THE EFFECT OF DIFFERENT FURROW IRRIGATION REGIMES ON INFILTRATION AND SUGARCANE YIELD AT UBOMBO

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Abstract

In surface irrigation, the soil serves as a medium for infiltration and conveying water from upstream to the downstream end of a field. In this study, infiltration properties of the Sibaya (Si) soil series (Glenrosa in the South African soil classification system) were determined by a volume balance method using a two-point approach technique. The purpose of the study was to examine the effect of different irrigation scheduling on infiltration characteristics, and on irrigation performance. A trial was conducted on a field with predominately Sibaya soil from 1999 to 2001. The five irrigation treatments were the Ubombo system, Penman Monteith (PM) derived irrigation scheduling factors of 1.25, 1.00 and 0.75, and alternate inter-row irrigation using Ubombo and 1.00 x PM scheduling on plant and first ratoon cane, respectively. Treatments were arranged in a randomised complete block design with four replications. The Ubombo scheduling method had the highest number of irrigation events followed by the 1.25 x PM, whilst the 0.75 x PM had the least. The infiltration variables indicated that, for the Ubombo and 1.25 x PM treatments, irrigation often occurred when the soil water content was still less than 50% depleted plant available water (DPAW). Frequent irrigation resulted in the crop depleting soil water, predominately at the 0.15-0.30 m soil depth and hardly any at 0.45 m, particularly when the crop was still young. There were no significant differences in yield between any of the treatments either in the plant or the ratoon crops. The plant crop consistently recorded higher yields than the first ratoon in all the treatments. Ubombo scheduling recorded the highest sugarcane yield in both seasons at 84 t cane ha^{-1} for the plant crop and 82 t cane ha^{-1} for the first ratoon. The 0.75 x PM had the lowest yield (77 t cane ha^{-1}) in the plant crop as well as in the first ratoon (74 t cane ha^{-1}).

Keywords: sugarcane, furrow irrigation, infiltration, scheduling

Introduction

Sugarcane production at Ubombo Sugar Company (Pty) Ltd (lllovo) is fully irrigated, as the estate is located in the Swaziland Lowveld in a semi-arid climate with a long-term mean annual water deficit (Class A pan) of about 1500 mm. Thus, irrigation is a crucial and an integral activity of sugarcane production. The estate currently uses sprinkler (47%), furrow (38%), and centre pivot (15%) irrigation systems.

At 25% of the production costs, irrigation is the single most costly practice in growing sugarcane. Consequently, there has been an increased and continuous effort towards improving management in all three of the irrigation systems. The greatest challenge to the management of irrigation is encountered in furrow irrigation. The soil and not the system hardware control infiltration in surface irrigation systems to a greater extent than in other systems. In furrow irrigation, soil infiltration properties control the major phases of irrigation: advance, recession, run-off, depth and uniformity of applied water. Soil infiltration characteristics are thus an extremely important soil parameter in the management of surface irrigation. In fact, optimal design and management of surface irrigation systems rely entirely on detailed knowledge of soil infiltration properties (Baustista and Wallender, 1993). Therefore, an insight into the infiltration process, and determining and possibly predicting infiltration in time and space. remains a vital and a first step in improving the management of furrow irrigation systems (Vogel and Hopmans, 1992; Shepard *et al.,*1993).

