Prediction of salt balances in irrigated soils along the lower Vaal River, South Africa

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Abstract

In arid and semi-arid regions irrigation tends to degrade soil and water quality through salt accumulation with devastating effects on some crops. This is, according to irrigators, also the case along the lower Vaal River in South Africa. Properly calibrated and tested salinity models could assist the agricultural community in improving salinity management under irrigation.

This paper reports on, firstly, salt balances of soils in this region being irrigated for different time periods, and secondly, salt content changes that can be expected as a consequence of future irrigation. Two empirical models, *viz.* a general and specific salt-balance model were used together with existing water- and soil-quality data to generate such information. The soils selected for this study had been irrigated for periods of between 17 to 53 years. Over these periods addition of salts as a result of farming practices varied between 79 and 280 $t \cdot ha^{-1}$, with irrigation water being the major contributor. Between 78% to 87% of the salts added to the soils had been leached from the root zone

Despite these large amounts of salts that have been removed, certain irrigation practices have promoted the build-up of salts in some of the soils. The freely drained sandy soils irrigated by centre pivot are of particular interest. Poor management of this system can reduce crop yields. On account of inadequate leaching salts are building up to levels that impair the potential evapotranspiration level of maize. Predictions also show that irrigation should rather be withdrawn from soils with poor internal drainage properties, such as the Arcadia soil at Spitskop. In contrast, flood irrigation on certain duplex soils, such as the Valsrivier at Vaalharts, with relatively good internal drainage properties, can improve their quality.

Keywords: drained soils, root zone, soil quality, undrained soils, water quality

Introduction

It is known that in arid and semi-arid regions irrigation tends to degrade soil and water quality through salt accumulation (Flowers and Yeo, 1986). Most irrigated crops are non-halophytes, which are affected by salt stress and need to be managed accordingly. Properly calibrated and tested salinity models could help the agricultural community to improve salinity management under irrigation.

A vast number of salinity models have been developed over the past 2 decades. Wagenet and Hutson (1987) encouraged researchers to understand the aim of modelling, because a lack of appreciation for different modelling approaches has caused confusion and disarray in modelling efforts. Models can broadly be categorised into two groups according to the purpose for which they were developed (Jones et al., 1987).

The 1st group of models aim to provide a better understanding of the dynamic nature of the biological, chemical and physical environment in which crops grow and are therefore process based. These models vary widely in their conceptual approaches and degree of complexity and are strongly influenced by environmental factors as well as the experience and bias of their developers (Clarke, 1973; Addiscot and Wagenet 1985; Wagenet and Rao, 1990). A short list of such models include MINEQL (Westall et al., 1976), EQ3/NR (Wolery, 1983), MINTEQ (Felmy et al., 1984), SHARON (De Rooy, 1991), LEACHM (Wagenet and Hutson, 1987), SWIM (Verburg et al., 1996), SOWATSAL (Hanks et al., 1991) and SWB (Barnard et al., 1997). These process-based models can be used to extrapolate results over non-related sites when properly calibrated and tested.

The 2nd group of models aim towards the prediction of the system's behaviour to be applied in improving the management thereof and are therefore problem orientated. Most of the empirical models fall in this category. Examples of such models are the equation for calculating the leaching requirement which had been applied in the Coachella Valley of California (Reeves, 1957) and the salt regime equation of Szabolcs (1986). It is also possible to calculate the accumulation of salts in soil using assumptions based on the mass balance equation of Aragües (1996). These empirical models have the disadvantage that they are site specific, which can restrict the extrapolation of results.

The aim of this paper is to present calculated salt balances of soils along the lower Vaal River in South Africa that had been irrigated for different time periods, and to predict salt content changes expected in these soils as a consequence of future irrigation.

