CHAPTER 5

SOIL PROPERTIES

5.1 Introduction

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

5.2 Kleinkopjé and New Vaal

5.2.1 Soil salinity

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

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

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

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

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

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

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

5.2.2 Soil pH and gypsum

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

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

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

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

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

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

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

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

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

SD- Standard devation Max - Maximum Min- Minimum

5.2.3 Soil nutrients and fertilization

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

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

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

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

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

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

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

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

	Mg (cmol$_{(c)}$ kg^{-1})											
Soil depth	Pivot Major			Pivot Four			Pivot TWF			New Vaal		
(m)	Mean±SD	Max	Min	Mean±SD	Max	Min	Mean±SD	Max	Min	Mean±SD	Max	Min
0.20	0.9±0.9	1.8	0.2	0.8±0.4	1.5	0.1	0.9±0.4	1.2	0.1	0.4±0.05	0.5	0.4
0.40	0.7±0.4	1.2	0.2	1.1±0.7	2.0	0.2	1.6±0.8	2.6	0.2	1.1±1.2	2.9	0.3
0.60	0.6±0.2	0.9	0.2	1.2±0.6	1.9	0.5	1.4±0.8	2.3	0.2	0.3±0.2	0.6	0.2
0.80	0.9±0.3	1.2	0.4	1.2±0.6	1.8	0.1	1.3±0.7	2.1	0.4	0.6±0.1	0.7	0.4
1.00	1.2±0.5	1.6	0.3	1.5±0.4	1.9	1.0	1.0±0.7	1.8	0.5	0.5±0.3	1.0	0.2
1.20	1.2±0.2	1.4	1.1	1.4±0.2	1.6	1.2	1.0±0.8	1.5	0.4	0.6±0.4	1.1	0.4
1.40	1.2±0.3	1.4	0.8	1.4±0.1	1.6	1.4	-	-	-	0.5±0.3	1.0	0.2
1.60	1.2±0.2	1.4	0.8	1.3±0.2	1.5	1.2	-	-	-	-	-	-

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

SD- Standard devation Max - Maximum Min- Minimum

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

	Mg (cmol$_{(c)}$ kg^{-1})			
Soil depth	Pivot Major	Pivot Four	Pivot TWF	New Vaal
(m)	Mean±SD	Mean±SD	Mean±SD	Mean±SD
0.20	0.09±0.01	0.77±0.09	0.31±0.00	0.64±0.04
0.40	0.09±0.02	0.60±0.19	0.36±0.01	0.20±0.03
0.60	0.08±0.01	0.32±0.14	0.30±0.03	0.41±0.02
0.80	0.07±0.05	0.24±0.06	0.35±0.05	0.37±0.00
1.00	0.10±0.03	0.22±0.05	0.70±0.04	0.28±0.06
1.20	0.12±0.03	-	1.30±0.03	0.32±0.03

