CHAPTER 3

FIELD SITES, MONITORING AND MODELLING

3.1 Introduction

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

3.2 Field site locations and experimental layout

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

3.2.1 Kleinkopjé

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

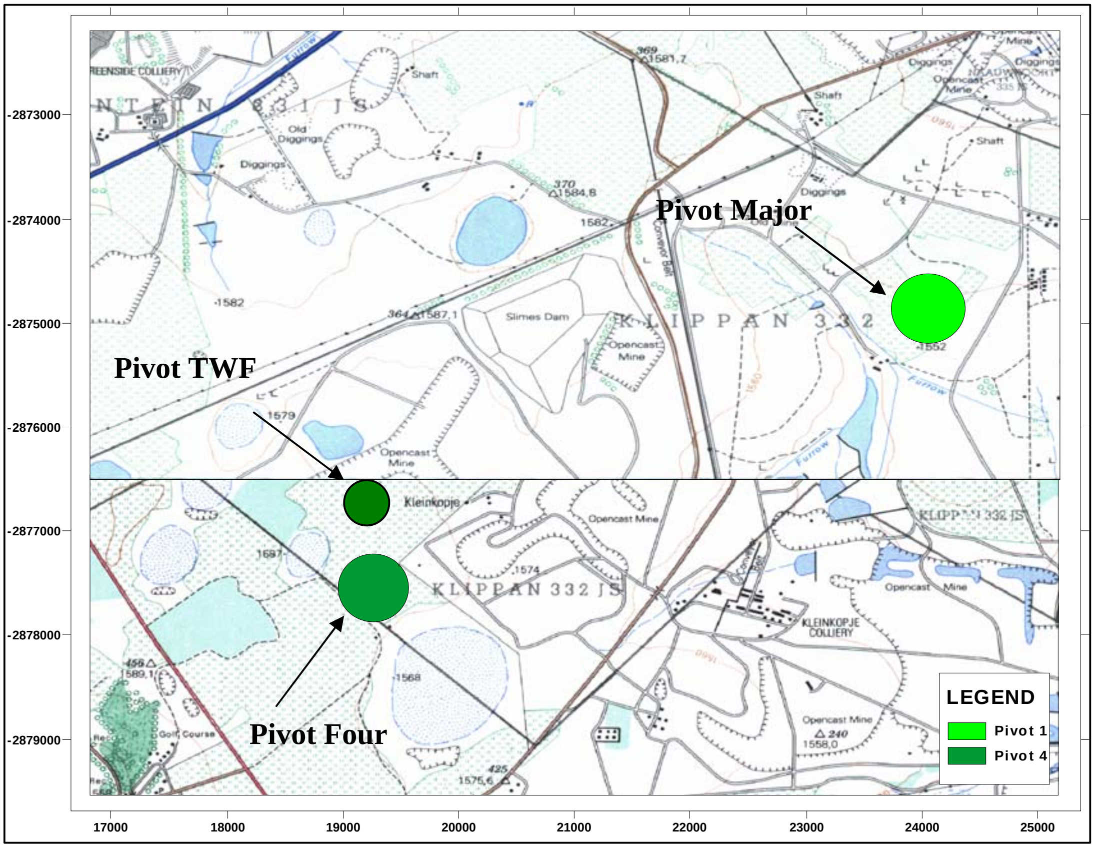
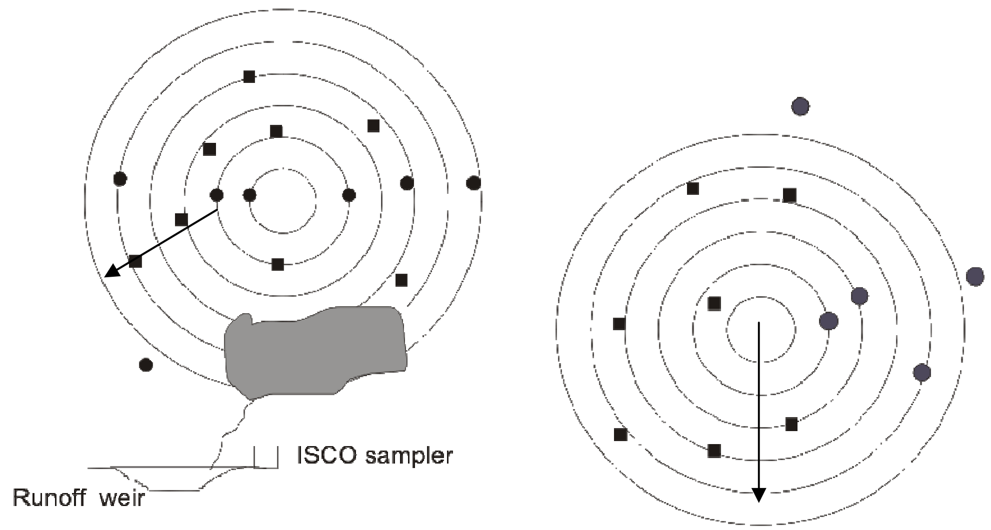
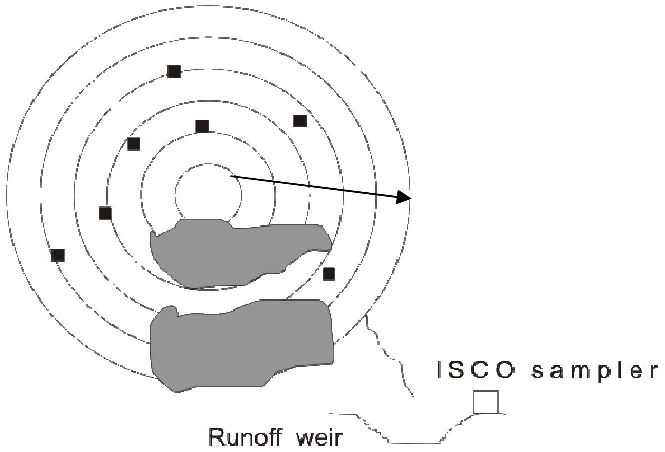


