CHAPTER 6

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

6.1 Introduction

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

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

6.2 Model simulations

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

6.2.1 Crop growth and soil water deficit

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

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

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

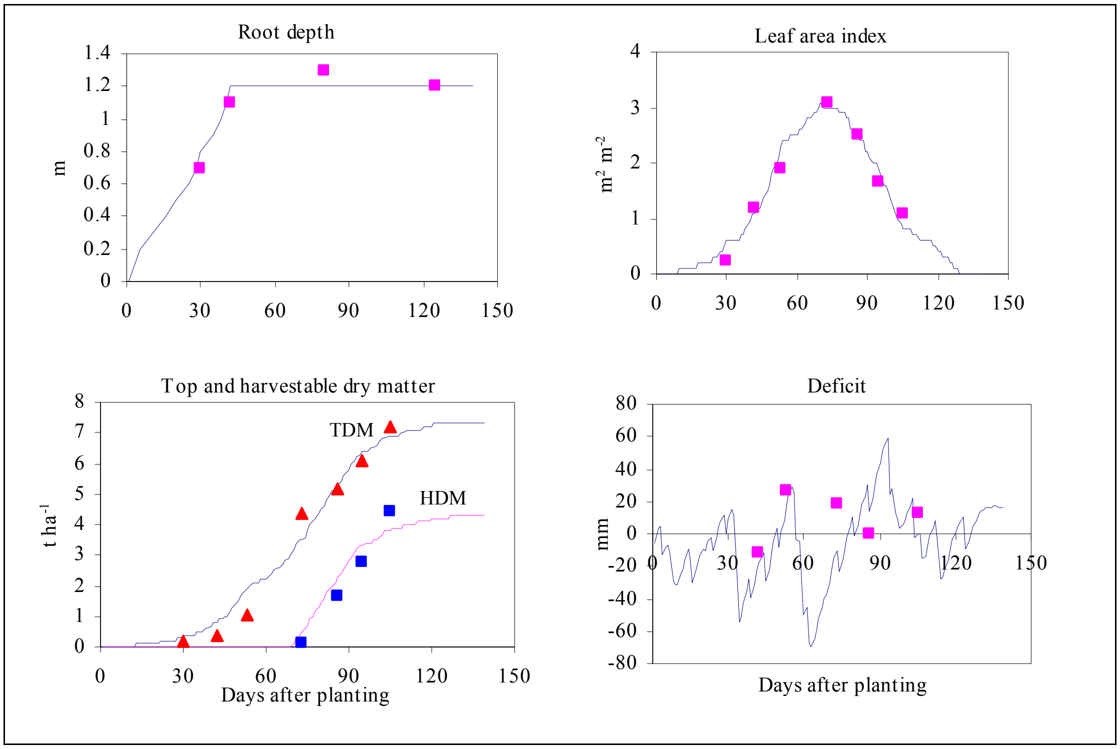


Figure 6.1 Observed (symbols) and simulated (lines) RD, LAI, TDM, HDM and deficit to FC for Maize cultivar cv. PHI 32P75, Pivot Major for the summer season 1999/2000