Approaches to the techniques of determining soil infiltration characteristics vary with different researchers, but can be broadly grouped into two categories: small area methods and large area methods. Cylinder infiltrometers, blocked furrow, bypass infiltrometers, flowing infiltrometers and flow through infiltrometers belong to small area methods, whereas furrow and border flow infiltrometers belong to the larger scale methods. Small area methods have often been criticized for many reasons. Firstly, they fail to indicate the typically dynamic field conditions (Walker and Skogerboe, 1987), as they do not simulate the geometric conditions of a furrow. Secondly, several replications are often needed to account for spatial variability of infiltration in a given field (Esfandiari and Maheshwari, 1997). The constraining costs and practical difficulties associated with the small area methods make the larger scale method an attractive alternative. The infiltration characteristics so obtained are representative for the whole area considered, as they use the whole furrow length. Large area methods are based on the advance of the water-front from the inflow end to the downstream end of the field**,** employing any of the four mathematical principles that can be applied. One such principle, the volume balance theory, developed by Lewis and Milne (1938), is recognized for its simplicity and proven ability to approximate both advance and infiltration parameters. Volume balance techniques have been extensively studied and documented in much of the irrigation literature. There are many variants of this approach, and solution by volume balance vary with different investigators: graphical or regression based (Wilke and Smerdon, 1965; Norum and Gray, 1970); numerical (Elliot and Walker, 1982); Laplace transforms (Renault and Wallender, 1992; Shepard *et al*., 1993); and optimization (McClymont and Smith, 1996; Esfandiari and Maheshwari, 1997). Smerdon and Blair (1988) examined most of the approaches and in spite of the different assumptions, concluded that different volume balance solution methods yield comparable results**.**

The use of volume balance techniques to determine soil infiltration involves the adoption of a functional form of the infiltration (Chriastiansen *et al.,* 1966). There are numerous infiltration models including those that are physically and empirically based (Austin and Prendergast, 1997). There are three commonly used infiltration equations for surface irrigation work, that of Kostiakov (1932);

$$Z = kt^a \qquad (1)$$

where: Z is the volume of infiltrated water per unit length of furrow or depth during an infiltration opportunity time, *a* (dimensionless) and *k* (m^3 min^{-1} m^{-1}) are empirical fitting parameters, and t is the time of infiltration opportunity.

a modified Kostiakov function (Austin and Prendegast, 1997);

$$Z = kt^a + f_0 t \qquad (2)$$

where f_o is the steady state infiltration rate.

as well as the equation developed by Philip (1957)**;**

$$Z = St^{1/2} + At \qquad (3)$$

where *S* is sorptivity and parameter *A* is a fraction of saturated hydraulic conductivity.

The objectives of the trial were firstly to determine and examine the soil infiltration characteristics of the Sibaya (Si) soil series at the experimental site as affected by different irrigation schedules; and secondly to investigate the response of sugarcane to the different irrigation regimes.

Methods and Materials

The research was conducted for two seasons (1999/2000, 2000/2001) at Big-Bend, Swaziland (26°46’04”S, 31°56’11”E) and 106 m above sea level. The mean annual rainfall is 650 mm occurring mainly in summer between November and January.

The soils at the site were predominately of the Si series (Nixon, 1986) and the sugarcane cultivar was N23. Row spacing was 1.52 m and furrow length varied between 130 to 160 m.

There were five irrigation schedule treatments based on estimated crop evapotranspiration (ET): Ubombo irrigation (T_1), Penman-Monteith (PM) derived ET scheduling factors of 1.25 (T_2), 1.00 (T_3), and 0.75 (T_4), and an alternate inter-row irrigation (T_5). The alternate inter-row irrigation was, in the first season (plant cane), scheduled as the Ubombo system (T_5, 2000) whereas in the second season (first ratoon) was scheduled according to 1.00 x PM (T_5, 2001). The treatments were arranged in a randomized complete block design and replicated four times. In brief, the Ubombo scheduling system (T_1) involves filling up the profile with water after harvest, and crop water use is estimated using canopy factors ranging from 0.1 to 1.0 depending on season and age of the crop. Soil water is depleted to between 20% and 50% of total available water (TAW), depending on season, before irrigating.

When a treatment was due for irrigation, water was directed into individual furrows using spiles. Inflow rate, depth of flow with time, and furrow water advance and recession times were some of the measurements made during an irrigation event. This was done throughout the season for both the plant and ratoon crops. The inflow rate was measured with a low pressure propeller meter (Walker and Skogerboe, 1987) and readings were manually taken at two minute intervals. The water front advance was monitored and when it passed markers at 10 m intervals, the time was noted and recorded. After the closure of the spiles, the times at which water receded along the 10 m intervals were recorded. The cross sectional area was determined using a profilometer (Walker and Skogerboe, 1987) at five places along the furrow length and the mean value was used in the equation.