Figure 3.1 Topographic map of the Kleinkopjé area, indicating the position of Pivot Major, Pivot Four and Pivot TWF



a) Pivot Major (30ha) b) Pivot Four (30ha)



c) Pivot TWF (20ha)

┈┈┈ Wheel tracks

■ Intensive monitoring station and plant and soil sampling sites

⬣ Areas occasionally waterlogged during summer

↓ Main direction of slope

Figure 3.2 Experimental layout of the irrigated fields at Kleinkopjé

3.2.2 New Vaal

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

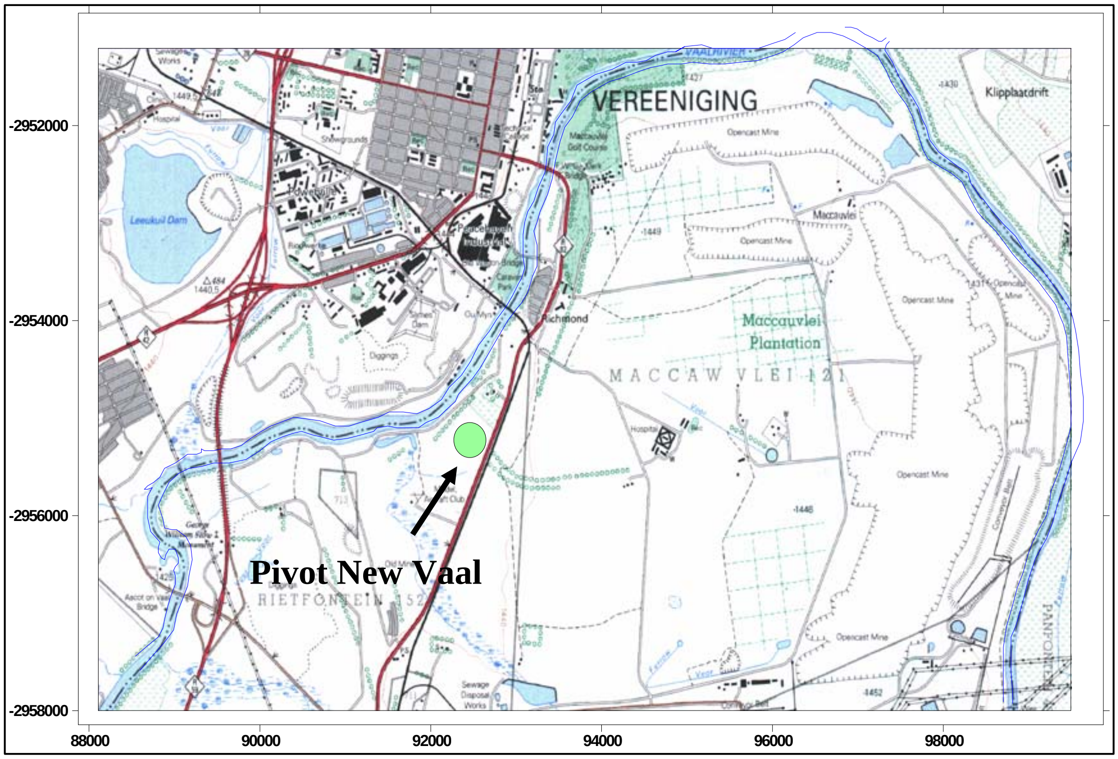
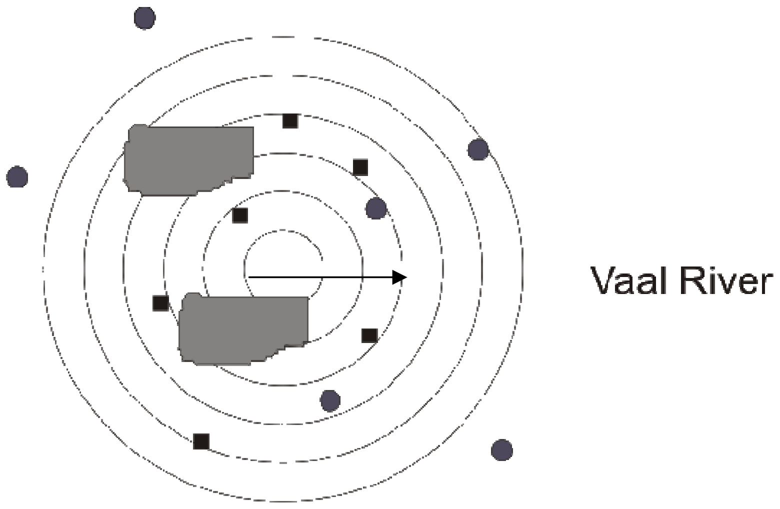


