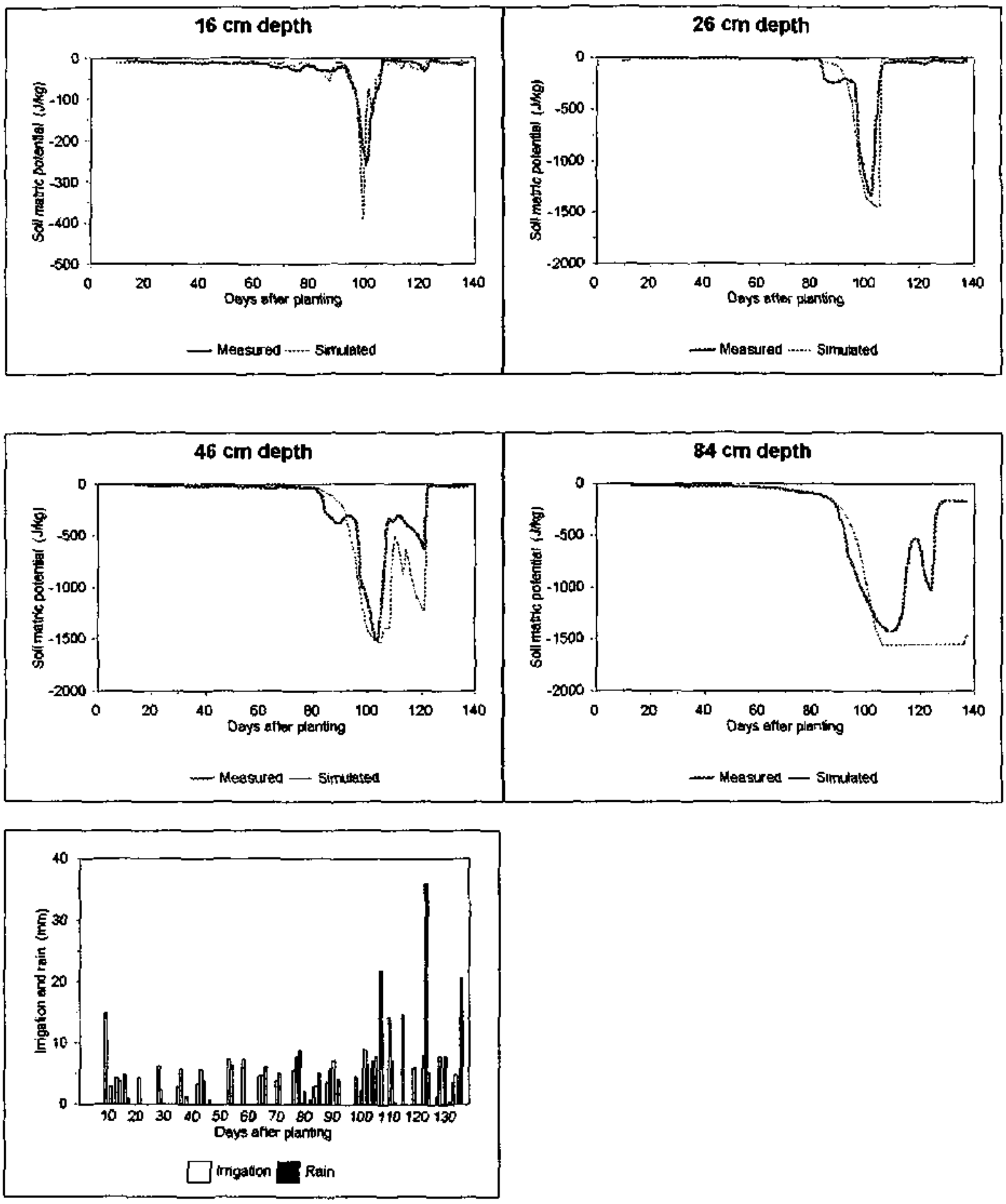


Figure N7. Measured and simulated soil matric potential with the cascading water balance model at different depths in the soil profile, as well as irrigation and rainfall (wheat crop, winter 1999 season, pivot Fourth, deficit irrigation treatment, replication 2).