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

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

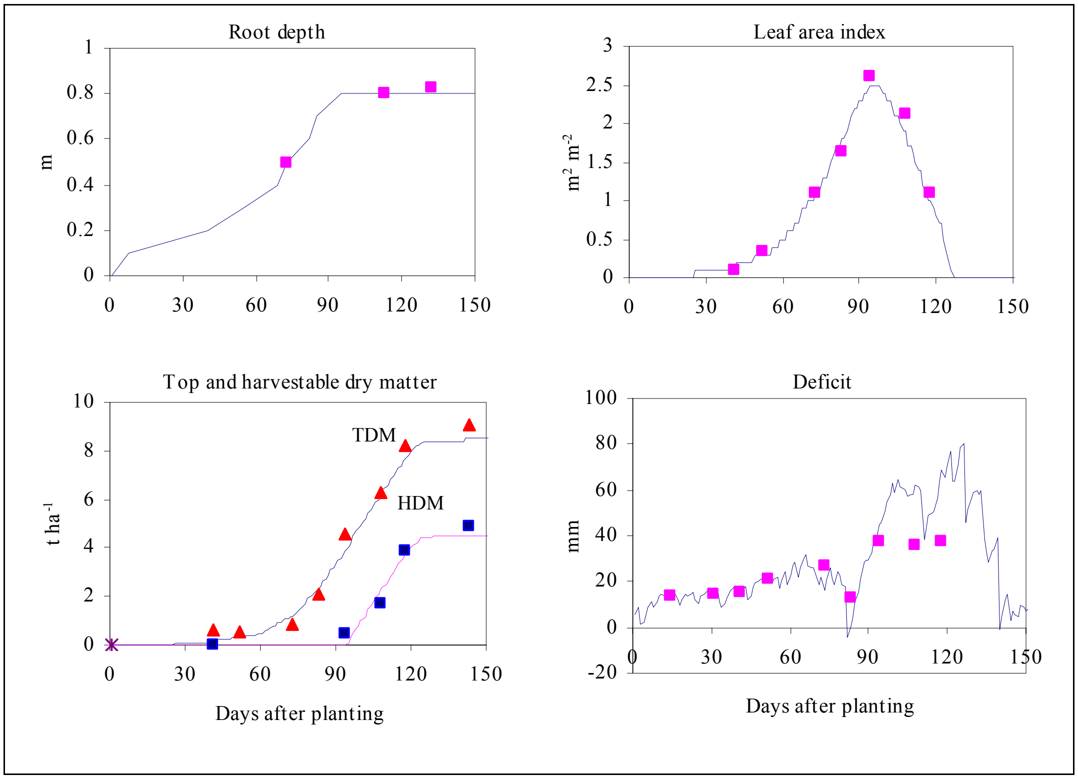


Figure 6.2 Observed (symbols) and simulated (lines) RD, LAI, TDM, HDM and deficit for Wheat cv. SST 825, Pivot Major, winter season 2000

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

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

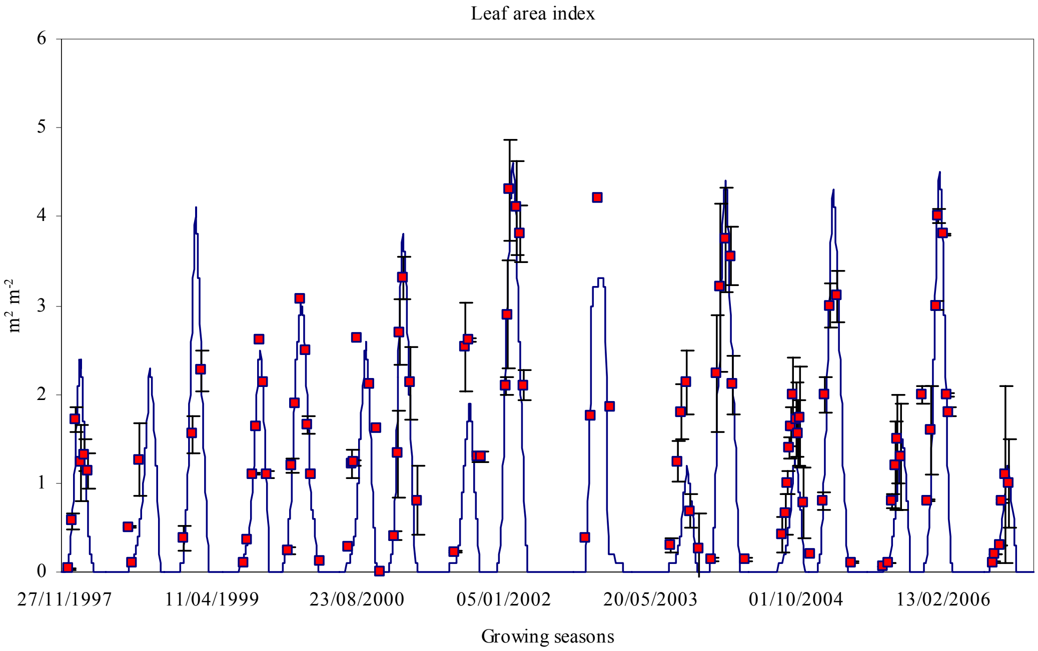


Figure 6.3 Simulated (solid lines) and measured (symbols) LAI of crops rotated between 1997/98 and 2006 for Pivot Major