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

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

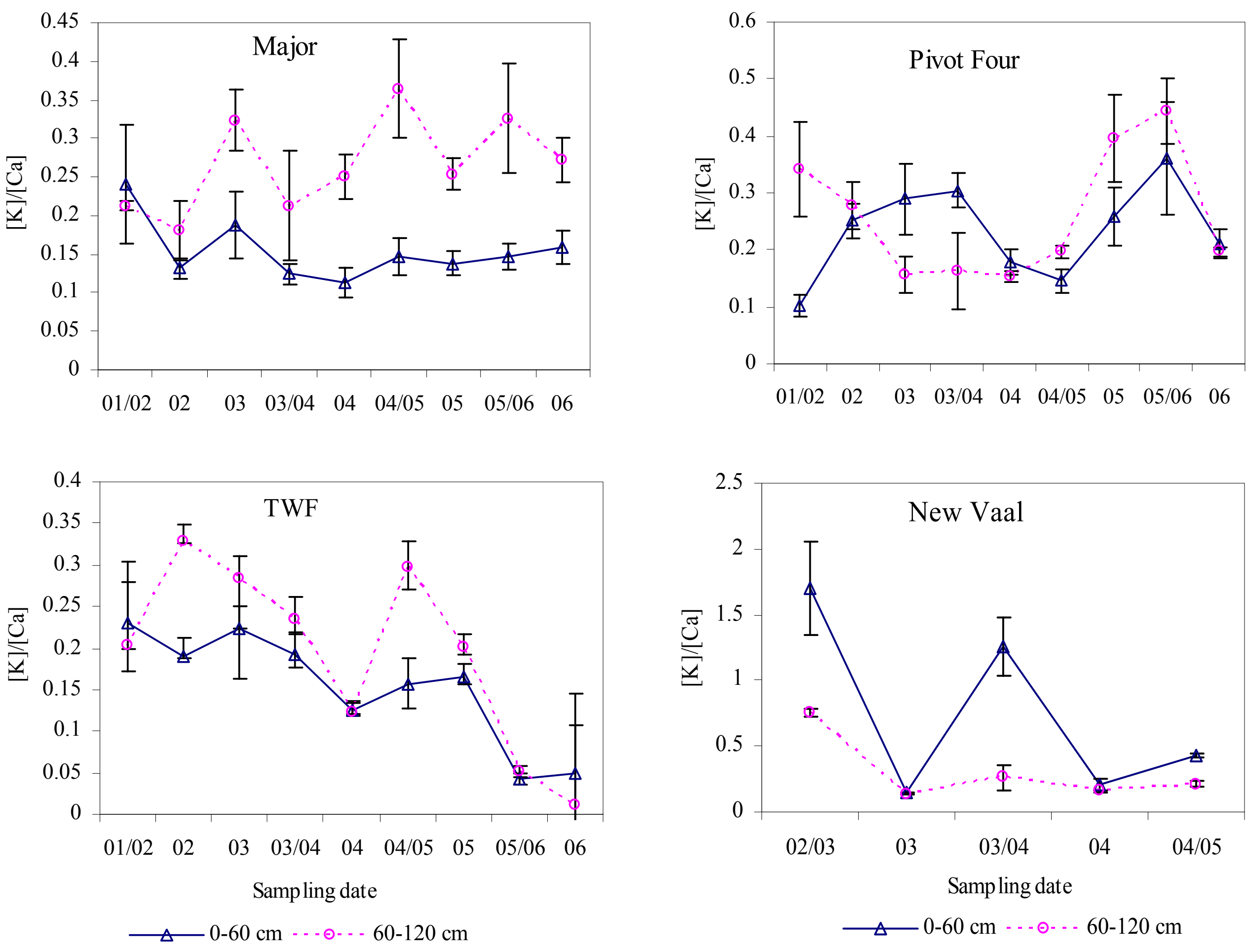


Figure 5.1 Temporal changes of exchangeable [K]/[Ca] for the irrigation sites

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

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

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

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

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

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

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

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

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

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

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

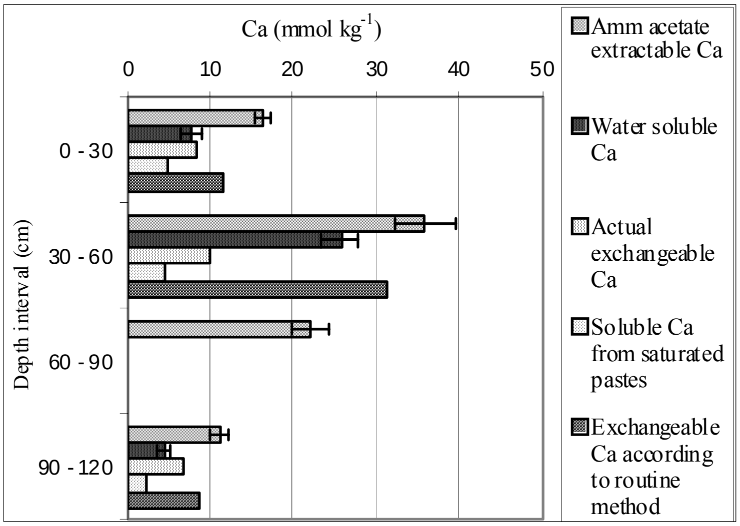


Figure 5.2 Interference of gypsum in the determination of exchangeable Ca using the routine method (Major, 2004)