Material and methods

The location of the study area within South Africa is shown in Fig. 1. In the lower Vaal River, starting at the Bloemhof Dam downstream to the confluence with the Orange River, water quality is influenced largely by inflows from other rivers. For this study the lower Vaal River was therefore divided into four segments, namely V1: from Bloemhof Dam, downstream to the Vaalharts Weir near Warrenton; V2: from Vaalharts Weir, downstream to the Vaal-Harts confluence at Delportshoop; V3: from

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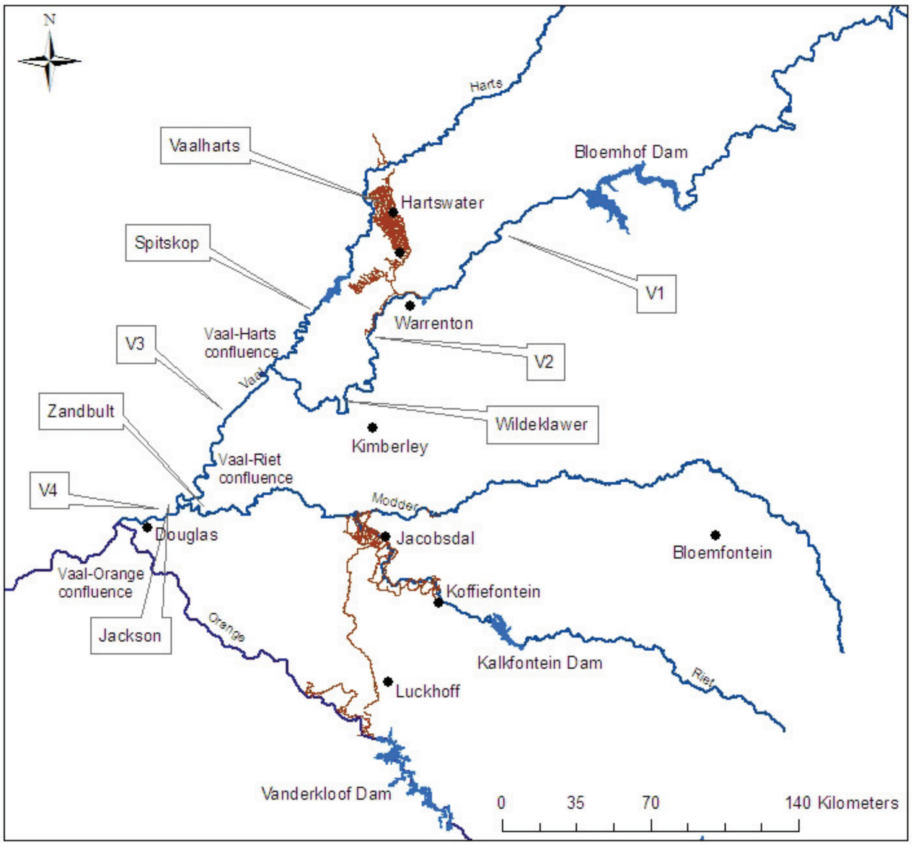

Figure 1
Map of the study area showing the river segments and selected sites

Delportshoop, downstream to the Vaal-Riet confluence, and V4: from the Vaal-Riet confluence downstream to the Vaal-Orange confluence. In each of these segments representative sites comprising irrigated and virgin soils were included in data selection for the prediction of salt balances. Relevant soil and water quality data reported by Du Preez et al. (2000) were used for this purpose. A general description of each study site, viz. Vaalharts, Spitskop, Wildeklawer, Zandbult and Jackson is given in Table 1.

TABLE 1
General description of the study sites

Site*	Soil form**	Soil depth (m)	Years irrigated	Irrigation system	Water table depth (m)
Vaalharts (V1)					
Virgin sand	Hutton	1.8	0	None	None
Irrigated sand	Bainsvlei	1.8	53	Flood	1.6
Irrigated & drained sand	Bainsvlei	1.8	53	Flood	1.0
Virgin clay	Valsrivier	1.6	0	None	None
Irrigated clay	Valsrivier	1.6	53	Flood	None
Spitskop (V1)					
Virgin clay	Arcadia	1.2	0	None	None
Irrigated clay	Arcadia	1.2	53	Flood	None
Wildeklawer (V2)					
Virgin sand	Hutton	1.6	0	None	None
Irrigated sand	Bainsvlei	1.6	17	Centre pivot	None
Virgin sandy loam	Oakleaf	1.8	0	None	None
Irrigated sandy loam	Oakleaf	1.8	30	Flood	None
Zandbult (V3)					
Virgin sand	Hutton	2.0	0	None	None
Irrigated sand	Hutton	2.0	19	Centre pivot	None
Virgin sandy loam	Oakleaf	1.0	0	None	None
Irrigated sandy loam	Oakleaf	1.0	29	Flood	None
Jackson (V4)					
Virgin sand	Bloemdal	1.6	0	None	1.3
Irrigated sand	Bloemdal	1.6	45	Centre pivot	1.1