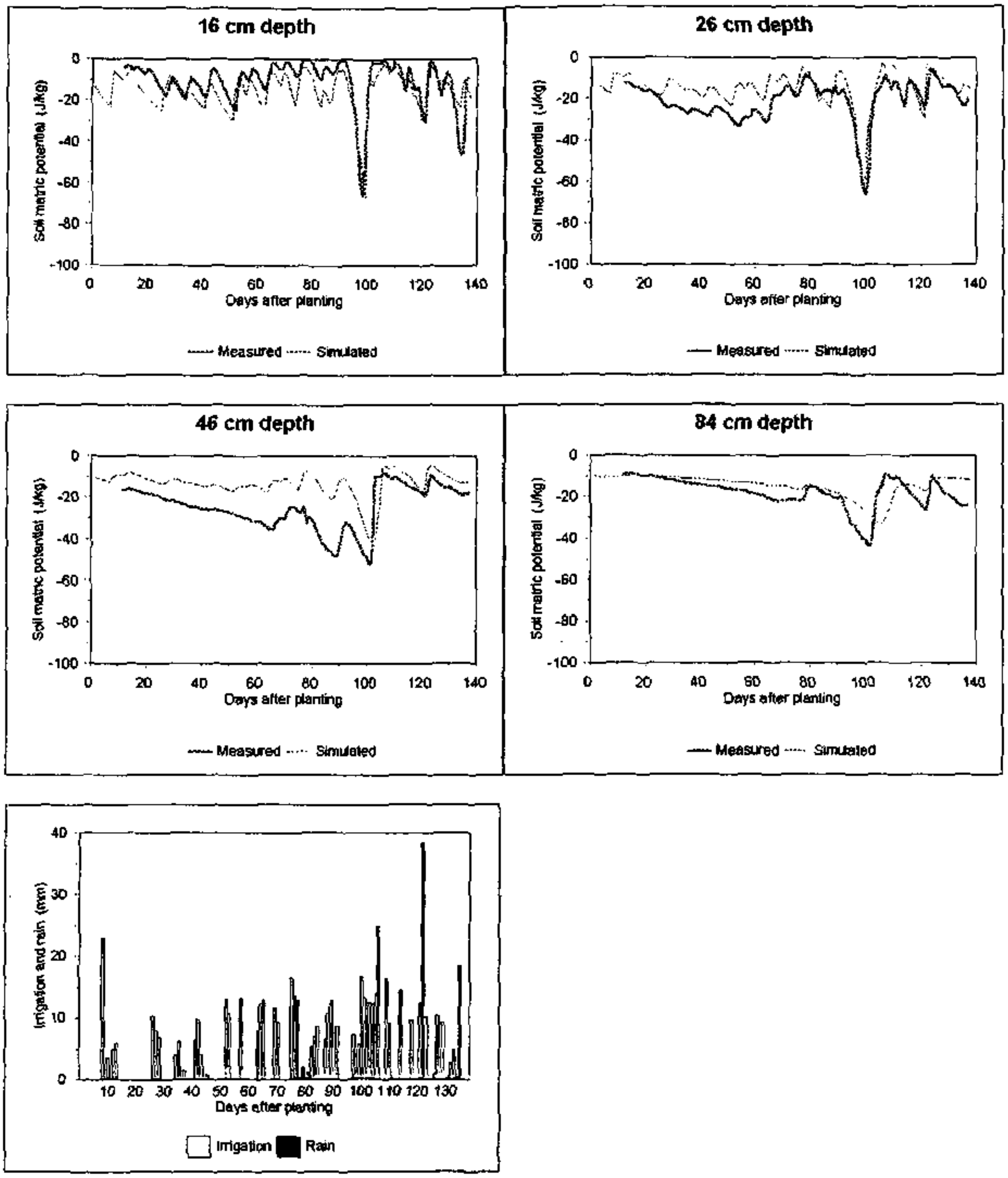


Figure N8. Measured and simulated soil matric potential with the finite-difference water balance model at different depths in the soil profile, as well as irrigation and rainfall (wheat crop, winter 1999 season, pivot Fourth, leaching fraction treatment, replication 2).

