Water and salt balances of two shallow groundwater cropping systems using subjective and objective irrigation scheduling

Johannes Hendrikus Barnard[1]*, Leon Daniel van Rensburg[1], Alan Thomas Peter Bennie[1] and Christiaan Cornelius du Preez[1]

[1]*Department of Soil, Crop and Climate Sciences, University of the Free State, P.O. Box 339, Bloemfontein 9300, South Africa*

ABSTRACT

Evidence suggests that, in general, subjective rather than objective irrigation scheduling decisions are adopted by farmers. Irrigators have 'calibrated' themselves with years of experience to irrigate subjectively according to perceived crop water requirements. This study aimed to determine the associated benefits of objective versus subjective scheduling of two shallow groundwater cropping systems. Weekly measurements included rainfall and irrigation amounts, soil water content, groundwater table depth, artificial drainage volumes, and electrical conductivity of irrigation water, groundwater and drainage water. Simulations of evaporation and transpiration were done with the SWAMP model. Based on soil water and salinity status, matric and osmotic stress during the four cropping seasons is considered unlikely. When rainfall-plus-irrigation was compared to evapotranspiration, objective scheduling resulted in an under-supply of 15%, and rainfall and shallow groundwater served as supplementary water sources. Subjective scheduling did not use rainfall efficiently as a source of water and resulted in an over-supply of 10%. Approximately 50% less salt was leached with objective compared to subjective irrigation scheduling. Under shallow groundwater conditions, irrigating subjectively according to crop water requirement results in excessive irrigation, salt addition and leaching compared to objective scheduling. Farmers can address some of the environmental problems associated with irrigation by adopting objective scheduling and reducing the leaching fraction (< 0.15) of shallow groundwater cropping systems.

Keywords: evapotranspiration, leaching, salinity, water conservation, water degradation

INTRODUCTION

On-farm water and salt management must be continually evaluated and improved. Salt tends to accumulate in poorly drained soils under irrigation if inadequate water and salt management practices are applied. Furthermore, over-irrigation may deteriorate the quality of water resources, because of salt pollution resulting from excessive drainage and leaching (United States Salinity Laboratory Staff, 1954; Van Schilfgaarde, 1990; Letey, 1994; Rhoades, 1997; Hillel, 2000; Oster and Wichelns, 2003; Hillel and Vlek, 2005; Kijne, 2006; Le Roux et al., 2007; Van Rensburg et al., 2008; Van Rensburg et al., 2011). The days when the sole purpose of irrigation was to increase crop production are now in the distant past. Farmers are under increasing pressure, specifically to prevent the degradation of water resources, and also to produce higher yields with less water (Hillel and Vlek, 2005; Pott et al., 2009; Kijne, 2011). Advocates for a more sustainable irrigation sector attempt to empower farmers and encourage them to continually evaluate and improve on-farm water and salt management (Kijne, 2006).

Research over recent decades has contributed tremendously to the advancement of on-farm water and salt management (Oster and Wichelns, 2003; Hillel and Vlek, 2005; Kijne, 2006; Kijne, 2011). Means became available to utilize rainfall and groundwater within or just below the potential root zone, as a water source to supply in crop water requirements (Ayars et al., 2006; Jhorar et al., 2009; Isidoro and Grattan, 2011; Singh, 2013). Theory and practices for the reduction of drainage water and subsequent use for crop production is better understood than ever before (Rhoades et al., 1992; Singh, 2004; Malash et al., 2005; Sharma and Minhas, 2005). Advances in soil water measuring technology have made soil water monitoring easy and more affordable for farmers and service providers (Van der Westhuizen and Van Rensburg, 2011; Van Rensburg, 2010; Annandale et al., 2011).

Despite this tremendous progress, excessive drainage, leaching, soil salinization and waterlogging still occur, and even increase annually in irrigation schemes across the world (Heuperman et al., 2002). This is also the case in the Lower Vaal River Basin, central South Africa, which includes the Orange, Riet and Modder Rivers. The sandy to clayey soils in the region (± 100 000 ha) are subject to extensive shallow groundwater conditions and have been irrigated for more than 50 years. The major field crops grown on these soils include maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), groundnut (*Arachis hypogaea* L.), cotton (*Gossypium hirsitum* L.) and barley (*Hordeum vulgare* L.). The majority of farmers use highly efficient irrigation systems like centre pivots (Herold and Bailey, 1996; Ellington et al., 2004; Viljoen et al., 2006; Ehlers et al., 2007; Van Rensburg et al., 2012).

According to Reinders et al. (2010), an efficient irrigation system will apply water at the desired amount, at an accurate application rate uniformly over the field, at the precise time, and with the smallest amount of non-beneficial water consumption. When these systems are used, farmers should have good control over their water and salt management practices if they employ sound irrigation scheduling decisions. Accurate irrigation scheduling could (i) reduce the amount of irrigation applied by utilizing rainfall and shallow groundwater as supplementary water sources, (ii) minimize irrigation-induced drainage, leaching and salt additions, and (iii) manage plant available water (matric and osmotic stress) to maintain optimum yields. Decisions on when and how much to irrigate

* To whom all correspondence should be addressed.
☎ +27 514012785; e-mail: barnardjh@ufs.ac.za
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need to be based on objective (scientific knowledge and measurements) as opposed to subjective scheduling decisions. Unfortunately, 80% of South African (Stevens et al., 2005) and 67% of Australian (Montagu and Stirzaker, 2008) irrigators do not use scientific irrigation scheduling. There remains therefore a great challenge to improve not only water use efficiency, but also salt management, of vast irrigated fields.

Montagu and Stirzaker (2008) argued that subjective irrigation scheduling methods would continue to dominate in enterprises such as pastures that do not benefit primarily from improved crop water management, unless drivers other than profitability or water productivity emerge. Jackson et al. (2008) proposed that irrigators should be assessed against broader issues that stretch beyond the crop field and are of local, national and global importance. These issues can possibly include energy consumption and greenhouse gas emissions, as well as soil and water resource degradation due to salinization. Another hypothesis might also be that irrigators who employ subjective scheduling have 'calibrated' themselves, in terms of crop water requirements, over decades of irrigation. Hence, it is argued that, because they irrigate according to crop water requirements, salt management will be good – with a perception of no significant benefit when adopting scientific scheduling. The aim of this study was to determine the associated benefits of objective versus subjective scheduling under field conditions.

METHODOLOGY

Two fields, similar in terms of climate, soil, tillage practices and cropping systems, were selected. Dissimilar irrigation scheduling decisions (objective and subjective, respectively) were applied by the farmers. With the subjective scheduling method (Case Study 1) irrigation was based entirely on experience of the farmer. The objective scheduling method (Case Study 2) employed an approach where soil water content was measured weekly with capacitance probes installed to a depth of 600 mm. Irrigation amounts were calculated as the difference between the measured soil water content and a predetermined drained upper limit. For both case studies, a weekly irrigation interval was used.

Location and description of case studies

The research was conducted in the central part of South Africa within the Orange-Riet (Case Study 1) and Vaalharts (Case Study 2) Irrigation Schemes (Fig. 1). Orange-Riet is situated between the Orange River and the Riet River in the Free State, with a small area positioned in the Northern Cape (Fig. 2a). North of Orange-Riet, situated between the Harts River and the Vaal River in the Northern Cape, lies Vaalharts (Fig. 2b).