Soil water content was measured periodically between irrigation events at five strategic locations along the furrow using a neutron probe in two replicates. Matric potentials were measured using tensiometers. A volume balance was used to determine soil infiltration properties. There are many techniques in the solution of the problem, and in this paper, a two-point technique was employed (Elliot and Walker, 1982). Water flowing overland from upstream to downstream ends of a field can be described by a power function of the form shown in equation 4:

$$x = pt^{r} \tag{4}$$

where x is the distance the water-front has advanced in time t, and r and p are empirical fitting parameters.

Soil infiltration characteristics were determined using the Kostiakov model (equation 1).

The two-point method requires inflow rate, cross sectional area and time taken by the water front to advance to the middle and end of the furrow. The Kostiakov infiltration parameters, *a* and *k*, can be determined using equations 5 and 6.

$$a = \frac{\log\left[\dfrac{\dfrac{Q_{in}t_1}{x_1} - A_o\dfrac{f_o t_1}{1+r}}{\dfrac{Q_{in}t_2}{x_2} - A_o\dfrac{f_o t_2}{1+r}}\right]}{\log\left[\dfrac{t_1}{t_2}\right]} \tag{5}$$

$$k = \frac{\left[\dfrac{Q_{in}t_1}{x_1} - A_o - f_o t_1\right]}{\sigma_z t_1^a} \tag{6}$$

Where A_o is the cross-sectional area of flow at the inlet (m^2), Q_{in} is the inflow rate (dm^3/s), t_1 and t_2 are the advance times taken to halfway and to the end of the field (min) respectively, x_1 (m) is the distance to mid-field, x_2 (m) is the distance to the end of the field and σ_z is the subsurface shape factor, defined in equation 7, where parameters *a* and *r* are as previously defined, in equations 1 and 4 respectively.

$$\sigma_z = \frac{a + r(1-a) + 1}{(1+a)(1+r)} \tag{7}$$

Results and Discussion

Effect of antecendent soil water content on infiltration

Antecendent soil water content is an important factor affecting infiltration, and the effect of initial soil water content was studied by comparing the distribution of the Kostiakov exponent, *a*, between the irrigation schedules.The value of exponent *a* depends on the initial soil water content. Low values of the Kostiakov infiltration exponent *a* indicate low initial soil water content, and high values of the exponent will result where the initial soil water content is high.

In the case of the Ubombo schedule (T_1) the Kostiakov exponent *a* tended towards unity (Table 1) for a majority of irrigation events, especially in the first season. The Kostiakov exponent *a* was clustered between 0.2 and 0.6 for the 0.75 (T_4) and 1.00 x PM (T_3) treatments, in both seasons. The alternate inter-row irrigation using the Ubombo schedule (T_5, 2000) also had its distribution skewed toward unity whilst the alternate inter-row irrigation using 1.00 x PM (T_5,2001) had a distribution clustered around 0.4 to 0.6. These findings are in agreement with those of Maheshwari and Jawardane (1988) and Hume (1993) who reported that variation in the value of infiltration parameters depend largely on soil water content before irrigation. In the case of the Kostiakov model, the values of infiltration parameters, *a* and *k*, increase and decrease respectively as the initial soil water content increases.

The variation in the distribution of the Kostiakov exponent *a* among the different schedules can be attributed to irrigation scheduling. Frequent irrigation prevents the development of a suction gradient as soil water is consistently maintained at high levels (Figure 1a). The decrease in infiltration rate on soils with an initial high water content is principally due to a decreased matric potential gradient between the wetting front and the underlying soil**.** This is otherwise a dominant component on an initial dry soil under furrow irrigation systems, where the infiltration is essentially two-dimensional. In the early stages of an irrigation event, the suction gradient can be as significant as the gravitational gradient especially on an initially dry soil under furrow irrigation systems (Fonteh and Podmore, 1993). Mailhol *et al.* (1999) also reported that at higher soil water contents, the capillarity of the soil to absorb water is reduced.