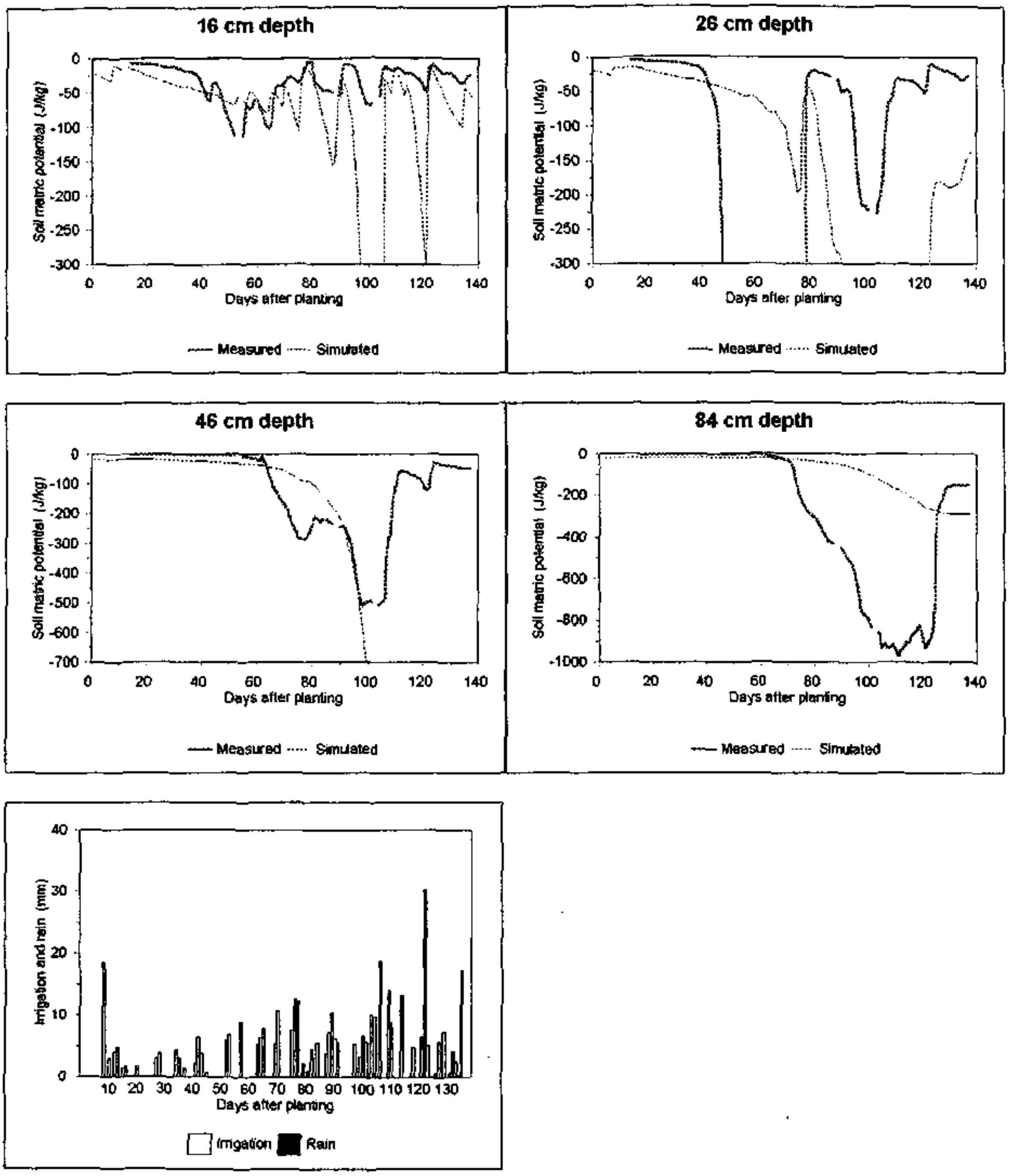


Figure N9. Measured and simulated soil matric potential with the finite-difference water balance model at different depths in the soil profile, as well as irrigation and rainfall (wheat crop, winter 1999 season, pivot Fourth, field capacity treatment, replication 2).