Orange-Riet and Vaalharts have a semi-arid climate, with an aridity index of 0.23 and 0.26, respectively (Van Rensburg et al. 2012). At both schemes, rainfall mainly occurs in the form

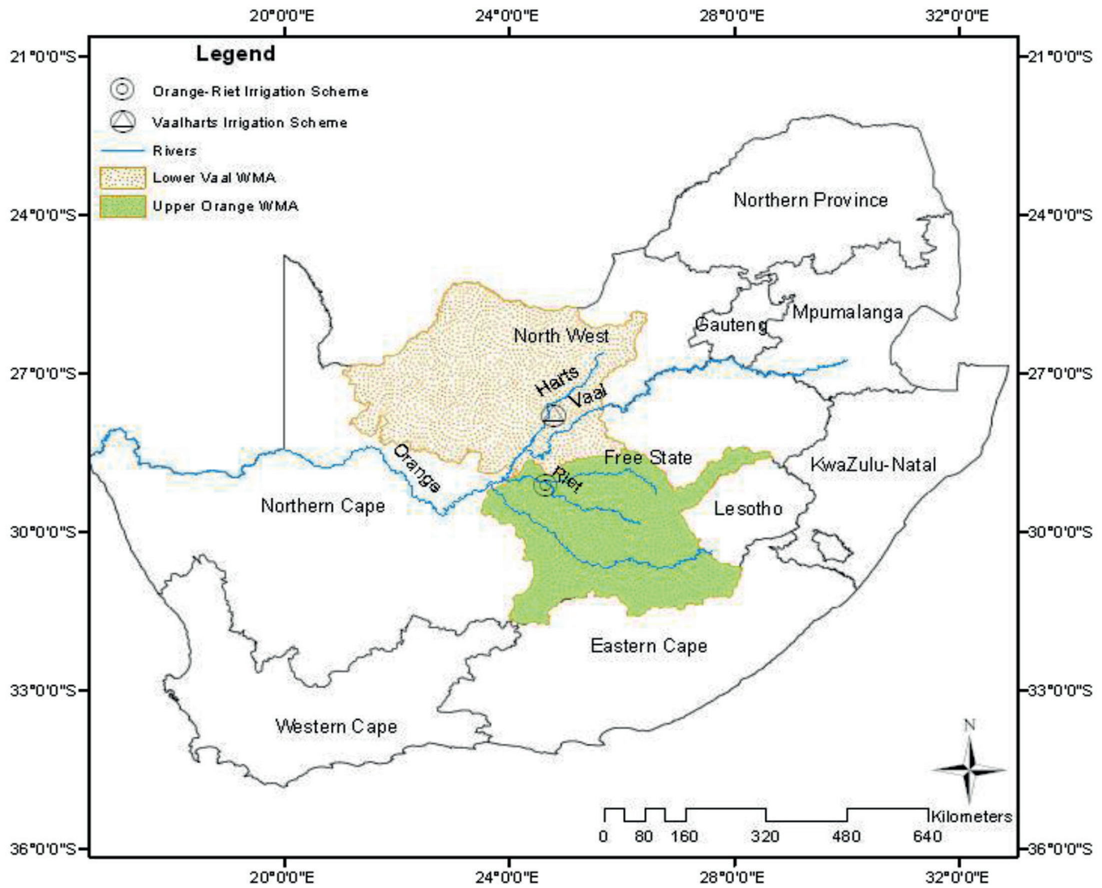

Figure 1

Geographical position of the Orange-Riet and Vaalharts Irrigation Schemes within the Upper Orange and Lower Vaal Water Management Areas (WMA) in South Africa

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of thunderstorms during the summer months. The long-term rainfall from November to April is normally more than 40 mm per month (means for these months amount to 52 and 50 mm for Orange-Riet and Vaalharts, respectively) The soil of Case Study 1 comprises aeolian sandy deposits on lime and is classified as a Hutton form and Ventersdorp family (Soil Classification Working Group 1991). The A and B1 horizons fall in the fine sandy textural class and the B2 and C horizons in the fine loamy sand textural class, all exhibiting an apedal massive structure.

Soil physical properties, including silt-plus-clay content, saturated hydraulic conductivity and bulk density are presented in Table 1. This soil has a groundwater table that fluctuates between 1 600 and 1 900 mm.

The soil of Case Study 2 is, in terms of textural class, saturated hydraulic conductivity and bulk density, for all practical purposes the same as that of Case Study 1. The only difference is that there were enough signs of wetness at a depth of 1 100 mm, due to a fluctuating groundwater table, to classify