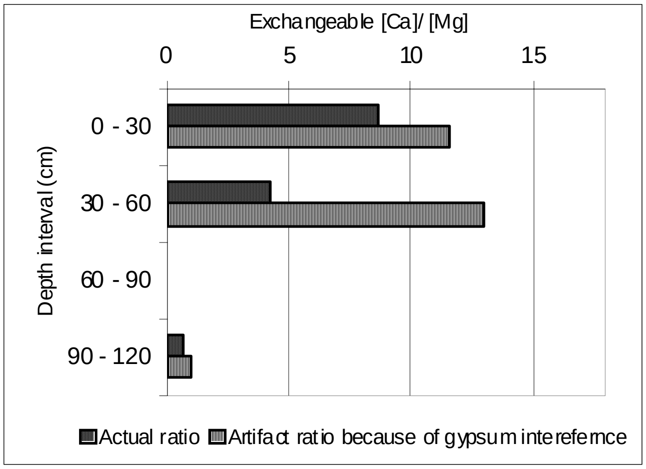


Figure 5.3 Actual [Ca]/[Mg] ratio versus [Ca]/[Mg] artifact ratio because of gypsum interference

5.3 Syferfontein

5.3.1 Soil salinity

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

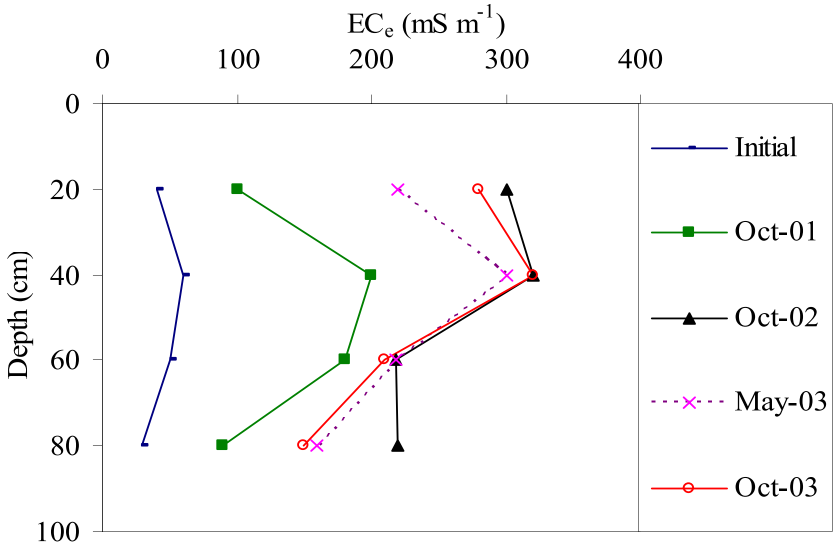


Figure 5.4 Average EC_e (mS m^{-1}) of the soil at initial condition and during the trial period

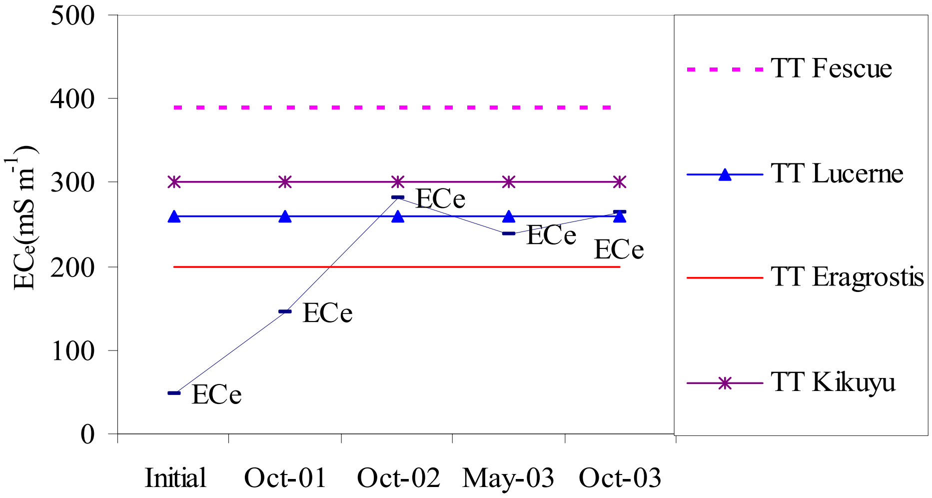


Figure 5.5 EC_e (mS m^{-1}) measured during the trial period and threshold tolerance (TT) of pastures