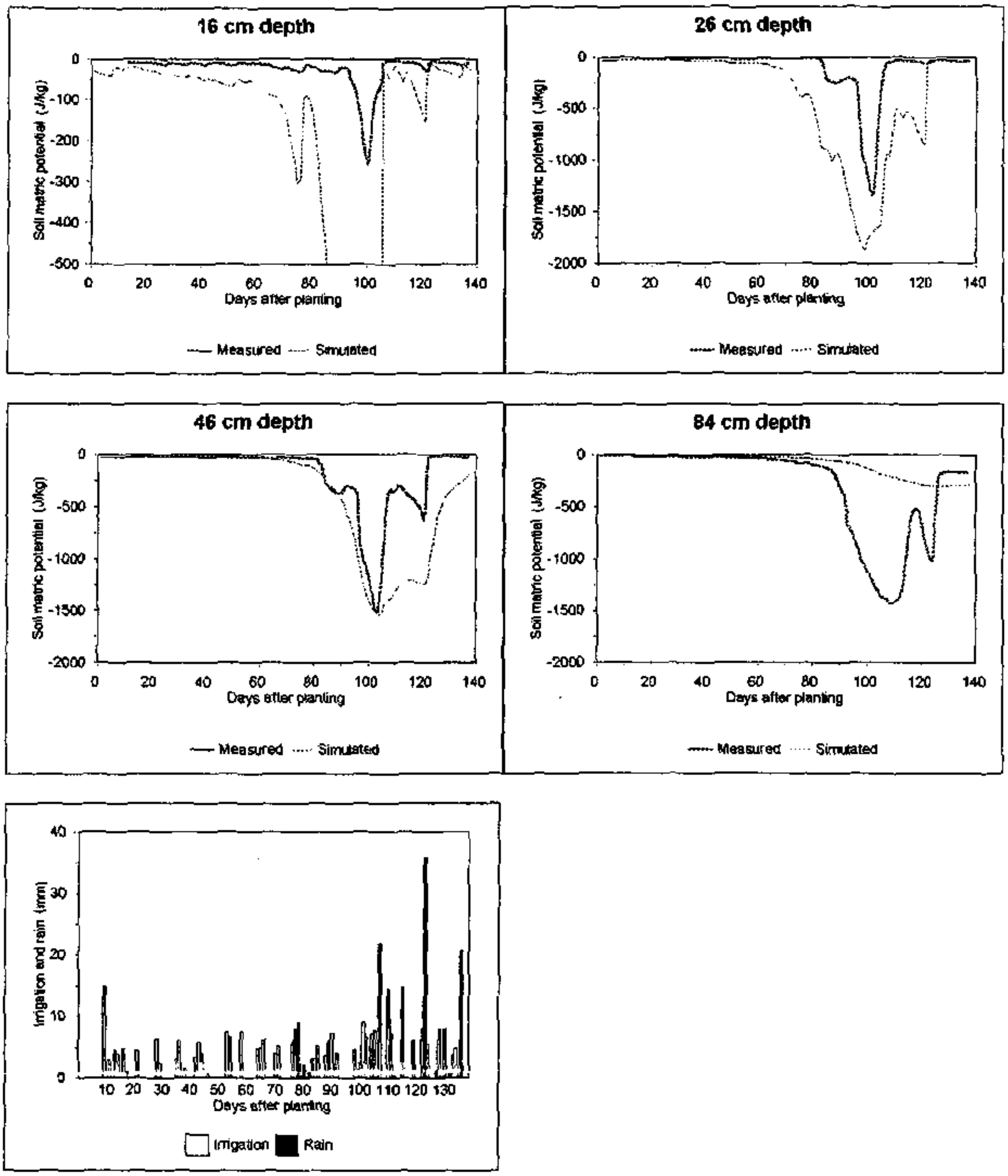


Figure N10. Measured and simulated soil matric potential with the finite-difference water balance model at different depths in the soil profile, as well as irrigation and rainfall (wheat crop, *winter 1999 season, pivot Fourth, deficit irrigation* treatment, *replication* 2).