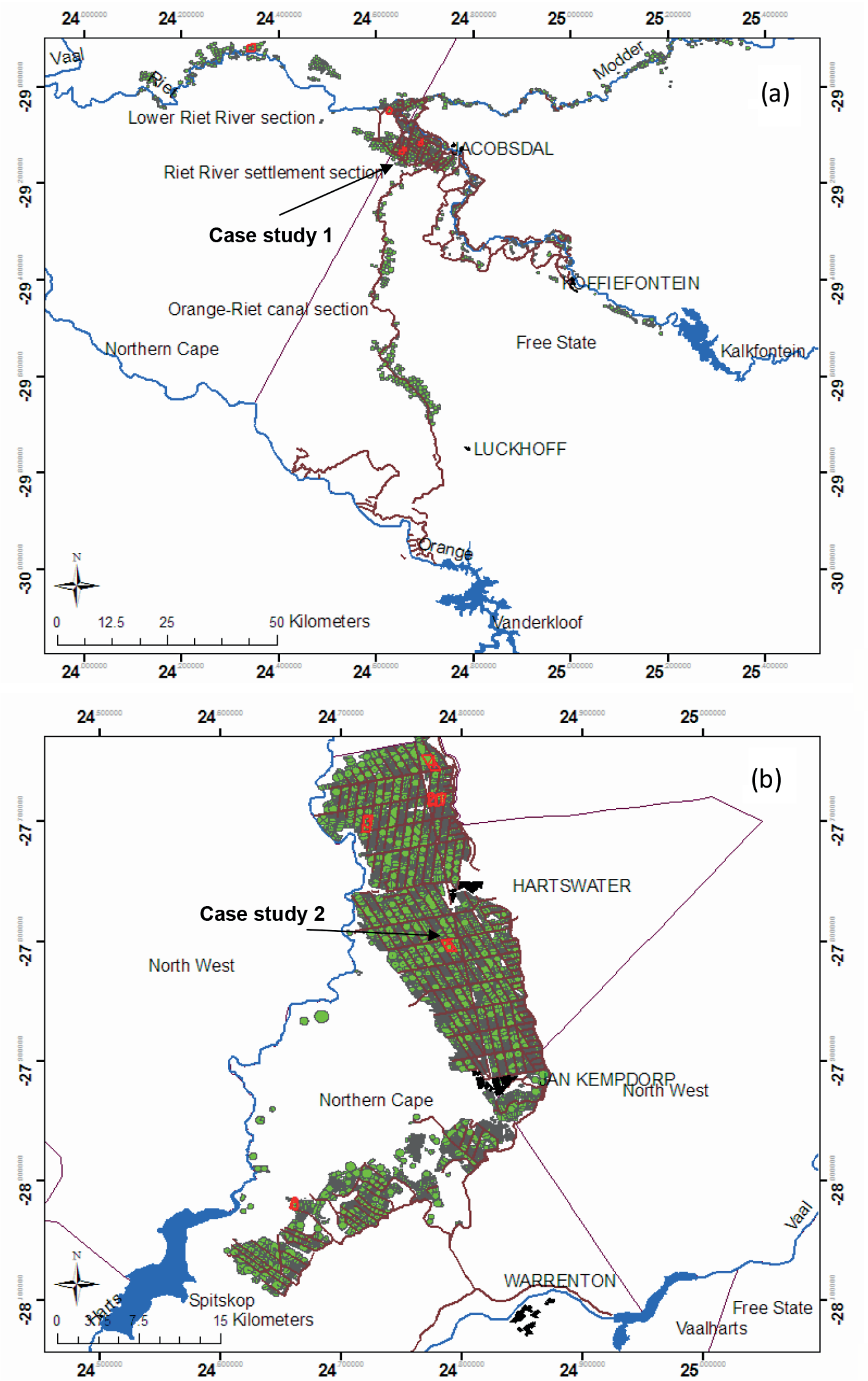

Figure 2

Geographical position of Case Study 1 (a) within the Orange-Riet Irrigation Scheme and Case Study 2 (b) within the Vaalharts Irrigation Scheme this soil as a Bloemdal form and Roodeplaat family (Soil Classification Working Group 1991). At both fields, an internal drainage system was installed at a depth of 1 800 mm in order to remove sub-surface drainage water.

TABLE 1
Selected physical properties of soils in the Orange-Riet (Case study 1) and Vaalharts (Case Study 2) Irrigation Schemes

Soil physical property	Soil horizon	Case study 1	Case Study 2
Silt-plus-clay (%)	A	9	10
	B	12	12
	C	14	13
Saturated hydraulic conductivity(mm hour^{-1})	A	50	40
	B	31	35
	C	23	24
Bulk density (kg m^{-3})	A	1 594	1 605
	B	1 629	1 640
	C	1 671	1 656

Case Study 1 followed a winter wheat–summer maize crop rotation during the measuring period of 2 years. Case Study 2 followed a wheat–maize crop rotation during the first year, but a barley–maize cycle during the second year. Wheat was replaced with barley during the second year due to infection by the fungus *Gaeumannomyces graminis* var. *tritici*. Details of other agronomical practices employed at the two fields are summarized in Table 2.

Measurements

Data were collected during four growing seasons to quantify the soil water and salt balances at the two locations. Two measuring positions, or1 and or2 (Case Study 1) and v1 and v2 (Case Study 2), were selected per crop field located above an artificial drainage lateral. Two neutron probe access tubes were installed 1 m apart (2 m deep) in the centre of a 16 m^2 area per measuring point. One observation well was also installed 2 m further from the access tubes (63-mm diameter PVC tubes, 3 000 mm deep with the bottom end perforated). Approximately 10 m from the 16 m^2 area a square area of 6 m^2 was cleared to install a rain gauge level to the soil surface.

TABLE 2
Summary of agronomic practices applied during the four cropping seasons at Case Study 1 (Orange-Riet, or1 and or2) and Case Study 2 (Vaalharts, v1 and v2)

Case Study 1				
Crop	Wheat	Maize	Wheat	Maize
Cultivar	Duzie	Pannar 6236 B	Carnia 826	Pannar 6236 B
Planting date	July 2007	December 2007	July 2008	December 2008
Harvesting date	December 2007	July 2008	December 2008	July 2009
Planting density	85 kg·ha^{-1}	85 000 seeds·ha^{-1}	110 kg·ha^{-1}	90 000 seeds·ha^{-1}
Fertilizer applied	200 kg·ha^{-1} 2:3:2 (22) 440 kg·ha^{-1} 10:1:2 (24) 375 kg·ha^{-1} UAN (32) 1 kg·ha^{-1} tri-pholate	300 kg·ha^{-1} 4:2:1 (28) 350 kg·ha^{-1} 10:1:2 (24) 225 kg·ha^{-1} UAN (32) 300 kg·ha^{-1} 3:1:2 (20) 2 kg·ha^{-1} maize pholate 1 L·ha^{-1} Marinure DS	200 kg·ha^{-1} 2:3:2 (22) 220 kg·ha^{-1} 10:1:2 (24) 330 kg·ha^{-1} UAN (32) 1 kg·ha^{-1} tri-pholate 2 kg·ha^{-1} wheat pholate 0.5 L·ha^{-1} Marinure DS	350 kg·ha^{-1} 4:3:4 (33) 600 kg·ha^{-1} UAN (32) 150 kg·ha^{-1} 8:1:1 (18)
Total kg N ha^{-1}	214	215	159	256
Total kg P ha^{-1}	27	41	23	35
Total kg K ha^{-1}	29	45	21	45
Cultivation practices	Burn, disc & plant	Burn, disc & plant, then rip between rows after 24 days	Burn, disc & plant	Burn, disc & plant
Case Study 2				
Crop	Wheat	Maize	Barley	Maize
Cultivar	Carnia 826	Pannar 6236 B	Cocktail	Pannar 6236 B
Planting date	June 2007	December 2007	June 2008	December 2008
Harvesting date	November 2007	May 2008	November 2008	May 2009
Planting density	100 kg·ha^{-1}	85 000 seeds·ha^{-1}	75 kg·ha^{-1}	90 000 seeds·ha^{-1}
Fertilizer applied	500 kg·ha^{-1} 7:2:3 (31) 500 kg·ha^{-1} AN (21) 100 kg·ha^{-1} urea (46)	300 kg·ha^{-1} 4:3:4 (33) 400 kg·ha^{-1} 10:1:6 (20) 400 kg·ha^{-1} UAN (32)	250 kg·ha^{-1} 2:3:4 (30) 500 kg·ha^{-1} AN (21)	350 kg·ha^{-1} 4:3:4 (33) 600 kg·ha^{-1} UAN (32)
Total kg N ha^{-1}	242	211	122	239
Total kg P ha^{-1}	26	30	25	35
Total kg K ha^{-1}	39	50	33	47
Cultivation practices	Burn, plough, wonder till & plant	Bale, burn, rip & plant	Burn, wonder till & plant	Bale, burn, rip & plant

N = nitrogen, P = phosphorus, K = potassium, UAN = urea ammonium nitrate, AN = ammonium nitrate

TABLE 3
Efficiency measurements of the centre pivot at Case Study 1 and Case Study 2, namely the Heermann and Hein uniformity coefficient (CU_H), distribution uniformity (DU_{lq}), application efficiency (*AE*) and system efficiency (*SE*)

Centre pivot	Irrigation system efficiency (%)				Area (ha)	Design application rate (mm·d⁻¹)
	CU_H	DU_{lq}	*AE*	*SE*		
Case Study 1	90	87	94	81	30	14
Case Study 2	93	84	95	80	51	11

Soil water content was measured with a calibrated neutron probe, groundwater table depth manually with a measuring tape and artificial drainage with a bucket and stop watch (L min^{-1}). Artificial drainage was converted to mm water drained by taking the drainage area into consideration. Electrical conductivity of the irrigation water, groundwater and water flowing from the artificial drainage system were measured with a calibrated handheld CON 6/TDS 6 Hand-held Conductivity/TDS Meter (Oakton instruments, Vernon Hills, USA).