Figure 3.3 Topographic map of the New Vaal area



┈┈┈ Wheel tracks

■ Intensive monitoring station and plant and soil sampling sites

⬣ Areas occasionally waterlogged during summer

↓ Main direction of slope

Figure 3.4 Experimental layout of the irrigated fields at New Vaal

3.2.3 Syferfontein

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

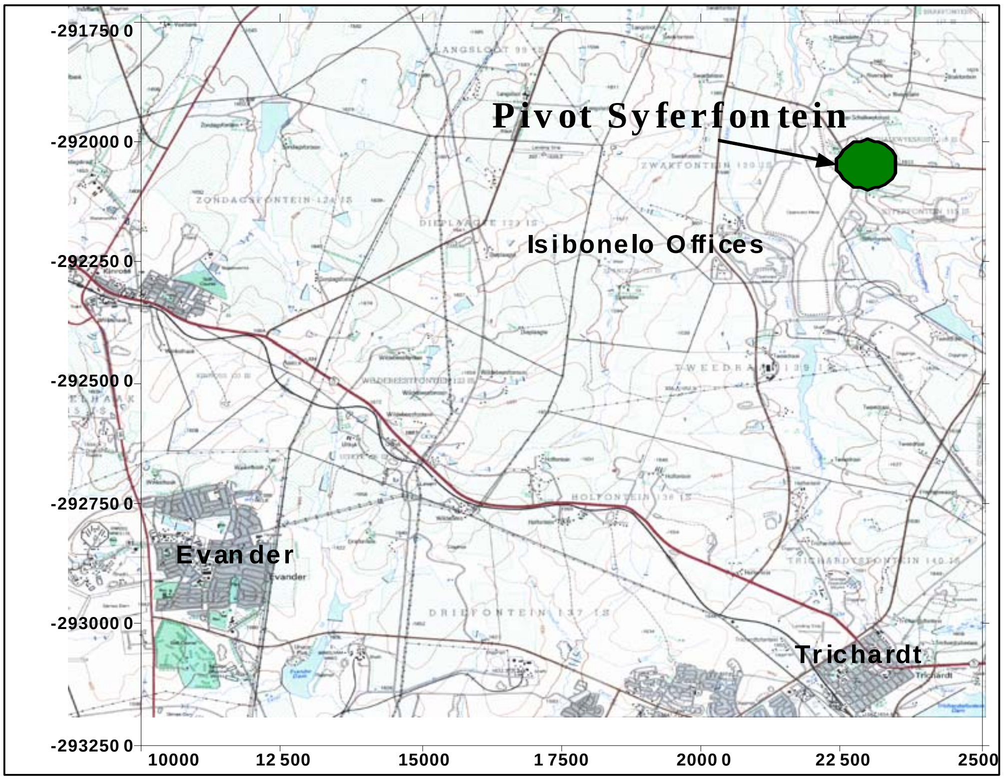
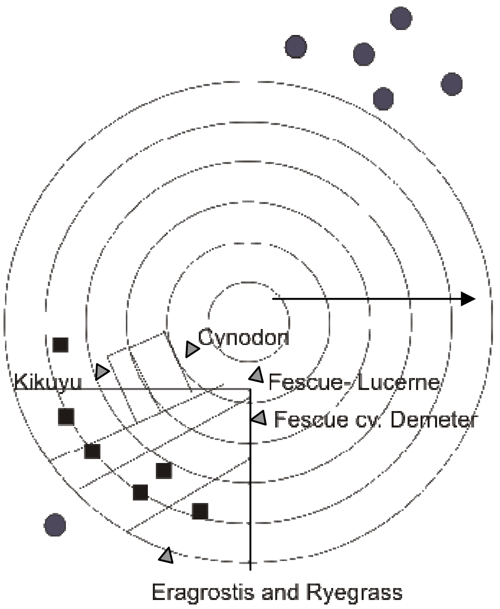


Figure 3.5 Regional setting of Syferfontein irrigation site



…… Wheel tracks

■ Intensive monitoring station and plant and soil sampling sites

↓ Main direction of slope

Figure 3.6 Experimental layout of the irrigated fields at Syferfontein.

3.2.4 Waterberg

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

46B$_1$	FCR$_1$	23R$_2$	23B$_1$	FCB$_2$	46R$_3$
FCB$_1$	FCR$_4$	46B$_2$	FCR$_2$	FCR$_2$	46R$_4$
46R$_1$	23R$_1$	FCB$_4$	23B$_2$	46R$_2$	23B$_3$
FCB$_3$	23R$_4$	46B$_3$	23B$_4$	46B$_4$	23R$_3$

24 m

30 m

FC	irrigation to field capacity (FC)
23	leaching fraction of 23% that applies 30% more water than that needed to return the profile to FC
46	leaching fraction of 46% that applies 85% more water than that needed to return the profile to FC
R	Ryegrass/rye
B	Barley

The subscript indicates replicate number.