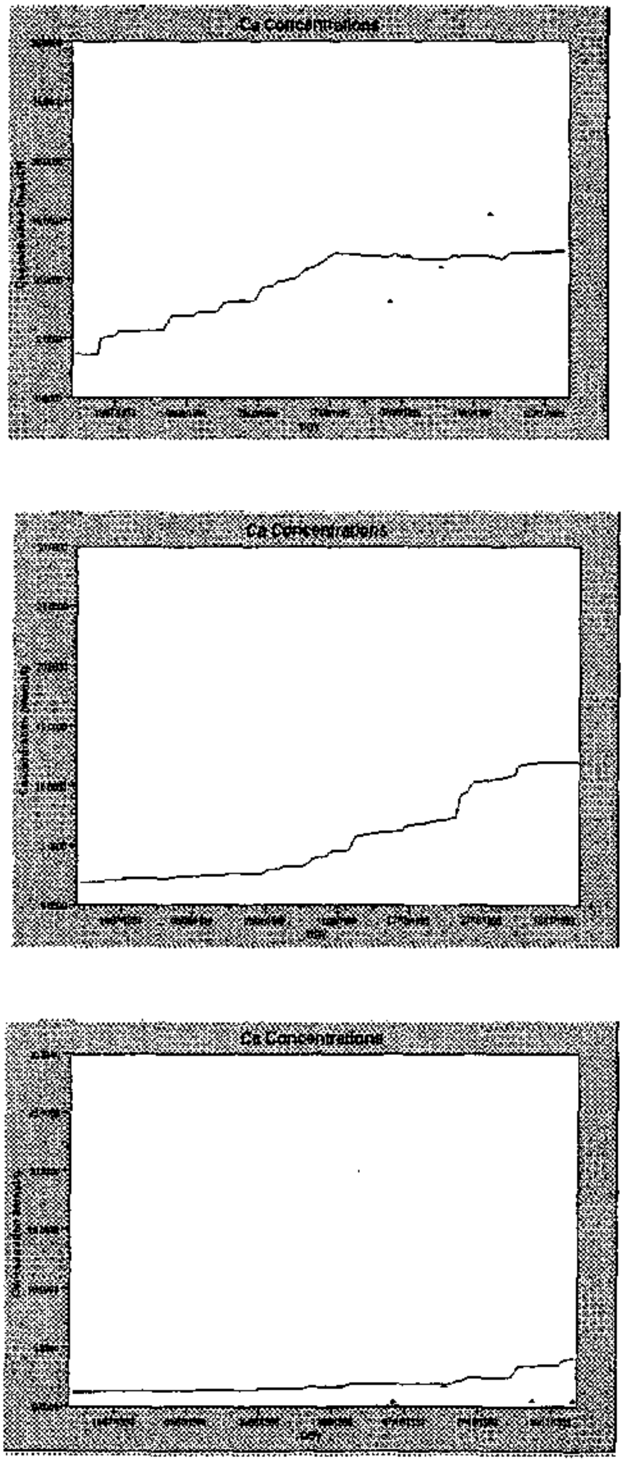


Figure N11. Measured (symbols) and simulated (line) concentration of calcium in the soil solution (*wheat crop, winter 1999 season, pivot Fourth, leaching fraction treatment*, replication 2) at different depths in the soil profile (top graph: 0.4 m; middle graph: 1.0 m; bottom graph: 1.4 m).