These measuring points were assumed to be representative of the fields, since field evaluation indicated that both centre pivots were efficient in water application (Table 3, Appendix 1). It is recognized that the soil water and salt content will vary across the two fields. The focus of the research was, however, not on the spatial quantification of soil water and salt balances, but rather on how the two scheduling approaches affected the processes involved.

At the start and end of each growing season, subsamples of the unsaturated soil above the groundwater table were taken at each measurement position per 300-mm depth interval, using a 75-mm diameter auger. These samples were dried at 40°C and passed through a 2-mm sieve for the determination of electrical conductivity of a saturated extract (EC_e, mS m^{-1}) with a standard procedure (The Non-Affiliated Soil Analysis Work Committee 1990). The crops within each 16 m^2 area were harvested at maturity, dried (45°C) to a constant weight and threshed to determine the seed mass and total above-ground biomass.

Soil water and salt balance

To solve the soil water balance equation where a fluctuating shallow groundwater table occurs within the potential root zone (maximum rooting depth of most crops, 0–2 000 mm) under field conditions is challenging. Crop water uptake between the soil surface and the capillary fringe (unsaturated zone) is recharged by water from irrigation or rainfall. Crop water uptake between the capillary fringe and the groundwater table (capillary zone) is recharged by (i) percolation from the unsaturated zone or (ii) upward capillary rise from the saturated zone. Water uptake from the saturated zone is recharged by lateral groundwater inflow into the potential root zone or vertical percolation from the capillary zone. When the depth of the groundwater table increases, uptake from the capillary fringe and/or lateral groundwater drainage is more than vertical percolation from the unsaturated zone and/or lateral groundwater inflow and vice versa. The soil water balance equation was rearranged to calculate the net lateral groundwater inflow (+*D*, mm) and drainage (–*D*, mm) during a specific week (*w*) from the change in soil water content of this zone (ΔW_{soil}, mm), rainfall (*R*, mm), irrigation (*I*, mm), evaporation (*E*, mm), transpiration (*T*, mm) and artificial drainage (*AD*, mm) over the same time period (Eq. 1). This is possible because the supply and/or removal of drainage water in the potential root zone will be reflected in soil water content measurements, i.e., the groundwater table is present within the potential root zone.

$$\pm D = \Delta W_{\text{soil}(w)} - (\Sigma^{7}_{dew} R_{(w)}) - (\Sigma^{7}_{dew} I_{(w)}) + (\Sigma^{7}_{dew} E_{(d)}) + T_{(d)} + AD_{(w)} \quad (1)$$

Validation of the Soil Water Management Program (SWAMP) (Bennie et al. 1998) was previously reported in Table 5 and Fig. 6 of Barnard et al. (2013) and Table 5 and Fig. 4 in Barnard et al. (2015). It was therefore assumed that weekly evaporation and actual transpiration (daily values were summed for a week) due to matric and osmotic stress were simulated accurately with SWAMP. It is recognized however, that calculations done with Eq. 1 depend on evaporation and transpiration estimates. Weekly changes in soil water content, rainfall, irrigation and artificial drainage were measured. From Eq. 1, the weekly salt balance of the potential root zone is described by Eq. 2, with daily simulations of the change in salt content (ΔS_{Soil}, kg·ha^{-1}) over 2 000 mm that were summed for the week, and weekly measurements of salt additions through rainfall (S_R, kg·ha^{-1}), irrigation (S_I, kg·ha^{-1}) and losses through artificial drainage (S_{AD}, kg·ha^{-1}). At the start of each growing season the net amount of salts remaining in the soil from fertilizer application (*F*, kg·ha^{-1}) was also taken into consideration, i.e., the amount removed by the crop yield was subtracted from the total amount applied (Van Rensburg et al., 2012).

$$S_{\pm D(w)} = (\Sigma^{7}_{dew})\Delta S_{(soil(d))} - S_{R(w)} - S_{I(w)} + S_{AD(w)} \quad (2)$$

Table 4 summarizes the input data, initial and boundary conditions used in simulations for the two case studies and Table 5 the equations used to calculate the unmeasured parameters required for simulations. A detailed description of the various algorithms and parameters can be found in Barnard et al. (2015).

RESULTS

Water management

Mean weekly measured rainfall, irrigation, soil water content and groundwater table depth for Case Studies 1 and 2 during the four cropping seasons are shown in Figures 3 and 4, respectively. The mean weekly calculated net lateral groundwater inflow and drainage are included. The seasonal soil water balances for the two measurement positions are also provided per case study in Table 6.

Rainfall at the two case studies was characteristic of a semi-arid climate zone: unpredictable, erratic and poorly distributed.

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At both case studies, less irrigation was applied during the summer months because of higher rainfall. Water applications increased when the crops reached their peak water demand at the start of the reproductive period (Figs 3 and 4).

The mean groundwater table depth of 1 840 mm and standard deviation of 46 mm was deep enough to allow sufficient storage in the unsaturated zone for rainfall and irrigation, or groundwater and artificial drainage was sufficient to remove excess water. During the early part of the second wheat season (Week 1, 2008), the groundwater table level rose sharply to 1 500 mm, because of high rainfall (115 mm) that fell during the drying phase (data not shown) of maize grown during the first season (2007) when evapotranspiration was low (Fig. 3). During the later part of the second wheat season the

TABLE 4
Input data, i.e., simulation length, initial and boundary conditions, used by SWAMP to simulate the soil water and salt balance for Case Study 1 and Case Study 2

Case Study 1: Subjective scheduling								
Measuring point	**or1**				**or2**			
	Wheat	**Maize**	**Wheat**	**Maize**	**Wheat**	**Maize**	**Wheat**	**Maize**
***ET_o* (mm·d⁻¹)**	5.4	6.1	5.3	4.7	5.5	6	5.3	4.7
Planting date	Table 2							
***GSL* (days)**	148	131	148	131	148	131	148	131
Yield (kg·ha⁻¹)	7 334	15 892	6 172	16 510	6 400	14 758	6 178	18 297
HI	0.48	0.60	0.43	0.60	0.46	0.58	0.43	0.58
***AFA* (kg·ha⁻¹)**	Table 2							
***z* (mm)**	300							
***S+C* (%)**	11							
***θ* (mm·mm⁻¹)**	0.21	0.23	0.25	0.22	0.22	0.26	0.27	0.25
***EC_e* (mS·m⁻¹)**	88	75	58	69	65	79	56	73
Z_{WT} (mm)	1 900	1 895	1 711	1 895	1 900	1 663	1 513	1 788
EC_{WT}, (mS·m⁻¹)	110	101	115	124	120	106	103	122
***R* (mm)**	Fig. 3							
***I* (mm)**	Fig. 3							
EC_I (mS·m⁻¹)	22	21	21	20	24	21	21	20
Case Study 2: Objective scheduling								
Measuring point	**v1**				**v2**			
	Wheat	**Maize**	**Barley**	**Maize**	**Wheat**	**Maize**	**Barley**	**Maize**
ET_o (mm·d⁻¹)	4.9	5.6	4.5	5.1	4.9	5.7	4.5	5.1
Planting date	Table 2							
***GSL* (days)**	145	131	145	131	148	131	147	131
Yield (kg·ha⁻¹)	6 549	13 586	6 134	12 983	4 927	13 101	6 025	11 536
HI	0.38	0.6	0.47	0.6	0.29	0.57	0.45	0.6
***AFA* (kg·ha⁻¹)**	Table 2							
***z* (mm)**	300							
***S+C* (%)**	11							
***θ* (mm·mm⁻¹)**	0.23	0.24	0.24	0.26	0.26	0.27	0.28	0.28
***EC_e* (mS·m⁻¹)**	88	115	54	103	143	165	98	139
Z_{WT} (mm)	1 754	1 494	1 632	1 516	1 426	1 185	1 143	1 142
EC_{WT} (mS·m⁻¹)	125	132	134	140	182	163	157	114
***R* (mm)**	Fig. 4							
***I* (mm)**	Fig. 4							
EC_I (mS·m⁻¹)	61	65	63	71	61	65	67	71