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

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

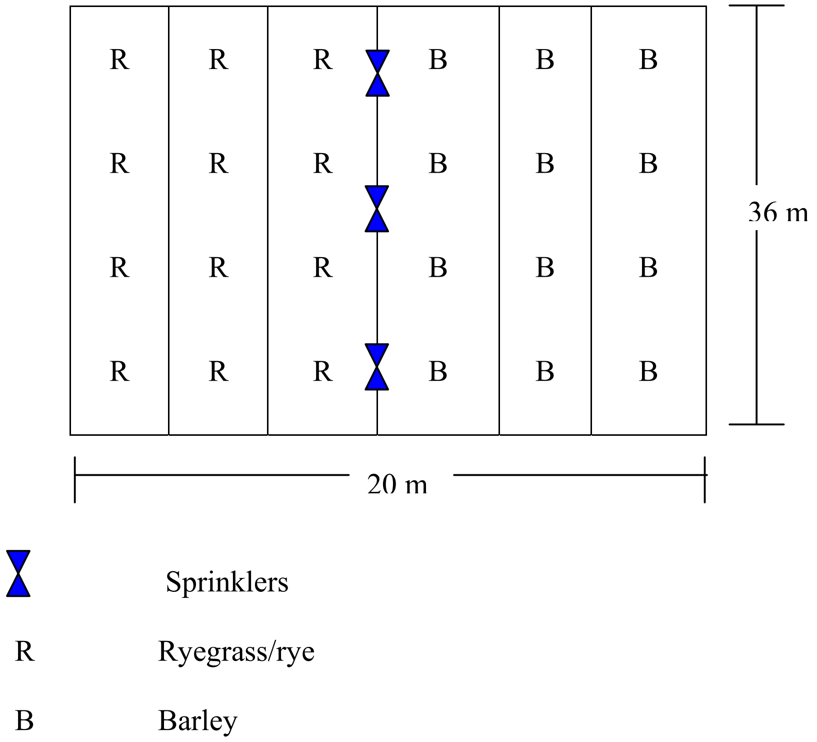


Figure 3.9 Schematic presentation of the line source Sprinkler irrigation system layout (winter, 2005) at Waterberg