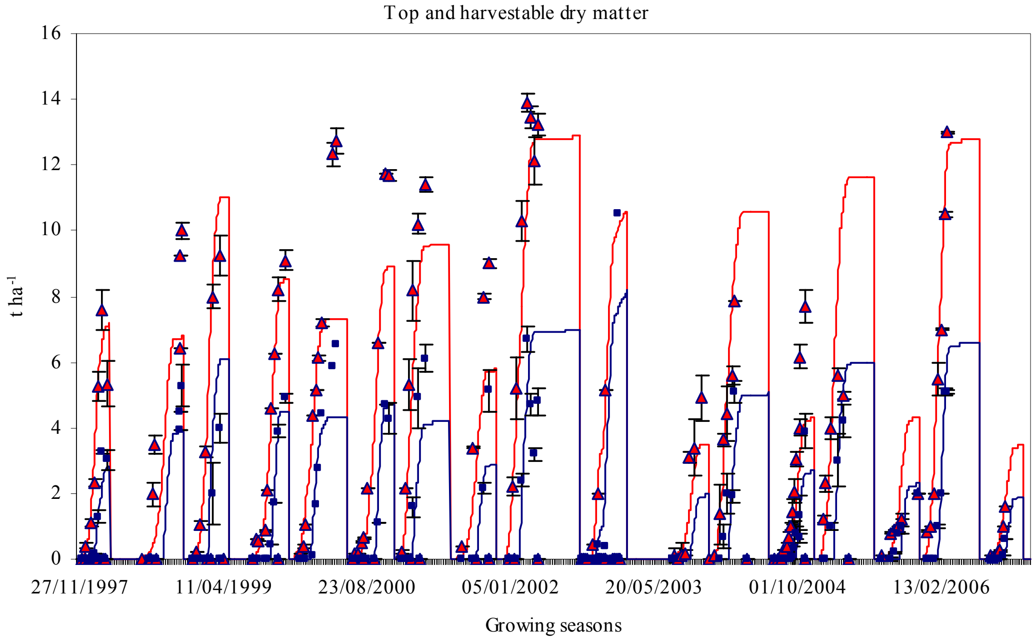


Figure 6.4 Simulated (solid lines) and measured (symbols) TDM and HDM of crops rotated between 1997/98 and 2006 for site Major

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

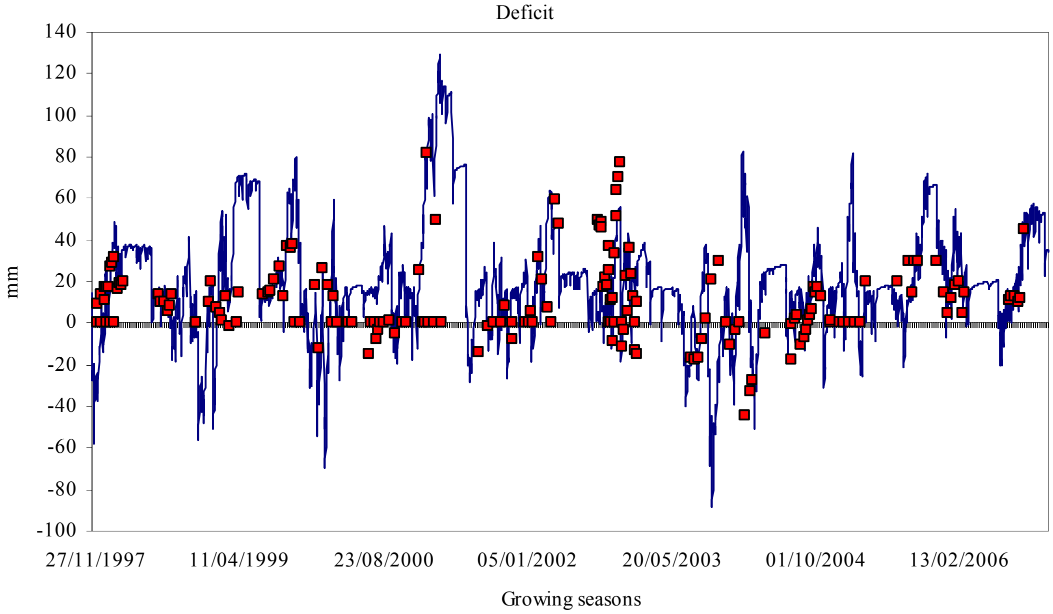


Figure 6.5 Simulated (solid lines) and measured (symbols) soil water deficit to field capacity (Major, 1997/98-2006), positive values are deficits and negative values indicate that the profile is wetter than field capacity