**Soils were irrigated with water from the Vaal River segments as indicated in brackets.*
***Soil Classification Working Group (1991)*

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Numerous process-based models are available to simulate salt accumulation in soils and hence to predict expected crop response. Unfortunately, most of these models need daily inputs of irrigation which were not available for the soils studied along the lower Vaal River. It was decided therefore to estimate the salt balances of these soils with two empirical models, *viz.* the general salt balance of Aragües (1996) and the specific salt balance of Szabolcs (1986). Both models are based on mathematical functions that were fitted to experimental field observations (Jones et al., 1987).

Aragües model

The general salt balance of Aragües (1996) is presented in Eq. (1):

$$C_iW_i - C_dW_d - M_{hc} + (M_{sp} - M_{sd}) + M_{is} + M_{pre} + M_{afm} + M_{pr} + M_{iwr} - M_{dp} = 0 \quad (1)$$

where:

- C_i = salt content of irrigation water (mg·ℓ$^{-1}$)
- W_i = amount of irrigation water (ℓ·ha^{-1})
- C_d = salt content of drainage water (mg·ℓ$^{-1}$)
- W_d = amount of drainage water (ℓ·ha^{-1})
- M_{hc} = salt removal by harvesting of crops (mg·ha^{-1})
- M_{sp} = precipitation of salts in soil (mg·ha^{-1})
- M_{sd} = dissolution of salts in soil (mg·ha^{-1})
- M_{is} = initial amount of salts present in soil dissolved from natural mineral deposits (mg·ha^{-1})
- M_{pre} = salt mass in rainfall (mg·ha^{-1})
- M_{afm} = salts added by fertilisers and other amendments to soil (mg·ha^{-1})
- M_{pr} = salts removed by runoff due to rainfall (mg·ha^{-1})
- M_{iwr} = salts removed by runoff due to irrigation (mg·ha^{-1})
- M_{dp} = salt mass leached below root zone (mg·ha^{-1})

The following assumptions and calculations were made to obtain the various inputs summarised in Table 2 for the Aragües model (Eq. (1)) in order to estimate salt balances in irrigated soils with virgin soils as reference:

- Maize and wheat are the only two crops that were produced in rotation over the irrigation period as given by the farmer, *viz.* 2 maize crops and 1 wheat crop every 2 years
- The total grain yields during this period were calculated on the basis that the average grain yield of maize was 9 000 kg·ha^{-1} and that of wheat 5 000 kg·ha^{-1} annually
- An average water application of 600 mm per growing season through irrigation with no runoff was used to calculate the total amount of water applied for the irrigation period as given by the farmer
- In order to obtain the salt application through irrigation the average total dissolved solids (TDS) in the water of river segments V1 to V4 was calculated from the average electrical conductivity (EC) values reported by Du Preez et al. (2000), using a conversion factor of 6.5
- Salts applied through fertilisation amounted to 1 t·ha^{-1} every cropping season
- Removal of salts by the crops was calculated as 5% of the biomass that was removed from the field, *viz.* in the case of maize with a harvest index of 0.5 all the grain plus half of the residue and in the case of wheat only the grain
- Precipitation and dissolution of salts were negligible in the soils under investigation
- The salt content of a virgin soil is a reflection of the salt content of an irrigated soil before irrigation commenced
- The salt content of a soil was calculated with Eqs. (2) to (4) using the EC values of the profiles reported on by Du Preez et al. (2000).