5.3.2 Soil sodicity

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

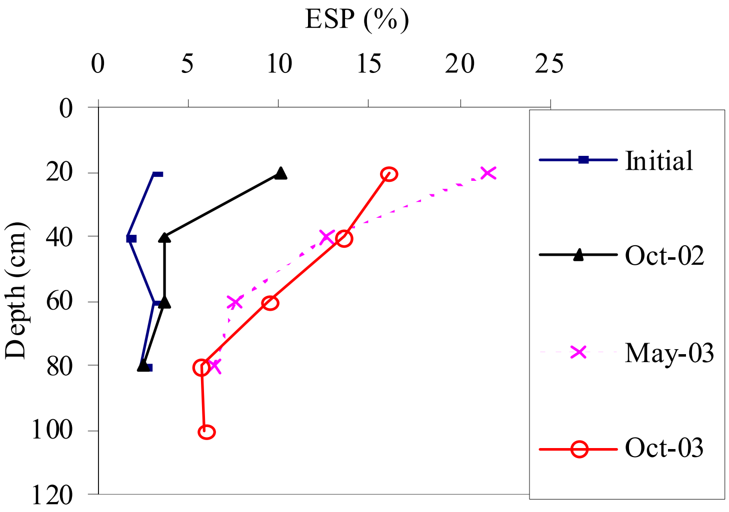


Figure 5.6 Average ESP (%) of the soil at initial condition and during the trial period

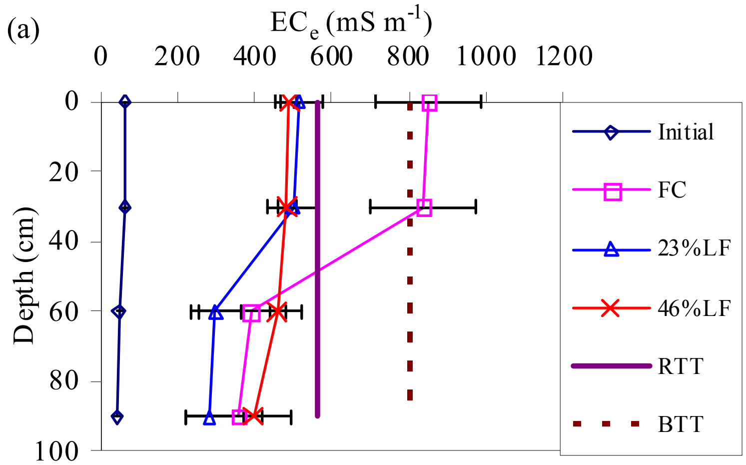
No crust formation was observed during the trial period, as the high clay content made the soil not prone to crust formation. Similar findings were also made by Ben-Hur *et al* (1985), who found that soils with 20 to 30% clay were the most susceptible to crust formation; those with clay content >40%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