6.2.2 Soil chemistry

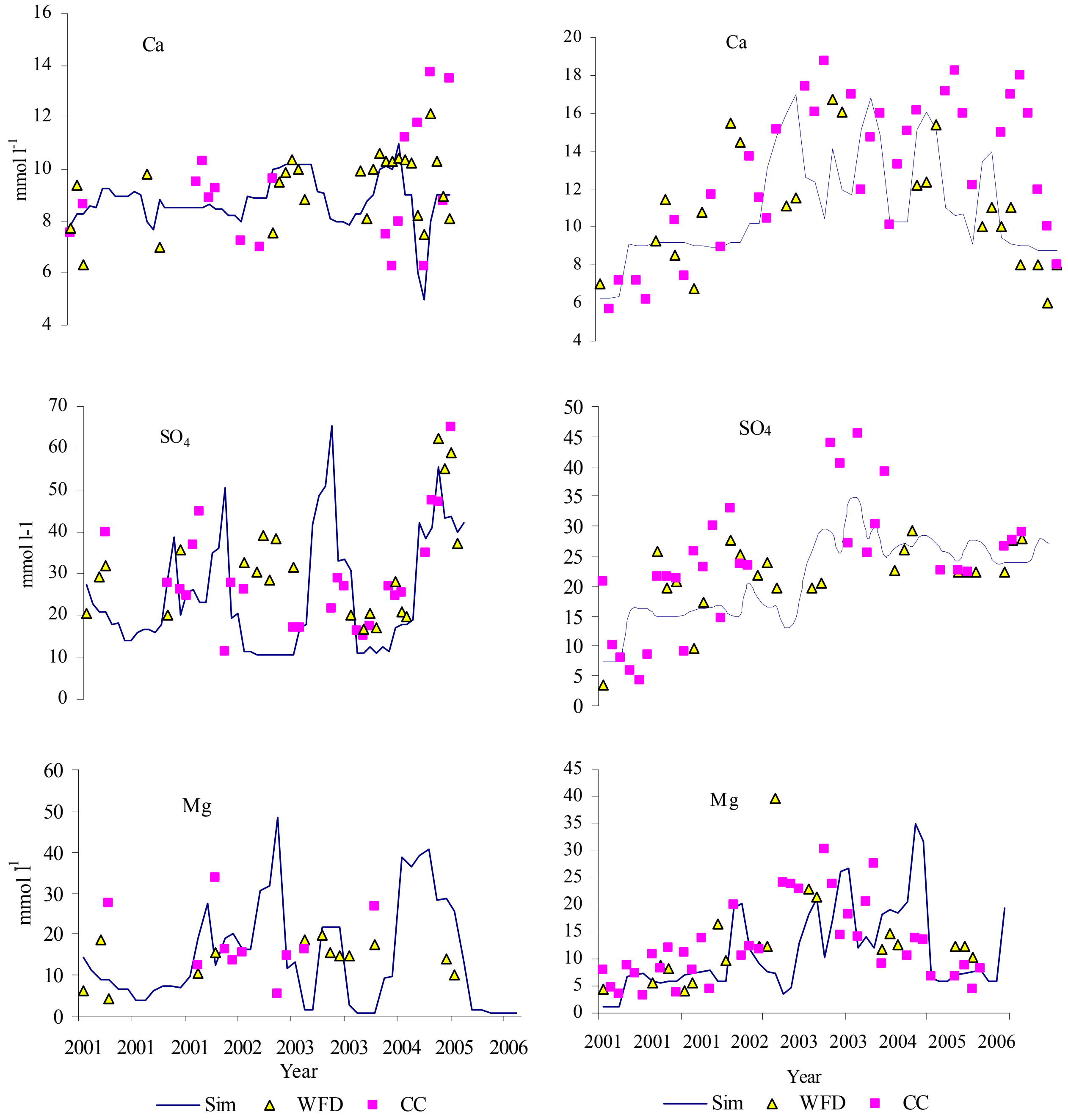
The soil solution concentrations varied considerably during the growing period due to irrigation water quality, variability of soil water chemistry, variability in soil type, and variability in climatic conditions. The major ions considered were Ca, Mg, SO_4, Na, K and Cl.