$$S = (C \times W)/10^9 \quad (2)$$

$$C = 6.5\,(\sum_{x=1}^{n} EC/n) \quad (3)$$

$$W = 10\,000\,\theta_{sat}\,D \quad (4)$$

where:

- S = total salt content of soil (t·ha^{-1}) to a depth D
- C = average salt concentration in saturation extracts (mg·ℓ$^{-1}$) to a depth D
- W = total amount of water in saturated soil (ℓ·ha^{-1}) to a depth D
- EC = electrical conductivity of the saturation extracts from the 200 mm soil layers (mS·m^{-1}). In cases where the *EC* of a deeper layer was not measured, the *EC* of the overlying layer was used.
- n = number of soil layers to depth D
- θ_{sat} = water content at saturation was calculated as 0.38 mm·mm^{-1} using an average bulk density of 1 630 kg·m^{-3} (Bennie et al., 1988) irrespective of soil type, but a value of 0.35 mm·mm^{-1} was used to compensate for entrapped air
- D = soil depth (mm) as given in Table 1

Szabolcs model:

The specific salt balance of Szabolcs (1986) is presented in Eq. (5):

$$b = a[d+(cu/mt_{fs} \times 10^5)] \quad (5)$$

where:

- b = soluble salt content of soil at end of observation period (mg·100 g^{-1} soil)
- a = soluble salt content of soil at beginning of observation period (mg·100 g^{-1} soil)
- d = salt regime coefficient of soil which represents the change in salt content during the observation period (mg·100 g^{-1} soil)
- c = salt content of irrigation water during observation period (g·ℓ$^{-1}$)
- u = quantity of irrigation water applied during observation period (m^3·ha^{-1})
- m = volume of soil layer for which salt balance is estimated (m^3·ha^{-1})
- t_{fs} = bulk density of the soil (kg·m^{-3})

The following assumptions and calculations were made to obtain inputs (Table 3) for the Szabolcs model in order to estimate salt content and osmotic potential changes in irrigated soils from 1999 to 2049:

- It was assumed that no runoff resulted from irrigation, that precipitation and dissolution of salts in the soils were negligible, the salt content of a virgin soil represents the salt content of an irrigated soil before irrigation started and that the soils have an average bulk density of 1 630 kg·m^{-3}, irrespective of type. The values given in Table 2 concerning the total amount of water applied through irrigation, the TDS in the water of river segments V1 to V4 and the salt contents of the soils were used as input for the model. In the case of the latter two parameters, it was however necessary to convert

TABLE 2 Inputs used for the Aragües model to estimate salt balances in irrigated soils with virgin soils as reference						
Site*	**Average salt content of soil (mg·ℓ⁻¹)**	**Average salt content of water applied (mg·ℓ⁻¹)**	**Total water application (ℓ·ha⁻¹) x1000**	**Total maize grain yield (t·ha⁻¹)**	**Total maize residue removed (t·ha⁻¹)**	**Total wheat grain yield (t·ha⁻¹)**
Vaalharts (V1)						
Virgin sand	118					
Irrigated sand	585	356	480 000	477	239	135
Irrigated & drained sand	582	356	480 000	477	239	135
Virgin clay	839					
Irrigated clay	552	356	480 000	477	239	135
Spitskop (V1)						
Virgin clay	475					
Irrigated clay	2 803	356	480 000	477	239	135
Wildeklawer (V2)						
Virgin sand	244					
Irrigated sand	891	342	154 000	153	77	45
Virgin sandy loam	557					
Irrigated sandy loam	453	342	272 000	270	135	75
Zandbult (V3)						
Virgin sand	560					
Irrigated sand	813	467	172 000	171	86	50
Virgin sandy loam	423					
Irrigated sandy loam	605	467	263 000	261	131	75
Jackson (V4)						
Virgin sand	997					
Irrigated sand	394	519	408 000	405	203	115

**Soils were irrigated with water from the Vaal River segments as indicated in brackets*

the values to appropriate units, viz. g·ℓ⁻¹ and mg·100 g⁻¹.