ET_o = *mean atmospheric evaporative demand over growing season,* GSL = *growing season length,* HI = *harvest index,* AFA = *amount of fertilizer applied,* z = *soil layer thickness,* S+C = *silt-plus-clay fraction (< 0.05 mm) of each layer,* θ = *volumetric soil water content of each layer at the start of season,* EC_e = *electrical conductivity of a saturated extract for every layer at the start,* Z_{WT} = *mean water table depth during the season,* EC_{WT} = *mean electrical conductivity of groundwater table during the season,* R = *rainfall,* I = *irrigation,* EC_I = *mean electrical conductivity of irrigation during the season,* * = *represents the mean value of the soil profile, although the value of each soil layer was used in SWAMP*

TABLE 5
Equations used to calculate the unmeasured parameters for simulations of the two case studies during the four growing seasons (refer to Barnard et al. (2015) for a description of the parameters and equations)

Process	Parameter	Equation	
Redistribution	a (mm·d^{-1})	$a = 45.72 - (1.334)(SC_{(k)}) + (0.011)(SC_{(k)})^2$	
	b (mm)	$b = 70.99 - (11.67)(SC_{(k)}) + (0.117)(SC_{(k)})^2$	
	θ_s (mm·mm^{-1})	$\theta s = 0.0029(SC_{(k)}) + 0.316$	
	DC	$DC_{(k)(d)} = 0.92\left(1 - \exp\left((b)\left(\frac{P_{(k)(d)}}{z_{(k)}}\right)\right)\right)$ where $b = 0.2673(SC_{(k)}) - 12.346$	
Evaporation	$z_{(k=1)}$ (mm)	$z_{(k=1)} = Exp\left[3.4244(SC_{(k=1)}) + 5.7193\right]$	
	θ_a (mm·mm^{-1})	$\theta_{a(k=1)} = 0.0012(SC_{(k=1)}) + 0.006$	
	$FB_{(d)}$	$FB_{(d)} = \left(\frac{FB_m}{100}\right)(T_{R(Rel)(d)})$	
Potential transpiration	Crop	Wheat/Barley *	Maize **
	Y_m (kg·ha^{-1})	20 000	26 300
	m	145	220
	A' (days)	40	15
	B' (days)	90	65
	C' (days)	130	110
	D' (days)	147	130
	a' (days)	0.2	0.4
	d' (days)	0.5	0.25
Root density	L_m	9.8	9.4
	RPR (mm·d^{-1})	16	20
	$L_{(d)}$	$L_{(d)} = L_m T_{R(Rel)(d)}\left(\frac{FB_m}{1}\right)$	
	$f_{(d)}$	$f_{(d)} = \frac{2.303}{(0.7)(RPR)(d)}$	
Actual transpiration	θ_{10} (mm·mm^{-1})	$\theta_{10(k)} = 0.0345(SC_{(k)})^{0.611}$	
	θ_{1500} (mm·mm^{-1})	$\theta_{1500(k)} = 0.00385(SC_{(k)}) + 0.013$	
	Ψ_p (kPa)	2 400 *	1 800 **
	F_{sr} (mm·d^{-1}·kPa^{-1})	Determined with iteration subroutine (Barnard et al., 2015)	
Water table uptake	K_s (mm·d^{-1})	$K_s = 2925.8 Exp^{-0.1218(SC_{k=CZ})}$ where $y = 0.0003(SC_{k=CZ}) - 0.011$	
Salinity	c-	1 = 0.075; 2 = 7.5; 3 = 0.072	

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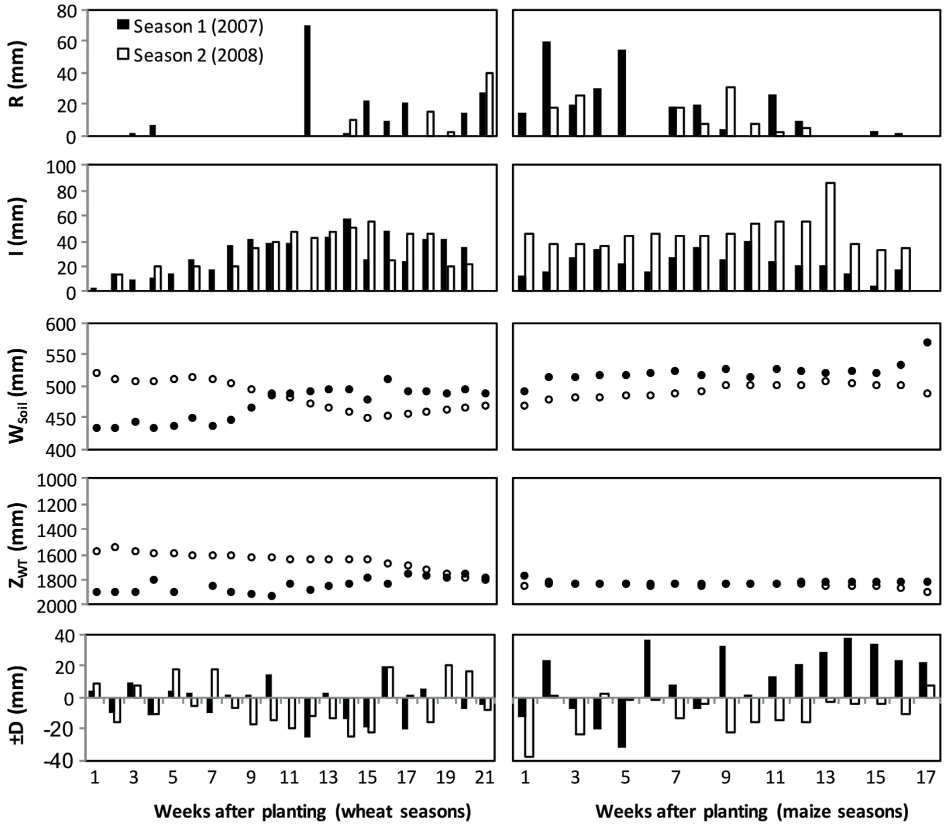

Figure 3

Mean weekly rainfall (R), irrigation (I), soil water content per 2000-mm depth profile (W_{Soil}), groundwater table depth (Z_{WT}) and net weekly groundwater contribution (+D, mm) or drainage (–D, mm) at Case Study 1