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

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

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

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



Major

Pivot Four

Figure 6.6 Observed and simulated concentration of Ca, SO$_4$ and Mg for Major and Pivot Four

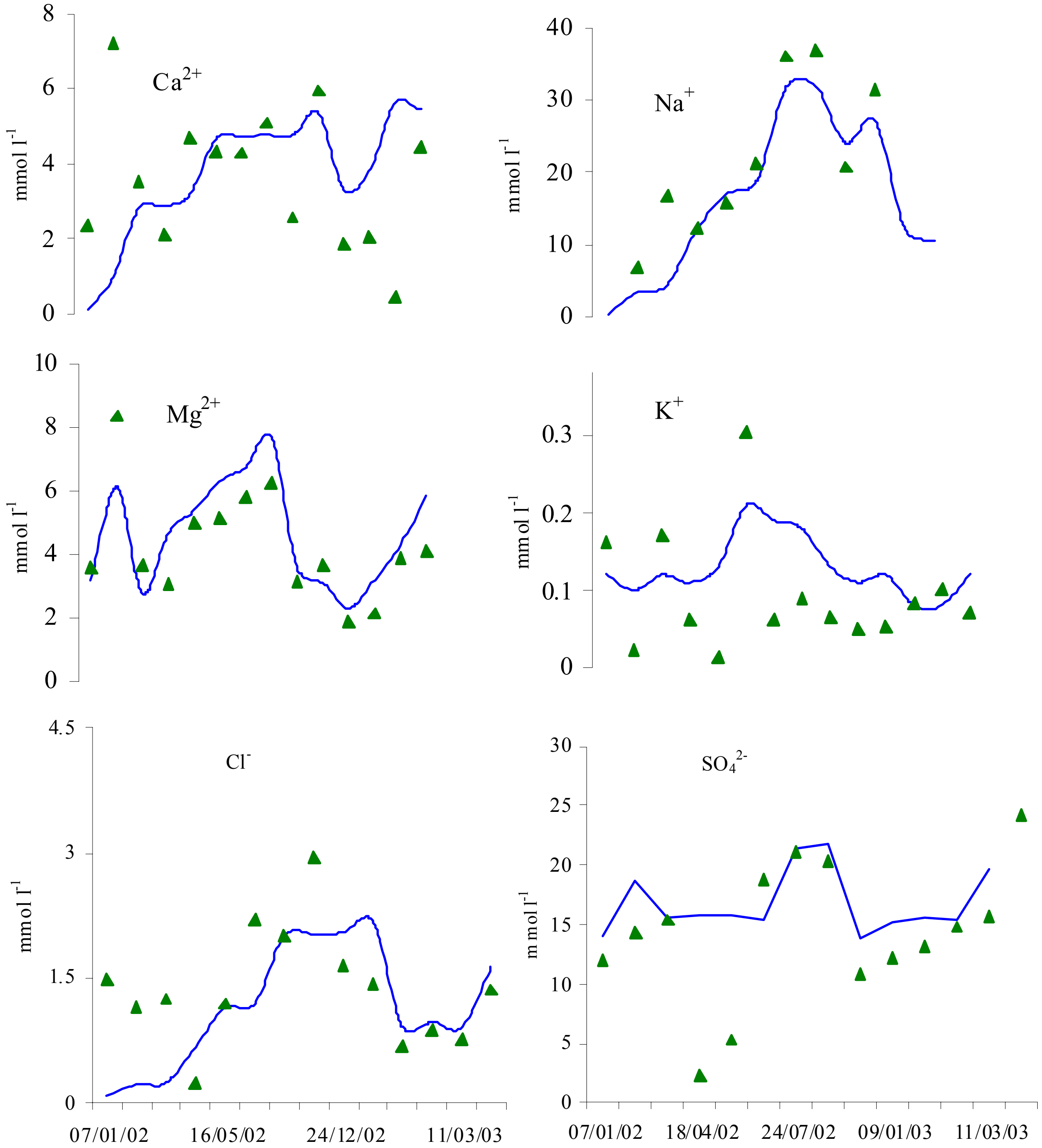


Figure 6.7 Simulated (solid lines) and CC or WFD (symbols) for concentration of Ca, Na, Mg, K, Cl and SO_4 in the soil solution at a depth of 0.4 m in the Eragrostis field (January 2002 - March 2003)