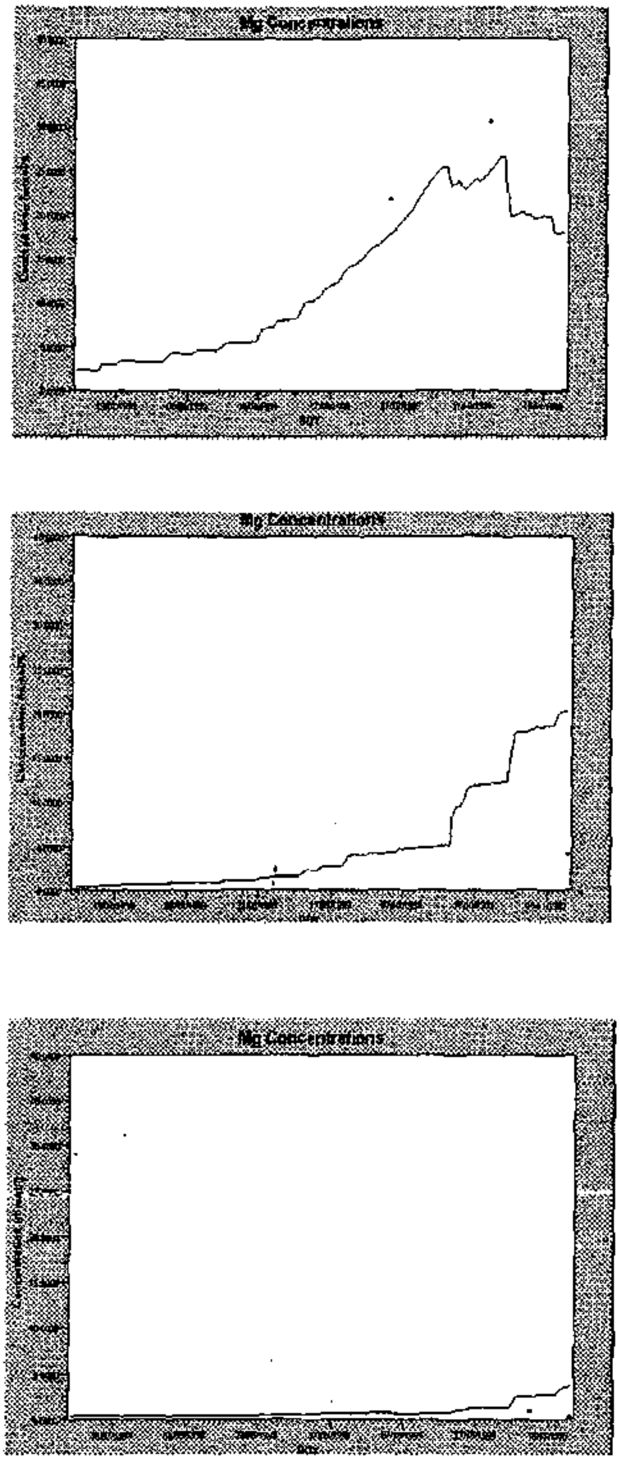


Figure N12. Measured (symbols) and simulated (line) concentration of magnesium in the soil solution (wheat crop, winter 1999 season, pivot Fourth, leaching fraction treatment, replication 2) at different depths in the soil profile (top graph: 0.4 m; middle graph: 1.0 m; bottom graph: 1.4 m).