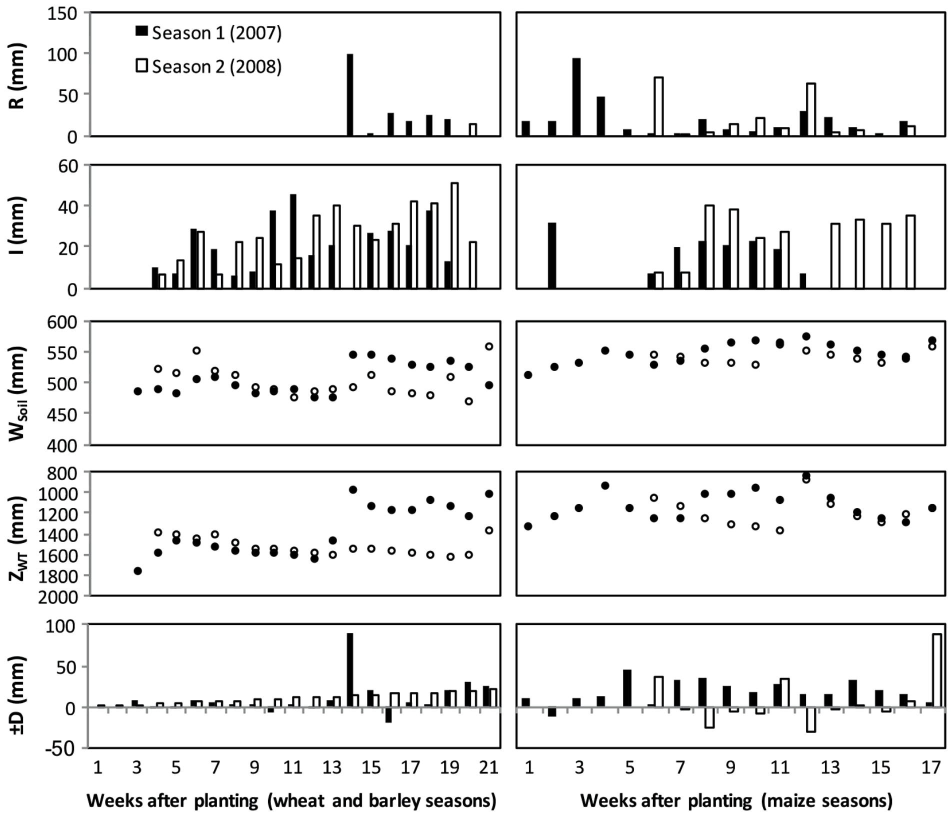

Figure 4

Mean weekly rainfall (R), irrigation (I), soil water content per 2000-mm depth profile (W_{Soil}), groundwater table depth (Z_{WT}) and net weekly groundwater contribution (+D, mm) or drainage (–D, mm) at Case Study 2

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TABLE 6

Seasonal groundwater contribution (+*D*) and drainage (-*D*) at Case Study 1 (or1 and or2) and Case Study 2 (v1 and v2), as calculated from the change in soil water content (ΔW_{Soil}), rainfall (*R*), irrigation (*I*), evaporation (*E*), transpiration (*T*) and drainage from the artificial drainage system (*AD*)

Case study	Crop	Monitoring position	ΔW_{Soil}	*R*	*I*	*E*	*T*	*AD*	+*D*	−*D*
			(mm)							
1	1st Wheat	or1	48	177	561	61	569	10	79	129
		or2	71	177	573	79	521	10	83	152
		Mean	59	177	567	70	545	10	81	141
	1st Maize	or1	97	262	359	38	715	23	322	70
		or2	19	262	359	57	684	23	255	93
		Mean	57	262	359	48	700	23	289	82
	2nd Wheat	or1	-49	65	550	47	516	22	110	189
		or2	-55	70	552	67	517	22	116	187
		Mean	-52	68	551	57	517	22	113	188
	2nd Maize	or1	41	115	739	38	565	10	15	215
		or2	17	115	733	53	647	10	43	164
		Mean	29	115	736	46	606	10	29	189
2	Wheat	v1	15	193	362	53	573	75	236	75
		v2	45	193	291	51	565	75	289	37
		Mean	31	193	327	52	569	75	263	56
	1st Maize	v1	20	315	128	48	566	150	351	10
		v2	2	310	172	49	581	150	312	12
		Mean	12	313	150	49	573	150	332	11
	Barley	v1	-68	14	459	57	524	94	226	92
		v2	-148	14	428	63	408	94	201	226
		Mean	-108	14	444	60	466	94	213	159
	2nd Maize	v1	125	203	310	37	488	141	392	114
		v2	30	207	239	36	429	141	278	88
		Mean	77	205	275	37	459	141	335	101

groundwater table depth dropped back to around 1 800 mm.

The groundwater table at Case Study 2 was much shallower compared to Case Study 1, i.e., on average, 298 and 677 mm shallower over the two winter and summer seasons, respectively. In addition, the groundwater table depth fluctuated more than in Case Study 1 (standard deviation was 55% higher). Weekly changes in the groundwater table depth at Case Study 2 correlated well ($r = -0.73$) to periods during which weekly rainfall contributed more than 50% to weekly evapotranspiration. This was attributed to smaller storage capacity of the unsaturated zone above the capillary fringe for rain and irrigation compared to Case Study 1. Shortly after these high rainfall and irrigation events, the groundwater table depth dropped sharply again. This showed that the drainage system at Case Study 2 was functioning well, which in addition to lateral groundwater drainage quickly removed excess water.

Subjective scheduling did not utilize rainfall efficiently as a source of water. During three of the four cropping seasons, more water (rainfall-plus-irrigation) was supplied than evapotranspired by the crops.

During the first maize season, 20% less rainfall-plus-irrigation was supplied than required by the crop. However, during the first wheat, second wheat and second maize seasons, respectively, 17%, 7% and 23% over-irrigation occurred. Thus, in total over the four cropping seasons rainfall-plus-irrigation exceeded evapotranspiration by 10%. This over-supply resulted in 65 mm of artificial drainage and a net loss of 87 mm through lateral groundwater drainage. The subjective scheduling method, in general, did not utilize the saturated zone below the groundwater table to supply in-plant water requirements. Net lateral groundwater contribution (difference between groundwater contribution and drainage) during the first maize season amounted to 28% of evapotranspiration. During the other seasons net groundwater contribution was less than 0.

With the objective scheduling method (Case Study 2), rainfall was better incorporated into the schedule compared to subjective scheduling. During all four seasons evapotranspiration exceeded rainfall-plus-irrigation applied. The deficits amounted to 101, 159, 68 and 16 mm per season, respectively. Hence, over the four cropping seasons evapotranspiration was under-supplied by 15%. The difference between rainfall-plus-irrigation and evapotranspiration was supplemented by groundwater. A respective net gain of water to the potential root zone through the groundwater table of 207, 321, 54 and 234 mm per season was recorded (Table 6). In total over the four growing seasons, the groundwater contributed 36% towards evapotranspiration.