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

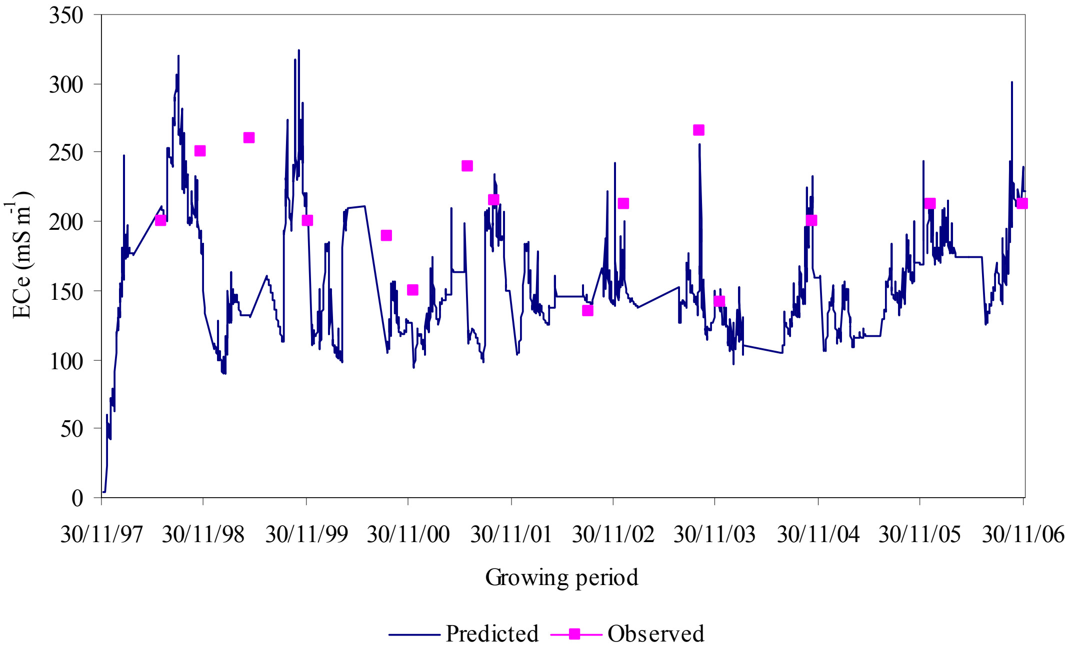


Figure 6.8 Observed and simulated EC_e (mS m^{-1}) for Pivot Major (1997-2006)

6.3 Soil water and salt balances

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

6.3.1 Kleinkopjé

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

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

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

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

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

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

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

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

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

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

6.3.2 Syferfontein

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

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

6.4 Long-term scenarios

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

6.4.1 Irrigation with gypsiferous rich mine water

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

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

6.4.2 Irrigation with Na_2SO_4 rich mine water

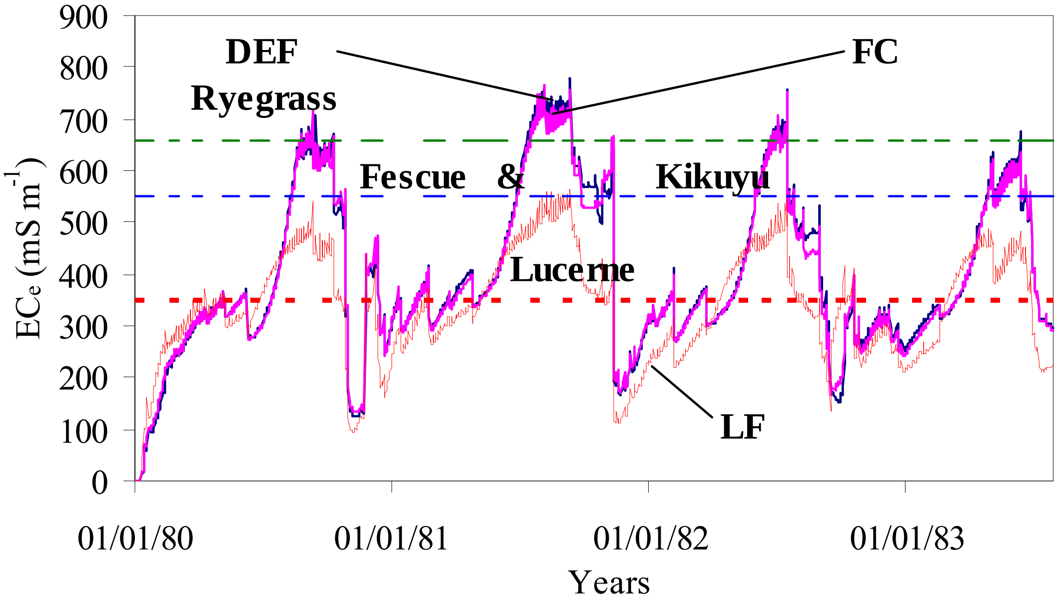
Twenty years of irrigation with Na_2SO_4 rich mine effluent were simulated using historic daily data collected from a meteorological station at Secunda. Three irrigation management strategies were also evaluated in an attempt to identify suitable irrigation management options for sustainable utilization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