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

3.3 Cropping systems

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

3.3.1 Kleinkopjé

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

Figure 3.11 Maize irrigated with gypsiferous mine water at Pivot Major

3.3.2 New Vaal

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

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

3.3.3 Syferfontein

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

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

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

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

3.3.4 Waterberg

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

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

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

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

3.4 Soil

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

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

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

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

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

3.5 Water qualities

3.5.1 Kleinkopjé and New Vaal

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

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

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

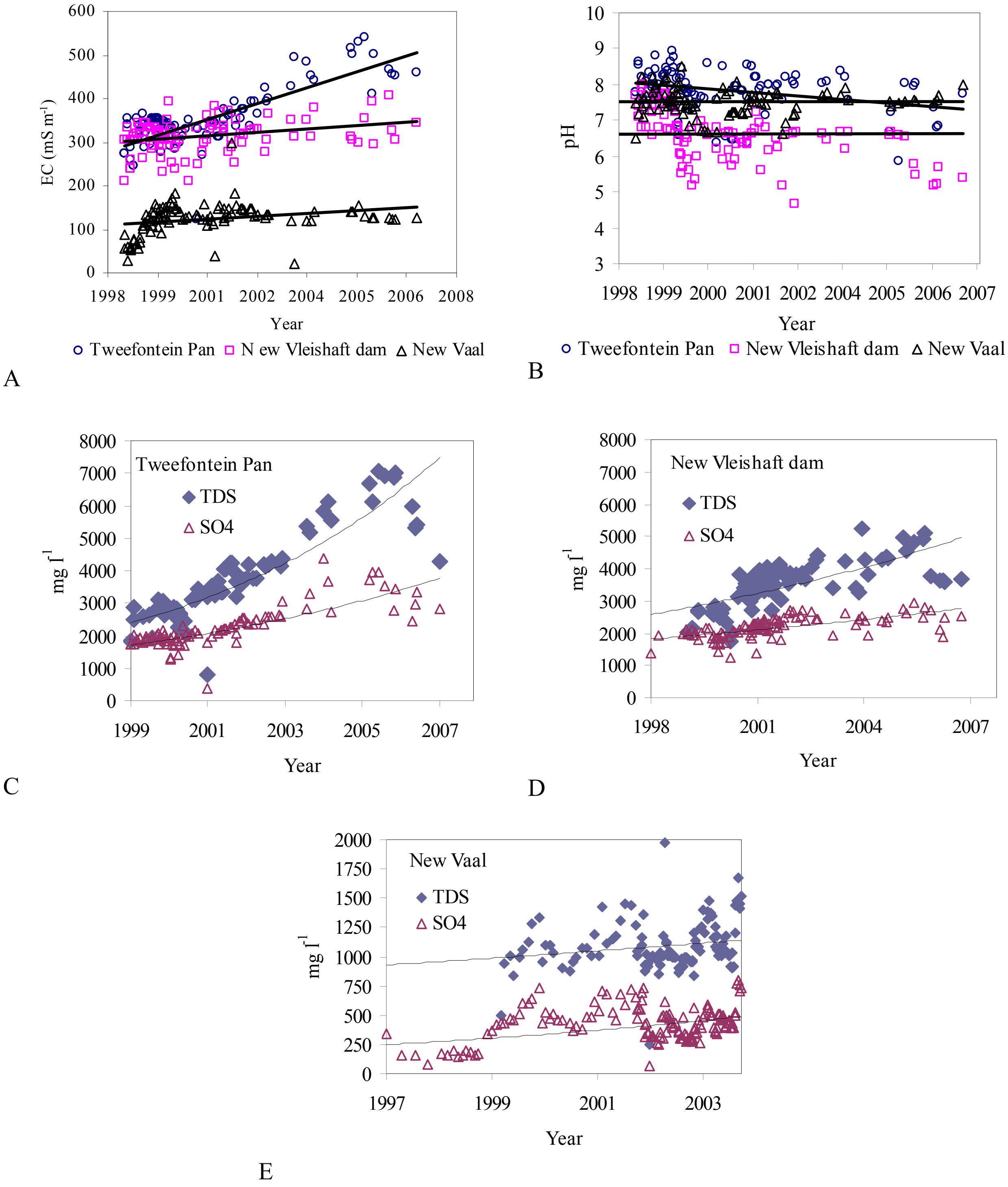


Figure 3.17 Irrigation mine water qualities of Kleinkopie and New Vaal

3.5.2 Syferfontein

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

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

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

3.5.3 Waterberg

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

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

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

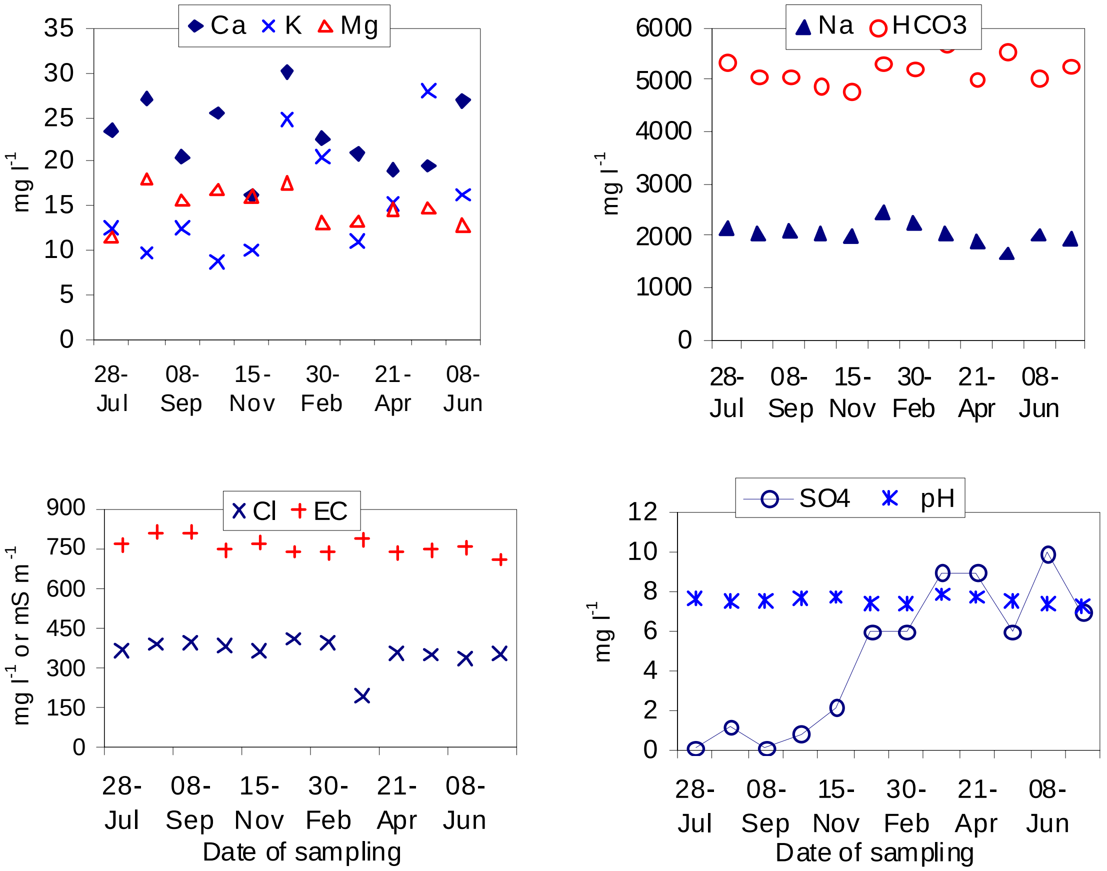


Figure 3.18 CBM irrigation water quality applied in winter 2005 and summer 2005/06