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

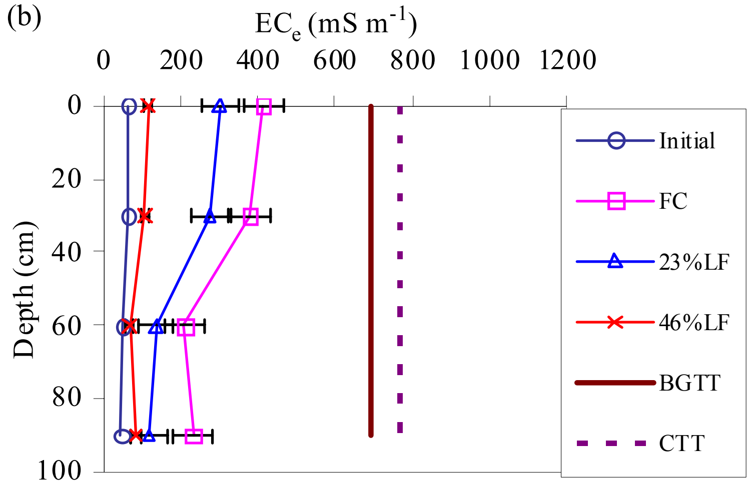
5.4 Waterberg

5.4.1 Soil salinity

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



RTT -ryegrass threshold tolerance BTT -barley threshold tolerance



BGTT -Bermuda grass threshold tolerance CTT -cotton threshold tolerance

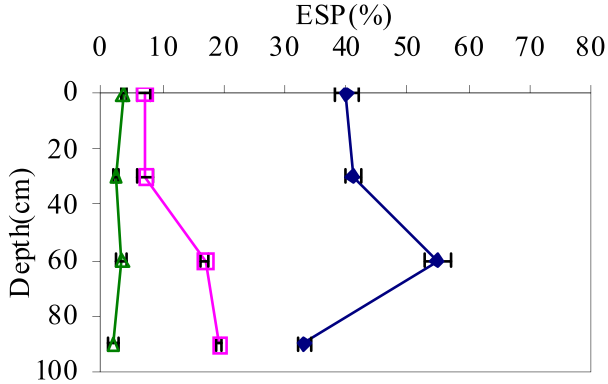
Figure 5.7 Soil saturated paste extracts at the end of (a) the winter 2005 trial and (b) the 2005/06 summer trial

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

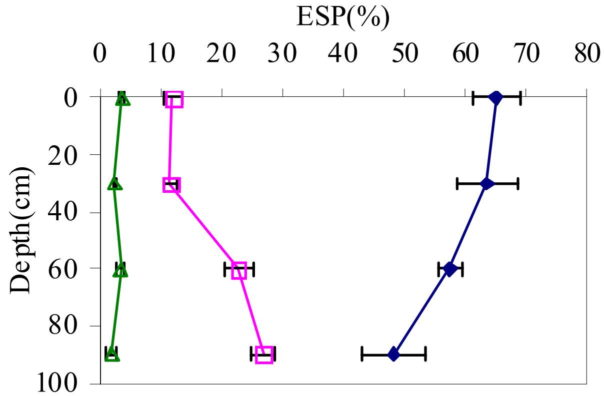
5.4.2 Sodicity and infiltration

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

(a) FC



(b) 23%LF



(c) 46%LF

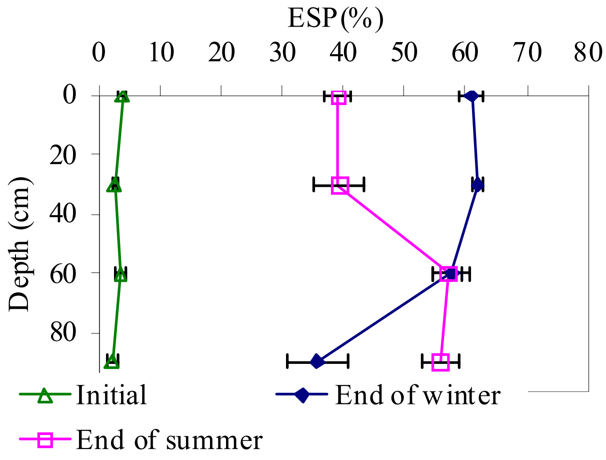


Figure 5.8 Exchangeable sodium percentage of the soil irrigated at (a) FC, (b) 23%LF and (c) 46%LF