- Removal of salts by the crops was not taken into account.
- The osmotic potential of a soil was calculated with Eq. (6) (Jurinak and Suarez, 1996) using the EC values of the profiles reported by Du Preez et al. (2000):

$$\psi = 0.4 \left(\sum_{x=1}^{n} EC/n \right) \qquad (6)$$

where:

ψ = average osmotic potential to the specified depth (kPa)

EC = electrical conductivity of the saturation extracts from the 200 mm soil layers (mS·m⁻¹). In cases where the EC of a deeper layer was not measured, the EC of the overlying layer was used.

n = number of soil layers to the specified depth.

Results and discussion

The salt balances estimated with the Aragües model for the soils at the different sites are presented in Table 4. As shown in Table 1 irrigation periods varied between 17 years at Wildeklawer and 53 years at Vaalharts and Spitskop. Addition of salts to the soils as a result of farming practices varied between 79 t·ha⁻¹ at Wildeklawer and 280 t·ha⁻¹ at Jackson, with irrigation water being the major contributor of salt. Fortunately, between 78% and 87% of the salts added to the soils had been leached from the root zone. In addition, the crops removed a significant amount of salts. The net result was a gain of 0.6 to 9.8 t salts·ha⁻¹ in six soils and a loss of 0.6 to 3.4 t salts·ha⁻¹ in three soils.

Four of the 6 soils that gained salts are sandy (Table 4). The irrigated sands at Vaalharts and Wildeklawer were classified as a Bainsvlei form and that of Zandbult as a Hutton form (Table 1). The internal drainage properties of these soils in combination with irrigation systems played an important role in the accumulation of salt in the root zone. For example, the Bainsvlei soil at Wildeklawer was irrigated with a centre pivot while flood irrigation was used on the Bainsvlei soil at Vaalharts. Despite the presence of the impermeable soft plinthic horizon of the Bainsvlei soil at Wildeklawer only the Bainsvlei soil at Vaalharts contained a water table at the time of sampling. This was attributed to over-irrigation associated with a less efficient flood irrigation system in use at Vaalharts. Water tables are seen as a forerunner of salinity (Ellington et al., 2004; Benyamini et al., 2005) and have resulted here in a salt gain of 3 t·ha⁻¹ in both the undrained and drained sands. This result indicates that the harmful influence of the water table was not ameliorated by drainage. Comparing the increase of salt in the Bainsvlei soil at Vaalharts (3 t·ha⁻¹) and Wildeklawer (3.6 t·ha⁻¹) illustrates another aspect of salt management. Centre pivots from this era were designed to supply just enough water to meet the peak water demand. Hence, the most likely way that salts could leach from the root zone was during periods of high rainfall, including flooding. It is however, expected that the soft plinthic horizon in the Bainsvlei soil would limit the effectiveness of this leaching process to some extent. This expectation is confirmed by the considerable lower salt increase (1.8 vs 3.6 t·ha⁻¹) on the deep, freely drained Hutton soil at Zandbult, on which a centre-pivot system was also used. The highest build-up of salts (9.8 t·ha⁻¹) occurred in the clay soil of the Arcadia form that was flood irrigated at Spitskop. This was expected as the soil contains swelling clays which restrict drainage and hence the leaching of salts (Le Roux et al., 2007). On the other hand the greatest loss of salt (1.6 t·ha⁻¹) was observed on the flood-irrigated duplex soil of the Valsrivier form at Vaalharts. Le Roux et al. (2007) described the morphology of the soil and

TABLE 3 Selected inputs used for the Szabolcs model to estimate salt regime coefficients indicating salt content changes in soils for the period being irrigated				
Site*	Salt content of soil (mg·100 g^{-1})		Average salt content of water applied (g·ℓ·$^{-1}$)	Total water application (ℓ·ha^{-1}) x 1000
	Initial	Present		
Vaalharts (V1)				
Irrigated sand	2.54	12.56	0.356	480 000
Irrigated & drained sand	2.54	12.50	0.356	480 000
Irrigated clay	18.00	11.85	0.356	480 000
Spitskop (V1)				
Irrigated clay	10.21	60.18	0.356	480 000
Wildeklawer (V2)				
Irrigated sand	5.23	19.12	0.342	154 000
Irrigated sandy loam	11.96	9.73	0.342	272 000
Zandbult (V3)				
Irrigated sand	12.03	17.45	0.467	172 000
Irrigated sandy loam	9.07	12.98	0.467	262 000
Jackson (V4)				
Irrigated sand	21.41	8.46	0.519	408 000

Soils were irrigated with water from the Vaal River segments as indicated in brackets.