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

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

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

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



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

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

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

6.4.3 Irrigation with $NaHCO_3$ rich mine water

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

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

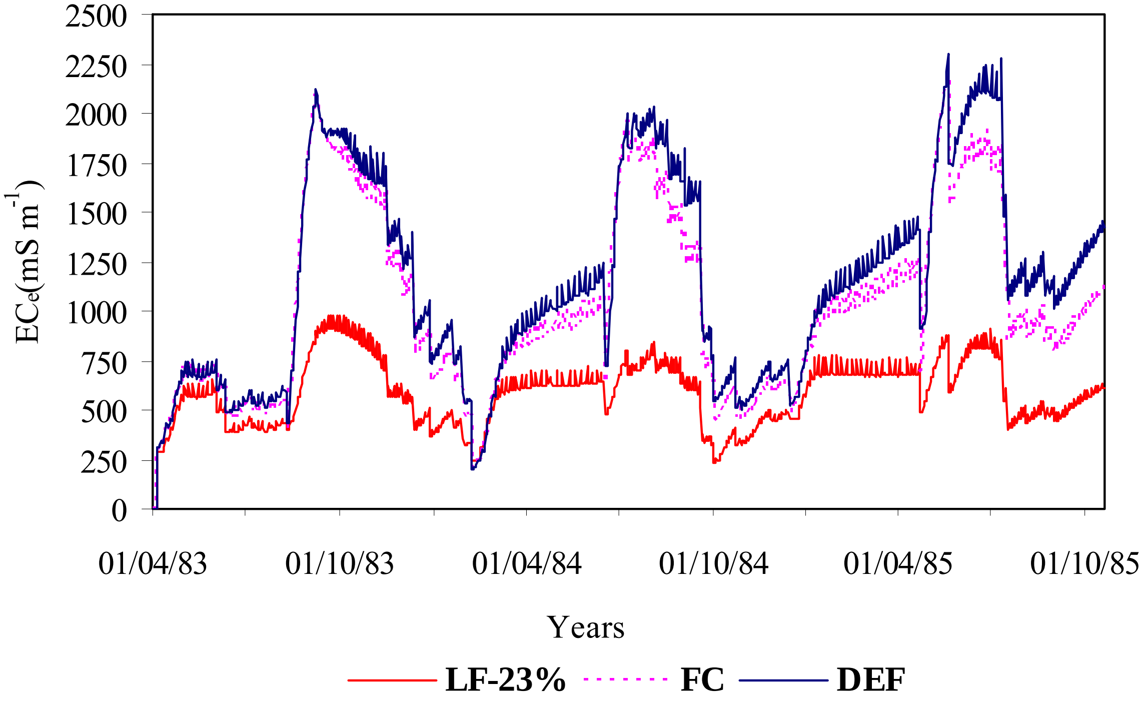


Figure 6.10 Simulated root density weighted soil saturated EC_e of a barley-cotton rotation irrigated at a threshold deficit of 15 mm with $NaHCO_3$ deep aquifer water for three arbitrarily chosen years