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

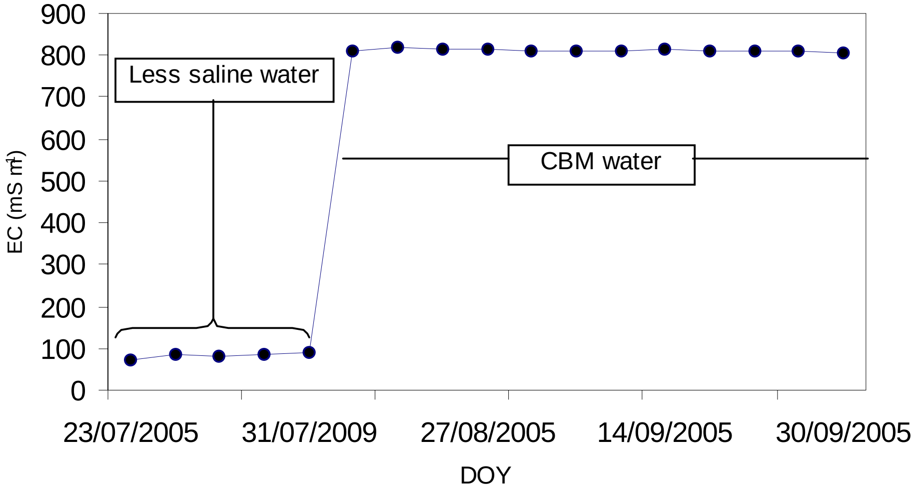


Figure 3.19 EC of the less saline water and CBM water irrigated in winter 2005

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

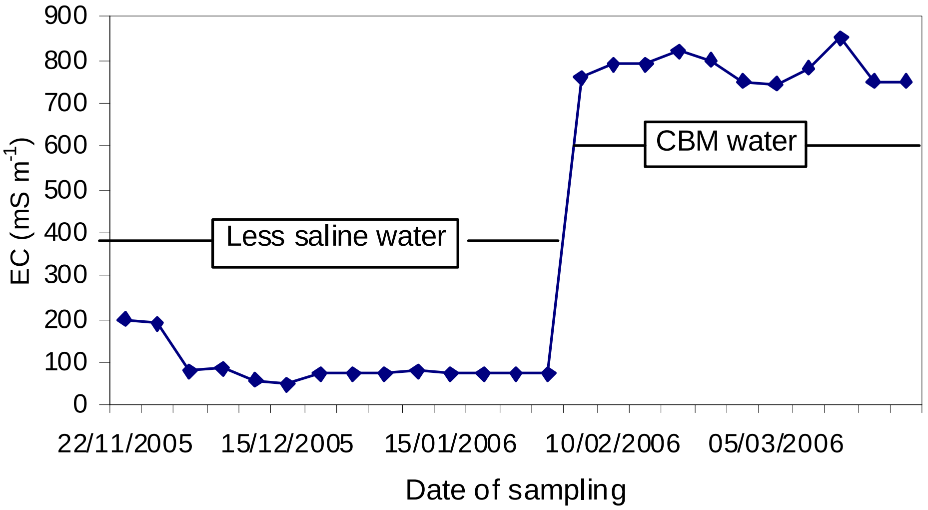


Figure 3.20 EC of the less saline water and CBM water irrigated in summer 2005/06

3.6 Monitoring the field water and salt balance

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

3.6.1 Atmospheric Evaporative Demand

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

The following metrological data were recorded with the weather stations:

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

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

3.6.2 Crop growth and nutritional status

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

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

3.6.3 Soil water balance

Irrigation and rainfall

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

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

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

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

Soil water content

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

Surface runoff

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

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