TABLE 4 Salt balances as estimated with the Aragües model in irrigated soils with virgin soils as reference								
Site*	Salt in soil (t·ha^{-1})	Salt addition (t·ha^{-1})			Salt removal (t·ha^{-1})			Salt gain or loss in soil (t·ha^{-1})
		Irrigation	Fertilisation	Total	Crops	Leached	Total	
Vaalharts (V1)								
Virgin sand	0.7							
Irrigated sand	3.7	171	80	251	43	205	248	+3.0
Irrigated & drained sand	3.7	171	80	251	43	206	249	+3.0
Virgin clay	4.7							
Irrigated clay	3.1	171	80	251	43	210	253	-1.6
Spitskop (V1)								
Virgin clay	2.0							
Irrigated clay	11.8	171	80	251	43	199	242	+9.8
Wildeklawer (V2)								
Virgin sand	1.4							
Irrigated sand	5.0	53	26	79	14	62	76	+3.6
Virgin sandy loam	3.5							
Irrigated sandy loam	2.9	92	45	137	24	114	138	-0.6
Zandbult (V3)								
Virgin sand	3.9							
Irrigated sand	5.7	81	29	110	15	93	108	+1.8
Virgin sandy loam	1.5							
Irrigated sandy loam	2.1	123	44	167	23	143	166	0.6
Jackson (V4)								
Virgin sand	5.6							
Irrigated sand	2.2	212	68	280	36	244	280	-3.4

Soils were irrigated with water from the Vaal River segments as indicated in brackets.

showed that it has better internal drainage properties than the Bainsvlei soil. The absence of a water table in the Valsrivier soil confirmed their observation. Despite the flood irrigation used on the two sandy loam soils of the Oakleaf form at Wildeklawer and Zandbult, no water tables were observed. Their salt content increased at Zandbult and decreased at Wildeklawer with the same amount, viz. 0.6 t·ha^{-1}.

As already mentioned, the Szabolcs model can be used to estimate the change in salt content of a soil if the salt regime coefficient is known. It was therefore necessary to calculate the salt regime coefficients to estimate the salt contents and hence the osmotic potentials of the soils in the year 2049 as indicated in Table 5.

The salt regime coefficients were all negative, indicating a net outflow of salts from the root zone for the period the soils were irrigated. Comparisons of these coefficients are complicated by the difference in irrigation periods. Nevertheless, at Vaalharts and Spitskop all the soils were irrigated for 53 years and it is clear that the outflow of salts from the clays exceeded that of the sands, especially at Spitskop.

TABLE 5
Salt content and osmotic potential changes in irrigated soils from 1999 to 2049 as estimated with the Szabolcs model

Site*	Salt regime coefficient (mg·100 g^{-1}·yr^{-1})	Salt application rate (mg·100 g^{-1}·yr^{-1})	Salt content of soil (mg·100 g^{-1}) 2049	Osmotic potential of soil (kPa)	
				1999	2049
Vaalharts (V1)					
Irrigated sand	-10.80	10.99	22.00	-62	-109
Irrigated & drained sand	-10.80	10.99	21.90	-62	-108
Irrigated clay	-12.48	12.36	6.04	-59	-30
Spitskop (V1)					
Irrigated clay	-15.54	16.48	107.33	-298	-531
Wildeklawer (V2)					
Irrigated sand	-11.22	12.03	59.77	-95	-297
Irrigated sandy loam	-10.57	10.49	6.02	-48	-30
Zandbult (V3)					
Irrigated sand	-12.83	13.12	31.70	-86	-157
Irrigated sandy loam	-25.95	26.08	19.72	-64	-98
Jackson (V4)					
Irrigated sand	-18.33	18.04	-5.93	-42	0