On the other hand, with treatments like 0.75 x PM (T_4) (Figure 1d), which are usually drier at the soil surface before irrigation, as irrigation is withheld for an extended period, the hydraulic gradient increases as the soil water is depleted and the effect of the initial soil water content is thus reflected in the values of the parameters of the Kostiakov infiltration model upon irrigation. Under such circumstances, the Kostiakov infiltration exponent a tended to cluster between 0.4 and 0.6 (Table 1).

The distribution of a in the rather drier treatments, 0.75 x PM (T_4) and alternate inter-row irrigation using 1.00 x PM (T_5, 2001), was surprisingly not clustered around zero. This could be attributed to irrigation being due normally when the crop had just, or was about to exhaust the freely available water in the profile. The irrigation schedules, by their nature, did not permit the crop to deplete soil water beyond the readily available range (less than –100 kPa) and under such circumstances the infiltration exponent tended to be between 0.4 and 0.6. With the Kostiakov exponent a varying between 0.4 and 0.6, and not significantly different from 0.5, the exponent can be fixed at 0.5 with minimal error introduced, and subsequently the infiltration model can be interpreted physically using Philip's infiltration model (Hartley, 1992).

Generally, the distribution of the infiltration exponent a particularly for Ubombo schedule (T_1), was more skewed towards 1.0 in the first season than in the second season (Table 1). This means that the soil conditions were slightly drier in the second season than in the first, and that agrees well with the tensiometer data (Figures 2a and 2f). The explanation is that the first ratoon could have had a more extensive root system together with a greater rate of canopy cover than the plant cane, resulting in greater water uptake. Nixon (1992) reported that first ratoon crops have a more extensive root system than that of plant cane. This, in turn, might have lead to overestimation of Et for the plant crop hence the reason for over-irrigation. For the other treatments, the light rainfall events that were regularly received in the first season could have kept the soil surface slightly wet thus altering the infiltration process. The tensiometer readings, for Ubombo schedule (T_1) for the first season, would range from -55 to -75 kPa, -50 to -65 kPa, and -8 to -12 kPa at 0.15 m, 0.30 m, 0.45 m respectively. Likewise, 0.75 x PM (T_4) was irrigated when the soil water content was greater than 50% DPAW. Tensiometer readings nearly always showed a higher matric potential than -80 kPa at both 0.15 m and 0.30 m, and -75 kPa at 0.45 m. Further examination of the tensiometer data suggested that irrigation scheduling determined the preferential depth of water uptake by the crop.

Table 1. Class distribution frequency (%) of the Kostiakov exponent *a* among different irrigation deficit schedules based on the Ubombo system or Penman-Monteith evapotranspiration factors.

Irrigation schedule	Season										mean				
	1999/2000					2000/2001									
	Class limits of exponent "*a*"(%)					Class limits of exponent "*a*"(%)									
	< 0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0	< 0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0	< 0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0
Ubombo schedule	4.55	4.54	18.18	29.55	43.19	17.89	32.52	11.38	6.5	31.77	11.22	18.53	14.78	18.025	37.48
1.00 x Penman- Monteith	9.09	11.37	43.19	18.18	18.18	3.85	42.3	25	7.7	21.15	6.47	26.835	34.095	12.94	19.665
0.75 x Penman -Monteith	15.15	30.30	27.28	15.15	12.12	11.43	37.17	45.69	8.57	8.57	13.29	33.735	36.485	11.86	10.345
Alternate row irrigation[1]	9.76	9.75	31.71	24.39	24.39	14.58	45.84	20.83	10.42	8.33					