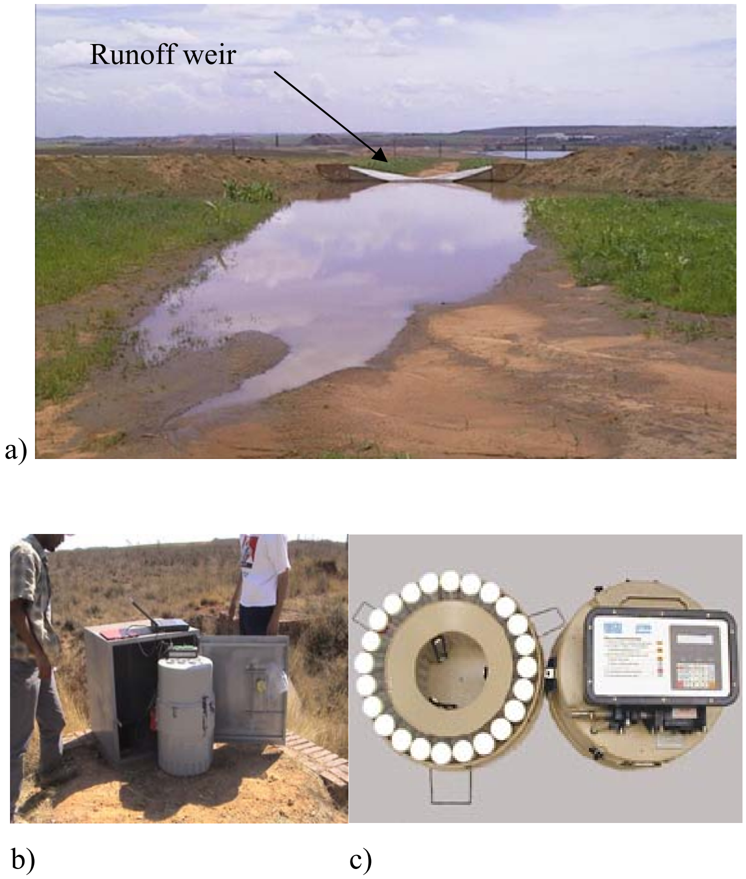


Figure 3.21 a) Runoff weir layout and b) ISCO sampler at Pivot Major and c) Top view of ISCO sampler with 24 sample bottles

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

3.6.4 Salt balance

Soil sampling and analysis

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

Soil water sampling and analyses

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

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

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

Surface runoff water quality

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

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

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

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

3.7 Modelling

3.7.1 Soil Water Balance modelling

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

3.7.2 Modelling, data processing and validations

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

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

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

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

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

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

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

Conclusions

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