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

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

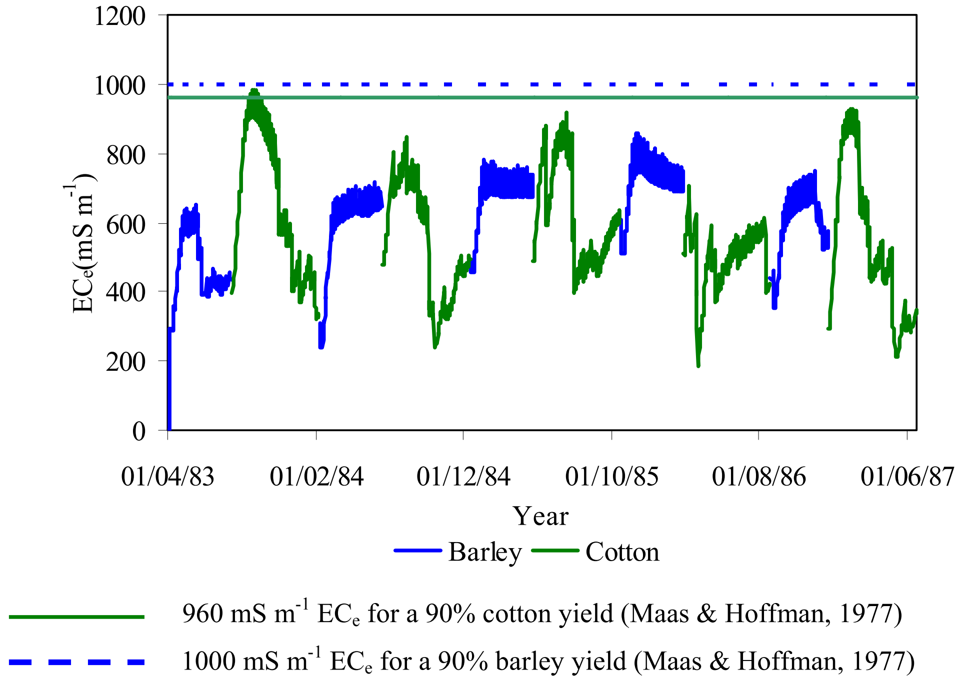


Figure 6.11 Simulated root density weighted soil saturated EC_e of a barley-cotton rotation irrigated at a 23% LF and threshold deficit of 15 mm, compared to Maas & Hoffman (1977) norms for a 90% yield potential

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

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

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

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

Conclusions

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

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

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

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

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

References

ANNANDALE, J.G., BENADÉ, N., JOVANOVIC, N.Z., STEYN, J.M. & DU SAUTOY, N., 1999. Facilitating irrigation scheduling by means of the soil water balance model. Water Research Commission Report No. 753/1/99, Pretoria, South Africa.

ANNANDALE, J.G., JOVANOVIC, N.Z., BENADÉ, N. & TANNER, P.D., 1998. Modelling the long-term effect of irrigation with gypsiferous water on soil and water resources. *Agr. Ecos. & the Environ.* 76, 109-119.

ANNANDALE, J.G., JOVANOVIC, N.Z., CLAASSENS, A.S., BENADÉ, N., LORENTZ, S.A., JOHNSTON MA, TANNER P.D., AKEN M.E. & HODGSON, F.D.I, 2001. The influence of irrigation with gypsiferous mine-water on soil properties and drainage water. Water Research Commission Report No. K5/858, Pretoria, South Africa.

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

BLACKWELL, J., JAYAWARDENA, N.S., BISWAS, T.K., & TOWNSEND, J., 2001. Sequential Biological Concentration for saline drainage water management in the Murrumbidgee irrigation area. A report to the Murrumbidgee sustainable development committee for the period of November 1997 to November 2000. CSIRO Division of Land and Water Griffith, NSW.

DE JAGER, J.M., 1994. Accuracy of vegetation evaporation ratio formulae for estimating final wheat yield. *Water SA*, 20(4), 307-315.

JOVANOVIC, N.Z. & ANNANDALE, J.G., 1999. Crop growth parameters of 19 summer vegetable cultivars for use in mechanistic irrigation scheduling models. *Water SA*. 26(1), 67-76.

MAAS, E.V., 1986. Salt tolerance in plants. *Appl. Agric. Res.* 1, pp. 12-26.

MAAS, E.V. & HOFFMAN, G.S., 1977. Crop salt tolerance: Current assessment. *J. Irrig. and Drain. ASCE*, 103 (IR2), 115-134.