[1] scheduled according to Ubombo system in the 1st season and 1.00 x PM in 2nd

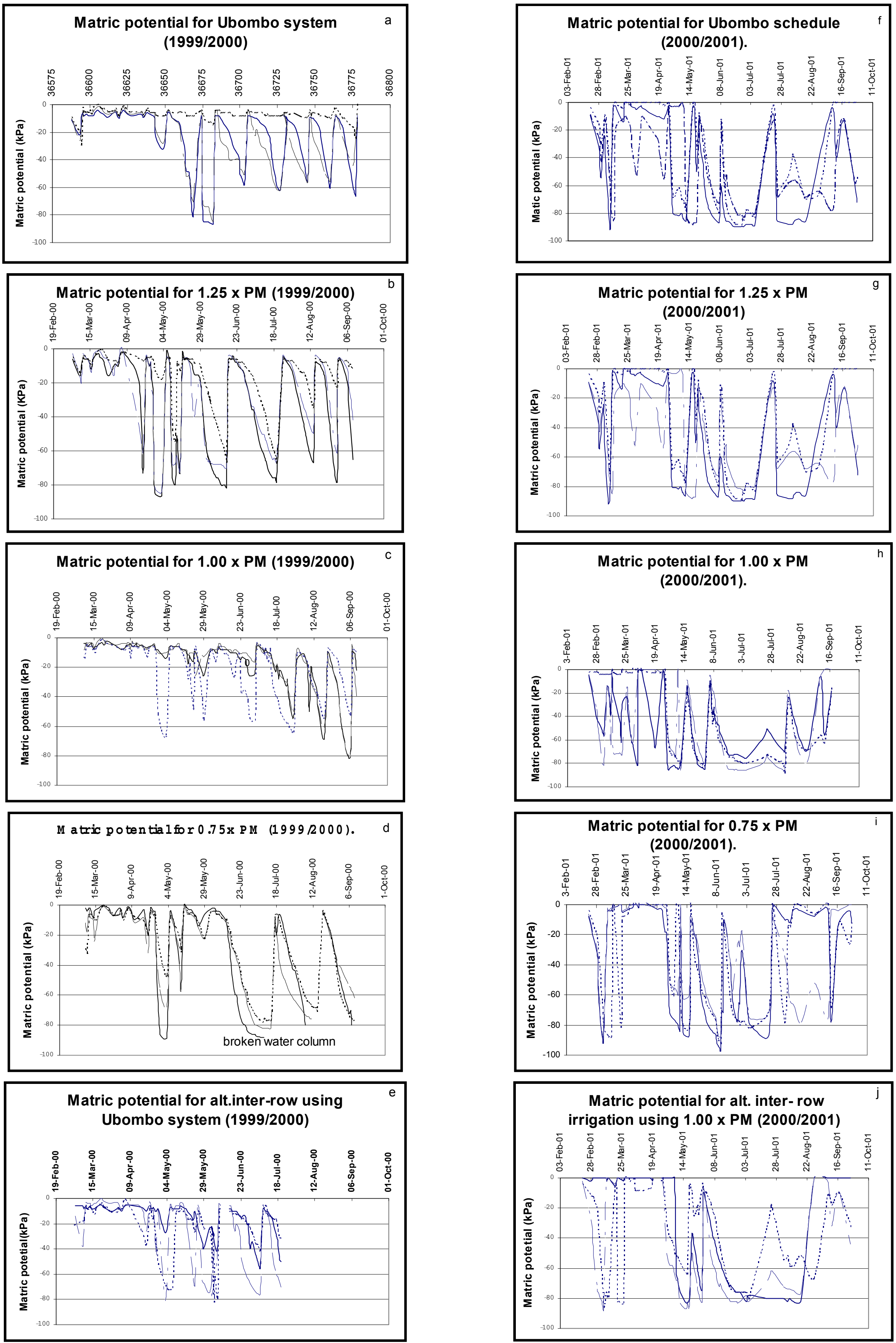

Figure 1a-1j. Soil water matric potentials at three depths for different irrigation deficit schedules using the Ubombo system or Penman-Monteith (PM) evapotranspiration factors for 1999/2000 and 2000/2001 seasons.

Cumulative infiltration

In furrow irrigation systems, the soil serves two purposes: a) infiltration and b) water conveyance from upstream to the downstream end of a field. High frequency irrigation keeps the soil water levels high, and during irrigation the conveyance component dominates over the infiltration process. Consequently, the water front advances relatively fast leading to less water applied per irrigation event. However, in cases where irrigation was delayed for an extended time, the infiltration component tends to dominate over conveyance. In turn, the water front usually advances rather slowly leading to higher amounts of water being applied per unit furrow length per irrigation event. The Ubombo system (T_1), which produced a frequent irrigation schedule, typified the former, resulting in reduced water applied per unit row length per irrigation event as opposed to the 0.75 x PM (T_4) and alternate inter-row irrigation using PM (T_5, 2000), which resulted in comparatively higher amounts of water applied per unit row length per irrigation event. A typical Ubombo (T_1) schedule was found to apply about 30 mm, yet about 40 mm would be applied in the 1.25 x PM (T_2). In the 1.00 x PM (T_3), about 50 mm was applied and 75 mm was applied on the 0.75 x PM (T_4). The alternate inter-row irrigation using 1.00 x PM (T_5, 2000) applied about 80 mm.