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

5.4.4 Soil solution EC

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

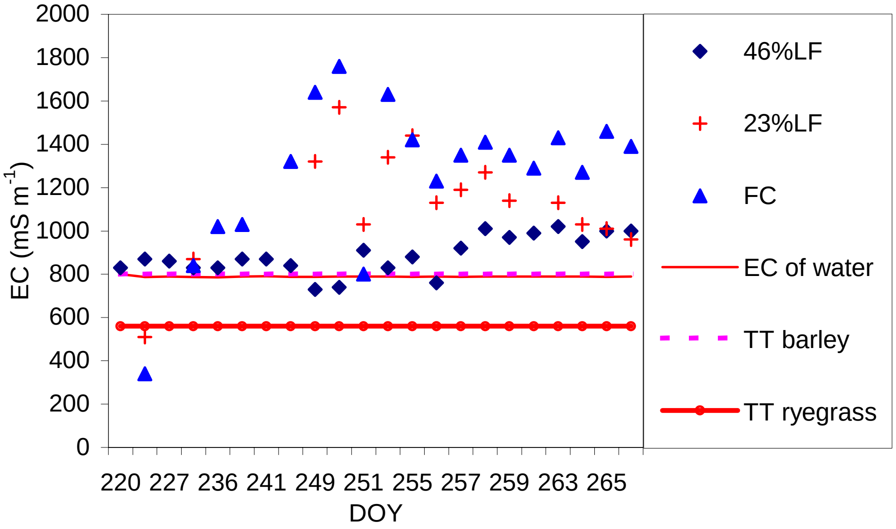


Figure 5.9 EC of the soil solution captured from WFDs installed at 30 cm depth in the FC, 23%LF and 46%LF treatments and threshold tolerance (TT) to salinity (EC_e) of the crops grown in winter 2005

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

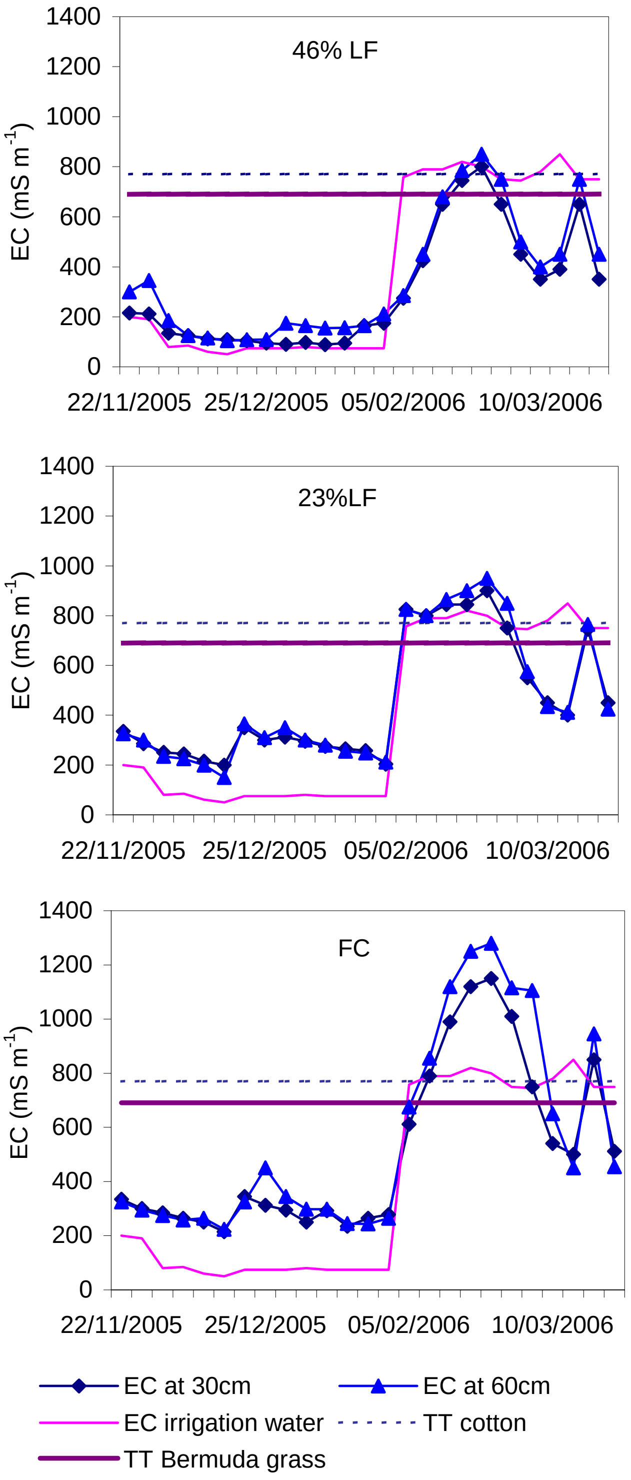


Figure 5.10 EC of the soil solution, EC of irrigation water and crop threshold tolerance (TT) during the summer 2005/06 growing period

Conclusions

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

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

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

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

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

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

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

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

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