**Soils irrigated with water from the Vaal River segments as indicated*

In order to predict the effect of salt accumulation for the year 2049 the assumption was made that the current irrigation practices will remain constant and so the estimated salt regime coefficients. Of the soils for which predictions were made, six will have a higher salt content and three of the soils will have a lower salt content compared to that in 1999 (Table 5). The expected changes in the salt content of the soils are in accordance with the salt gains and losses reported in Table 4. The salt content of the sands at Vaalharts, Wildeklawer and especially Zandbult will increase, while that at Jackson will decrease. In the case of the irrigated sandy loams a higher salt content is expected at Zandbult and at Wildeklawer a lower salt content in comparison to 1999. According to these estimations the salt content of the clay at Vaalharts will decrease and at Spitskop the salt content of the clay will increase. The reasons for the expected changes in salt content are similar to that explained for the gains and losses of salts in Table 4.

The change of osmotic potentials is in accordance with the salt contents in Table 5, indicating a decrease in the osmotic potential of the root zone in six of the sites compared to 1999. The osmotic potential ranged from -98 kPa to -531 kPa over the sites. Ehlers et al. (2007) showed that an increase in salinity leads to a linear decrease in the total seasonal evapotranspiration (ET) of both maize and wheat. Applying the predicted osmotic potential values of the six sites to the ET vs. osmotic potential equations of Ehlers et al. (2007), indicates that the seasonal ET of maize is more affected than that of wheat. Accordingly, a 10% decrease in the seasonal ET is expected when the soil solution reaches osmotic potential values of lower than -100 kPa and -280 kPa for maize and wheat yields, respectively. The osmotic potential of -530 kPa predicted for the Spitskop site reflects the worst case scenario. Under these conditions it is expected that the ET of maize will be reduced by about 50% in relation to a non-saline stress treatment, while that of wheat with only 20%. Stewart et al. (1977) are of opinion that salinity induced plant water stress has the same negative effect on yield as drought induced plant water stress. A reduction in ET of this magnitude, will impact negatively on sustaining economical yields. Fortunately, in most cases the negative impact can be avoided through the introduction of proper salinity management strategies as suggested by Rhoades (1997) and Hillel (2000). The results also suggest that the irrigation of clay soils with swelling properties, such as the Arcadia soil at the Spitskop site, should be avoided with water quality and drainage conditions similar to those at Spitskop.

Conclusions

The result of salt additions to croplands by irrigation farming practices along the lower Vaal River system and the impact thereof on the osmotic potential of soils over the long term were estimated with the aid of salt-balance models. These models have some shortfalls as they, e.g. do not accurately address the differential decline in water use by crops as the soils become saline and hence freeing more water for leaching. Despite of such shortfalls provide the predictive outcomes of the models useful insight on salinity changes in irrigated soils.

Nine soils were included in the study and they had been irrigated for periods of between 17 to 53 years. Over these periods the net result was a gain of 0.6 to 9.8 t salts·ha^{-1} in 6 soils and a loss of 0.6 to 3.4 t salts·ha^{-1} in 3 soils. Some of these gains and losses have been explained with the internal drainage characteristics of the soils in combination with the irrigation systems that are used on them. Predictions showed that if the current practices are sustained for the next 50 years the osmotic potential of 6 soils will decline to below the threshold of -100 kPa for maize. In two of these soils the threshold of -280 kPa for wheat will also be exceeded. Hence salt-induced water stress could reduce the yield of maize and even wheat significantly in future if appropriate precautionary measures are not introduced.

The models revealed that the ultimate fate of salts that enter a soil through irrigation farming practices is site specific. A set of measures will be needed therefore to manage salinity in the root zone of a soil at levels that are not harmful for crops. This aspect warrants proper investigation to ensure sustainable cropping in the study area.

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