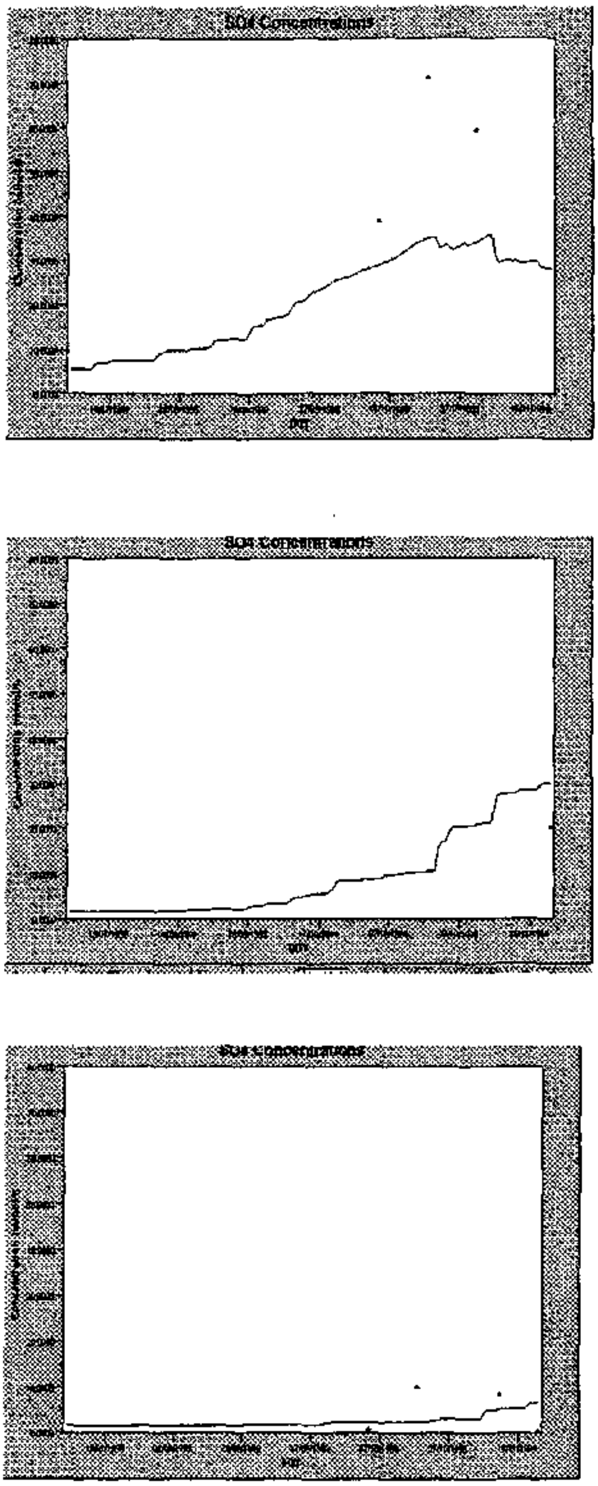


Figure N13. Measured (symbols) and simulated (line) concentration of sulphate in the soil solution (wheat crop, winter 1999 season, pivot Fourth, leaching fraction treatment, replication 2) at different depths in the soil profile (top graph: 0.4 m; middle graph: 1.0 m; bottom graph: 1.4 m).

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JH Moolman, WP de Clercq, WPJ Wessels, A Meiri and CG Moolman

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CC du Preez, MG Strydom, PAL le Roux, JP Pretorius, LD van Rensburg and ATP Bennie

It is foreseen that increasing water demand and salinisation in the Vaal River system could negatively affect irrigators in the Lower Vaal River in that they will increasingly have to contend with a water supply that is less assured and of lower quality. This exploratory investigation found the trend for water quality to deteriorate, to be much less pronounced than anticipated and to be dominated by annual and multi-year wet and dry cycles. Only isolated river stretches were exposed to relatively serious water quality problems. A comparison of a limited sample of virgin and irrigated soil profiles from irrigated areas showed that the salt content of soils was reduced under irrigation when they contained more than 4 t salt/ha$m in the virgin state, and increased under irrigation, when the virgin state salinity was lower. No decrease in crop yield was calculated with the present crop mix and the best observed water quality in various river segments, while crop yield was calculated to be reduced under the worst water quality conditions in most river stretches. Long-term model predictions indicated that all undrained soils could become unsuitable for crop production over the next 50 years as a result of excessive salt accumulation.

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