The differences in cumulative infiltration give information on the significance of lateral water movement near the soil surface. This is demonstrated in the differences in cumulative infiltration between inter-row irrigation using 1.00 x PM (T_5, 2001) and every inter-row 1.00 x PM (T_2) schedules, where one can compare the influence of a dry adjacent furrow with water-filled furrows. The data suggest that with an alternate inter-row irrigation using 1.00 x PM (T_5, 2001), lateral flow remains significant before the wetting front in a horizontal direction is midway between the two wet furrows. This is in contrast to the observation of alternate inter-row irrigation using Ubombo schedule (T_5, 2000), where water filled furrows bordered by a dry or wet furrow had little effect on infiltration. One can thus conclude that lateral water movement is not significant in soils with an initial high water content. The matric potential gradient in initially dry soils drives the increase in infiltration as well as lateral spread of water.

Irrigation performance indices

The Ubombo system (T_1) and the 1.00 x PM (T_3), generally had higher application efficiency[1], distribution uniformity[2] as well as the requirement efficiency[3] than the 0.75 x PM (T_4) and alternate inter-row irrigation using the 1.00 x PM (T_5, 2001). The irrigation indices indicated that the performance of the Ubombo system (T_1) and the 1.00 x PM (T_3) irrigation schedules was satisfactory yielding well above 80% efficiency (Table 2). The 0.75 x PM (T_4) and the alternate inter-row irrigation using 1.00 x PM (T_5, 2001), on the other hand, recorded satisfactory levels of application efficiency and often low levels of distribution and requirement efficiencies (Table 2). The observed differences can be explained in terms of the proportion of soil infiltration to water conveyance during irrigation events. With the former, the conveyance component dominated, resulting in water moving fast from the upstream to the downstream end of the field. This resulted in almost equal intake opportunity time along the furrow length, and subsequently a uniform subsurface distribution of water. Whereas with the latter, the soil infiltration process predominated, and higher amounts of water were applied to the upstream than the downstream end of the field. This led to disproportionate distribution of water and requirement efficiency (Table 2).

Sugarcane yield and quality

There were no significant differences in yield between any of the treatments either in the plant or the ratoon crops (Table 3). The plant crop consistently recorded higher sugarcane yields than that of the first ratoon in all the treatments, however the plant crop consistently yielded lower sucrose over all treatments than the first ratoon. Ubombo scheduling (T_1) recorded the highest sugarcane yield in

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[1] (average depth of irrigation water contributing to target/ average depth of irrigation water applied)*100.

[2] is a measure of the uniformity with which irrigation water is distributed along the furrow length.

[3] also called adequacy, is based on the percentage of the area adequately irrigated; varying from 0 to 100%.

both seasons at 84 t cane ha^{-1} for the plant and 82 t cane ha^{-1} for the first ratoon. The 0.75 x PM (T$_4$), on the other hand, recorded the lowest yield in both seasons at 77 t cane ha $^{-1}$ and 74 t cane ha $^{-1}$ for the plant and first ratoon respectively. The plant cane was not ripened whilst the first ratoon crop was ripened with fusilade (0.35 L ha^{-1}) five weeks before harvesting, which explains the higher sucrose percent cane in the 2000/2001 season. In the first season, cane grown on the relatively drier irrigation schedules, 0.75 x PM (T$_4$) and 1.00 x PM (T$_3$) recorded the highest sucrose percentages. The 0.75 x PM (T$_4$) had 14.4% sucrose in the plant cane followed by the 1.00 x PM (T$_3$) with 14.1% sucrose. In the second season, the relatively wet irrigation schedules, 1.25 x PM (T$_2$) and Ubombo scheduling (T$_1$), had the highest sucrose percentage. The 1.25 x PM (T$_2$) recorded 15.6% sucrose followed by Ubombo schedule (T$_1$) with 15.4% sucrose. The data suggest that water stressed conditions led to higher sucrose accumulation if the sugarcane was not ripened. However the frequently irrigated sugarcane crop (1.25 x PM (T$_2$) and Ubombo schedule (T$_1$)) benefited tremendously from ripening.