Salt management

Figure 5 shows the salt distribution within the soil profiles in both case studies for five sampling periods. The seasonal salt balances of the two fields are provided in Table 7. The EC_e values over the measuring period indicate no salt accumulation

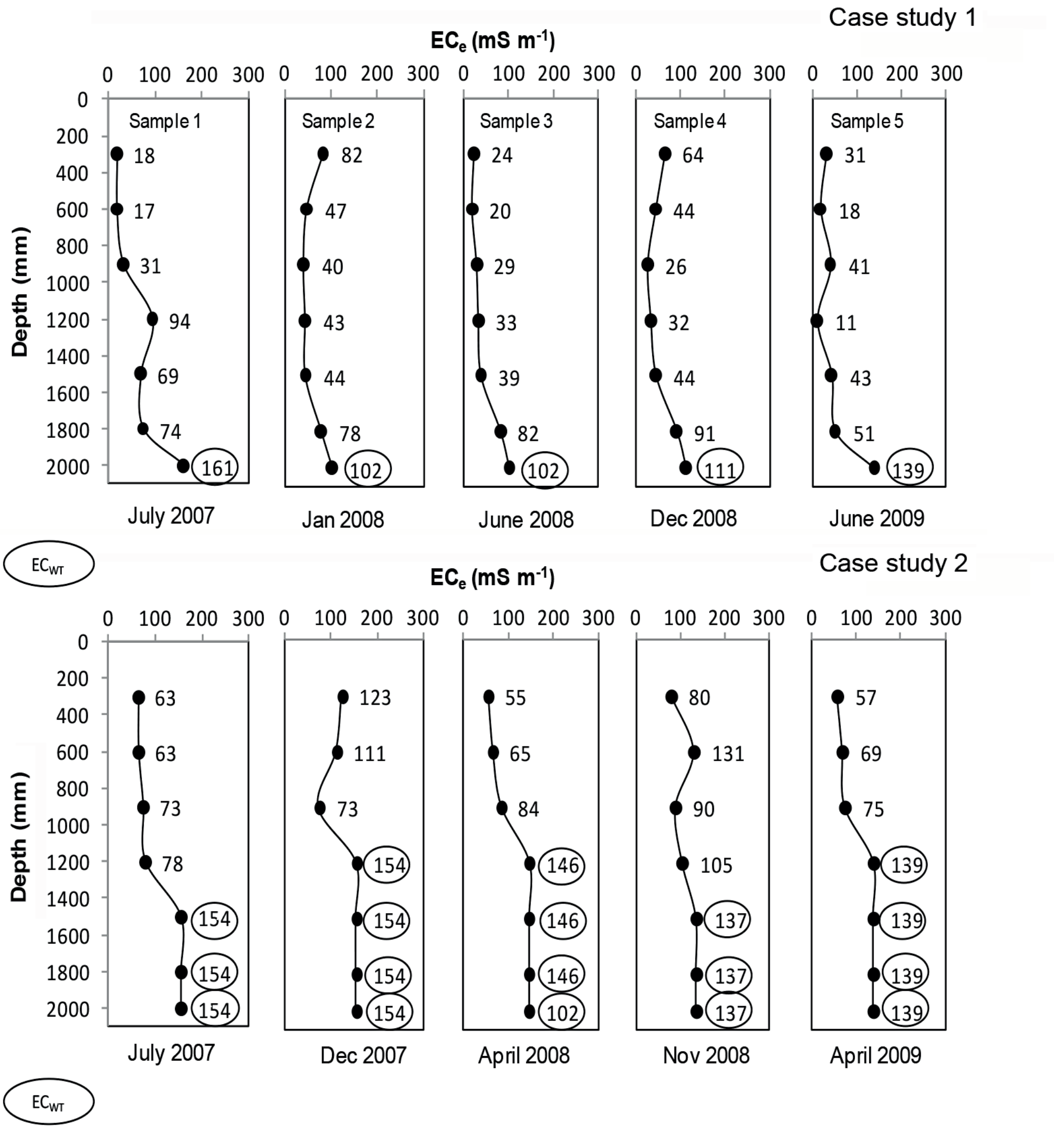

Figure 5

Mean salt distribution in the soil profile, expressed as the electrical conductivity of a saturated extract (ECe), at Case Study 1 and Case Study 2 for five sampling periods taken during the measuring period (encircled values represent the groundwater table, ECWT)

for both case studies (Fig. 5). The salinity of the groundwater table remained relatively constant. Over the four seasons, at Case Study 1 a mean electrical conductivity with a standard deviation of 113 ± 14 mS·m^{-1} was measured and at Case Study 2, 144 ± 13 mS·m^{-1}. Hence, salt was sufficiently leached into the groundwater table to prevent salt accumulation in the soil profiles and removed laterally through groundwater drainage to lower lying soils and/or artificial drainage.

The major sources of salt in the potential root zone were rainfall-plus-irrigation: over the four cropping seasons, 3 637 and 6 585 kg·ha^{-1} in total for Case Studies 1 and 2, respectively. Of this, rainfall contributed around 3% and 2% at Case Studies 1 and 2, respectively. The higher amount of salt added at Case Study 2 was ascribed to poorer quality irrigation water used compared to Case Study 1, viz. water having electrical conductivity of 68 and 21 mS·m^{-1}, respectively. If the salinity of the irrigation water was assumed to be 68 mS·m^{-1} over the four cropping seasons at both case studies, the more accurate objective scheduling method reduced salt additions to the soil by 4 701 kg·ha^{-1} compared to the subjective scheduling method.

Over-irrigation by the subjective scheduling method removed, over the four seasons, approximately 24% more salt from the potential root zone through artificial and lateral groundwater drainage than added through irrigation and lateral groundwater inflow. These EC_e results indicated improved soil quality over the measuring period, from a mean EC_e above the groundwater table (0–1 800 mm) of 51 to 33 mS·m^{-1} (Fig. 5).

For the objective scheduling method over the four seasons only 5% more salt was removed from the potential root zone than added through irrigation and lateral groundwater inflow. Hence, with both scheduling methods there was no risk of harming the crop due to salinity as the EC_e for yield decrease of maize, wheat and barley is 350, 600 and 800 mS·m^{-1}, respectively (Ehlers et al., 2007). Unfortunately, however, with both scheduling methods a considerable amount of salt was discharged to lower-lying soils. At Case Study 1, 16% of the total salt added was removed by artificial drainage, while the rest (84%) drained laterally to lower-lying soils. For Case Study 2 this amounted to 73% and 27%, respectively.

TABLE 7
Seasonal net groundwater contribution (+S_D) and groundwater drainage (−S_D) of salt from the potential root zone for measuring points at Case Study 1 (or1 and or2) and Case Study 2 (v1 and v2), as calculated from the change in salt content of the soil (ΔS_{Soil}), addition of salt through rainfall (S_R) and irrigation (S_I), and loss of salt through drainage from the artificial drainage system (S_{AD})

Crop	Measuring point	kg·ha⁻¹				
		ΔS_{Soil}	S_{R+I}	S_{AD}	+S_D	−S_D
Case Study 1: Subjective scheduling						
1st Wheat	or1	−1 555	952	87	141	2 561
	or2	−167	1 067	87	244	1 392
	Mean	−861	1 010	87	193	1 976
1st Maize	or1	173	652	216	1 645	1 908
	or2	−3	605	216	1 907	2 299
	Mean	85	628	216	1 776	2 103
2nd Wheat	or1	−291	876	205	466	1 428
	or2	100	880	205	557	1 132
	Mean	−96	878	205	511	1 280
2nd Maize	or1	−652	1 126	94	79	1 763
	or2	−693	1 117	91	438	2 157
	Mean	−673	1 121	92	258	1 960
Case Study 2: Objective scheduling						
Wheat	v1	598	1 685	792	1 222	1 517
	v2	329	1 498	842	2 316	2 642
	Mean	464	1 591	817	1 769	2 080
1st Maize	v1	−149	915	1 541	4 287	3 810
	v2	−1 263	885	1 541	4 720	5 326
	Mean	−706	900	1 541	4 504	4 568
Barley	v1	−358	2 171	975	1 368	2 922
	v2	−19	2 153	975	1 625	2 822
	Mean	−188	2 162	975	1 496	2 872
2nd Maize	v1	185	2 027	1 484	2 634	2 992
	v2	−851	1 836	1 484	2 129	3 332
	Mean	−333	1 932	1 484	2 381	3 162

DISCUSSION

Although the two case studies are similar in terms of climate, topography, soil, tillage practices and cropping systems, the most notable differences are the scheduling practices and irrigation water quality. Considering these differences, the water and salt management practices at the two case studies were discussed.

According to the mean water use efficiency (*ET*/*R*+*I*) (Perry, 2007; Heydari, 2014), less water was applied than used by the crop with objective scheduling during the winter (1.17) and summer (1.19) seasons compared to subjective scheduling (0.88 during winter and 0.99 during summer). This was possible because rainfall and the groundwater table were utilized better as sources of water for crop water requirements. Net lateral groundwater drainage, which led to lateral water movement to lower-lying soils and/or artificial drains, was over the four cropping seasons 204 mm less with objective compared to subjective scheduling. In terms of crop water productivity (WP), defined as the grain yield per unit water applied through rainfall-plus-irrigation, objective scheduling over four growing seasons produced a mean of 4 kg·ha⁻¹ more grain per unit (mm) water applied than subjective scheduling.

With objective scheduling soil water content can be measured on a daily basis. Hence, prior to irrigation the deficit to fill the soil profile to the drained upper limit minus storage for rainfall can be calculated and irrigation adjusted accordingly. If the technology is available, the capillary contribution from a shallow groundwater table can also be taken into account. Unfortunately, at Case Study 2, the farmer monitored soil water content only in the top 600 mm or 30% of the root zone and the groundwater table oscillated beyond this depth during the four cropping seasons. Our results showed that, over the four cropping seasons, the net lateral groundwater inflow (816 mm), expressed as a percentage of evapotranspiration (2 265 mm), amounted to a total of 36%. According to Ehlers et al. (2003) and Ayars et al. (2006), the groundwater table can supply up to 60% of crop water requirements, depending on soil texture and groundwater table depth and condition. Thus, the amount needed for irrigation could have been reduced further by forcing the crop to use more water from the shallow groundwater table. In practice, this means that farmers should use longer probes for measuring soil water content, or the probes should be used in conjunction with observation wells installed at critical points in the field.

The benefits of accurate irrigation scheduling in terms of reducing salt addition and leaching are substantial. If the same water quality was used at Case Study 1 as at Case Study 2, 4 701 kg·ha⁻¹ less salt would have been added with objective scheduling. At both case studies, all the applied salt through irrigation and lateral groundwater inflow into the potential root zone was leached through lateral groundwater and artificial drainage. When the gains and losses are taken into consideration, the initial salt content was reduced by 1 544 kg·ha^{-1} at Case Study 1 and 764 kg·ha^{-1} at Case Study 2.

A mean leaching fraction (–*D*/*R*+I) of 0.21 at Case Study 1 and 0.17 at Case Study 2 was sufficient for leaching salt from the soils. The leaching fraction at both case studies can however be reduced under these conditions. This is because of the presence of a groundwater table within or just below the root zone that changes the hydraulic properties of the soil. Water drains much faster through the capillary zone above the groundwater table (Ehlers et al., 2003). Hence, storage for soil water in this nearly saturated capillary zone is limited due to the shallow groundwater table depth. Under these conditions leaching into the groundwater table occurs frequently when irrigation and/or rainfall exceeds the available storage. The artificial drains and groundwater tables are linked to rivers (Ellington et al., 2004), which means users downstream are the recipients of the salt (Du Preez et al., 2000; Viljoen et al., 2006; Van Rensburg et al., 2012). Thus, discharge of salt from the potential root zone needs to be managed in a sustainable way. General recommendations are that periodic leaching should be applied only when the threshold salinity of the crop is reached, because the efficiency of leaching (mm·drainage per kg salt removed) will increase from a low to high soil salinity content (Monteleone et al., 2004; Barnard et al., 2010). It is anticipated that in these shallow groundwater table soils, irrigation can be substantially reduced to prevent leaching (reduce the leaching fraction). Because storage for soil water is limited in these soils, rain events above 40 mm will contribute tremendously to salt leaching. Hornbuckle et al. (2005) showed that use of a weir drainage system to control groundwater table depths, combined with deficit irrigation scheduling to maximize crop use of shallow groundwater tables, results in significant reductions in drainage volumes and salt loads compared to unmanaged systems.

CONCLUSIONS

With objective and subjective scheduling, the two farmers obtained optimum yields by managing plant available water to prevent soil matric stress. Over four cropping seasons the farmers irrigated only 53% of crop water requirements with objective scheduling, compared to 85% when subjective scheduling was employed. When rainfall was taken into account an over-supply of 10% occurred with subjective scheduling, whereas objective scheduling resulted in an under-supply of 15%. Hence, the benefit of objective scheduling was a reduced irrigation water requirement by better utilizing rainfall and shallow groundwater within the potential root zone as supplementary water sources.

Both farmers leached more than the applied salt from the potential root zone. Soil salinity above the groundwater table reduced from 51 to 33 mS m^{-1} and 69 to 67 mS m^{-1} with subjective and objective scheduling, respectively. The mean salinity of the groundwater table during the four cropping seasons amounted to 123 and 146 mS m^{-1}, respectively. Hence, the likelihood for osmotic stress was small during the cropping seasons.

The continuous removal of salt is generally not considered as good practice, because ideally salt should be accumulated and periodically leached during high rainfall events and/or fallow periods. Hence, under these conditions, when adopting objective scheduling, a leaching fraction of less than 0.15 could be used. In such a way, farmers can reduce the environmental problems associated with irrigation, namely degradation of water resources due to excessive leaching, and produce optimum yields with less water. Future research may include more case studies on a larger scale to verify the results and an investigation into the economic feasibility of alternative irrigation strategies.

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APPENDIX 1

The efficiency of each centre pivot was evaluated by placing 30 rain gauges evenly apart. The amount of irrigation water in the rain gauges was determined at a low (20%) and high (100%) pivot speed. The Heermann and Hein uniformity coefficient ($CU_{H,\%}$) and distribution uniformity (DU_{Ig}, %) was calculated with Eq. A1 and Eq. A2, respectively, where R_i is the distance (m) of the rain gauge at point *i* from the centre, y_i the application depth (mm) at point *i* as collected in the rain gauge, y_g the weighted average application of the total system (mm), and *A* the weighted average application of the lowest 25%. In addition, the application efficiency (AE, mm) and system efficiency (SE, mm) were calculated with Eq. A3 and Eq. A4, respectively, where GA is the gross application (mm), *Q* the centre pivot flow rate ($m^3 \cdot h^{-1}$), *t* the rotation time (h) and *A* the total wetted area of the centre pivot (ha).

$$CU_H = 100\left(1 \frac{\sum y_i - y_g}{R_i y_i}\right) \quad \text{(A1)}$$

$$DU_{Ig} = \frac{A}{y_g} 100 \quad \text{A2)}$$

$$AE = \frac{y_g}{GA} 100 \quad where \;\; GA = \frac{Qt}{10A} \quad \text{(A3)}$$

$$SE = \frac{(AE)(DU_{Ig})}{100} \quad \text{(A4)}$$