Table 2. Comparison of irrigation performance indices for the different irrigation schedules based on the Ubombo system or Penman-Monteith evapotranspiration factors.

	Irrigation Event	Irrigation performance index		
Irrigation schedule		Application efficiency(%)	Distribution uniformity(%)	Requirement efficiency(%)
Ubombo schedule	1	90.7	95.99	98.54
	2	92.01	99.69	97.71
	3	81.76	74.73	82.21
	4	95.53	100	94.97
	5	93.93	99.94	97.52
1.00 x Penman-Monteith	1	87.02	100	98.69
	2	89.73	100	98.59
	3	97.67	99.39	84.11
	4	94.79	96.64	95.84
	5	82.51	100	99.98
0.75 x Penman - Monteitn	1	74.67	60.43	93.87
	2	88.88	79.34	96.65
	3	100	68.97	30.31
	4	100	71.43	30.08
	5	100	88.94	86.57
1.00 x PM alternate inter-row irrigation	1	89.67	72.95	93.66
	2	91.41	94.84	100
	3	71.65	71.29	45.73
	4	75.85	37.72	37.98
	5	77.82	77.1	78.55

The lack of significant differences in yield between the treatments can be attributed to the crop not being subjected to water stress beyond the readily available water range (<-100 kPa) in any of the treatments.

Table 3. Effect of irrigation scheduling based on the Ubombo system or Penman-Montieth evapotranspiration factors on sugarcane yield, sucrose percent and sucrose yield.

Irrigation schedule	Season						mean	
	1999/2000			2000/2001				
	cane yield (t ha^{-1})	sucrose (%)	sucrose yield (t ha^{-1})	cane yield (t ha^{-1})	sucrose (%)	sucrose yield (t ha^{-1})	cane yield (t ha^{-1})	sucrose yield (t ha^{-1})
Ubombo schedule	84.6	13.66	11.6	81.3	15.40	12.5	82.95	12.0
1.25 x Penman-Monteith	82	13.35	10.9	81.3	15.63	12.7	81.65	11.8
1.00 x Penman- Monteith	80.1	14.09	11.3	78.3	15.33	12.0	77.3	11.4
0.75 x Penman -Monteith	77.3	14.39	11.1	74.5	15.31	11.4	81.45	11.4
Alternate inter-row irrigation[1]	83.8	13.58	11.4	77.0	15.16	11.7		

[1] scheduled according to Ubombo system in the 1st season and 1.00 x PM in 2nd

Conclusions

The infiltration characteristics of the Sibaya soil series at the site was found to vary mainly with the initial soil water content. Irrigation was more frequent, but with lesser amounts of water applied per event for the Ubombo schedule (T_1) than the 0.75 x PM (T_4) where large amounts of water were applied per irrigation event at a lower frequency. The Kostiakov model was able to provide an insight to the infiltration process for the different schedules.The values of infiltration parameters, *a* and *k*, increased and decreased respectively as the soil water content increased, which is in accordance to literature (Maheshwari and Jawardane, 1988; Hume, 1993; Mailhol *et al.,* 1999).

The different irrigation schedules did not subject any of the sugarcane crops in the various treatments to severe stress beyond that of the readily available soil water, and this could explain the statistically similar yields. Thus, under the studied irrigation regimes, the sugarcane crop did not reach a water stress threshold at which sugarcane growth and yield responded adversely to water stress.

Effective management of furrow irrigation systems relies on detailed knowledge of infiltration characteristics. The use of volume balance approach provided a simple, convenient and reliable technique of assessing and optimising the performance of irrigation systems, and also in assessing the merits of different irrigation schedules.

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