EVALUATION OF IRRIGATION EFFICIENCY IN THE SWAZILAND SUGAR INDUSTRY

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Abstract

Sugarcane is fully irrigated in Swaziland but there is little quantitative information about the field performance of irrigation systems in the sugar industry. This paper reports on the results of a programme to evaluate irrigation efficiency on commercial sugarcane farms. Internationally recognized procedures were adapted for local conditions and used to measure irrigation system performance. This was assessed in terms of the ability of the system to meet crop water requirements uniformly and to apply water efficiently. Application efficiencies of 72 to 89% were achieved under drip and centre pivot systems and efficiencies of 49 to 88% and 48 to 75% for dragline and furrow systems, respectively. The results reported in this paper highlight the value of evaluating the performance of irrigation systems as an integral part of effective irrigation management.

Introduction

Increasing demand for irrigation water in Swaziland and rising sugarcane production costs have underlined the need to use water efficiently. Under a new Water Act soon to be enacted, growers will be allocated a specified volume of water per year and will be required to measure and report the amount of water used to river basin authorities. They may also have to pay for the right to use irrigation water. With these proposed changes, there was an urgent need to quantify the efficiency of pumping, conveying, distributing and applying water to sugarcane fields. The Swaziland Sugar Industry initiated an irrigation programme to assist growers to use water more efficiently by providing information on appropriate irrigation methods, water measurement, irrigation system performance and the economics of irrigating sugarcane.

In the design and management of irrigation systems, efficient irrigation and maximum water use efficiency have become critical operational goals. Incorrect irrigation system design, installation or management could be the reason for irrigation inefficiency. By quantifying performance of irrigation methods, guidelines could be developed to improve their design and management. This paper reports on the evaluation of on-farm irrigation efficiency, which is part of a programme to improve water-use efficiency. The approach adopted was to determine the amount of water applied and the application uniformity during selected irrigation events using internationally recognized evaluation procedures. This information was used to determine the fraction of water delivered to the field that is stored in the root zone to meet sugarcane water requirements. Maximizing the fraction of water productively used by the crop was considered to be a first step towards the goal of increasing sugar yield per unit of water and maximizing the economic return on capital invested in irrigation systems.

Irrigation system evaluation

The major objectives of an evaluation were to determine how much water reached the crop, how uniformly it was distributed, and how much was lost during the application process. By using this approach the amount of water made available for use by the crop could be calculated. Determining where and how losses of water occur assists in scheme design, e.g. to determine furrow length, sprinkler spacing or centre pivot size.

Performance was quantified in terms of satisfying a target amount, defined either as the soil moisture deficit at the time of irrigation or the amount of water used by the crop since the previous irrigation. Evaluation procedures assumed that full irrigation with a high uniformity of application was the desired goal. Detailed procedures and instrumentation for conducting field measurements are available in the American Society of Agricultural Engineers (ASAE) Standards (1998) and evaluation manuals (e.g. Merriam and Keller, 1978).

Table 1. Measurements recorded during irrigation evaluations.

Dragline (Merriam, 1968)	**Centre pivot** (Heermann, 1990)	**Furrow** (Walker, 1989)	**Drip** (ASAE, 1998)
Duration of irrigation Sprinkler spacing Nozzle size Sprinkler flow rate Pump pressure Pressure at the nozzles and along laterals Amount of water caught in catch cans	Flow rate Amount of water caught in a radial row of catch cans Distance from pivot to each can Travel speed of end drive unit Lateral length to end drive unit Effective radius irrigated Width of the wetted strip of the end drive unit Operating pressure	Furrow inflow Furrow geometry Furrow length Depth of flow Advance times Furrow slope Recession time Runoff hydrograph	Emitter spacing Dripperline spacing Emitter discharge Pressure at selected points System discharge Area irrigated Pressure losses at filters.

Methods

Application efficiency (E_a), uniformity and adequacy were adopted as indices to assess the operational performance of irrigation systems (Walker, 1989), where E_a is the amount of water stored in root zone divided by amount applied. Formulae for the performance measures are given in the Appendix. Performance indices measure how well an irrigation application satisfies a desired target amount of water. Storage efficiency (E_s) was used as the measure of adequacy for furrow systems, where E_s is the amount stored in root zone divided by the amount required. The percentage of the irrigated area receiving at least the required amount was used to illustrate adequacy and distribution efficiency of sprinkler and drip systems.

Irrigation systems were evaluated by measuring operating and design parameters during typical irrigation events (Table 1). Prevailing weather conditions (wind speed, humidity, radiation, and temperature) were obtained from nearby weather stations. The program Catch 3D (Allen, 1991) was used to determine the coefficient of uniformity (CU) for dragline systems (Christiansen 1942). The adjusted CU (Heermann and Hein, 1968) was used to measure the uniformity of application of centre pivots.

For furrow irrigation, data required for determining infiltration characteristics of the soils were collected in the field using the evaluation procedure of Walker and Elliot (1982). The furrow simulation program SIRMOD (Walker, 1998) was used to calculate infiltration parameters using the field data and to assess the potential for improving performance. The distribution uniformity (DU) (Walker, 1989) was used to assess the uniformity of furrow irrigation. For drip systems, statistical uniformity (U_s) of emitter flow rates was used to measure application uniformity (ASAE, 1998).

Results and discussion

Dragline systems

Results from 19 dragline fields, obtained with existing design parameters (18x18m and 20x18m spacings with 4.76mm nozzles), under moderate wind conditions (2 to 4 m/s), show a range in coefficients of uniformity from 65% to 88% (Table 2). Evaporation losses were calculated using wind speed, evapotranspiration and sprinkler spray characteristics (Keller and Bliesner, 1990) and ranged from 4% to 12%. The other unaccounted water losses could be attributed to wind drift and water falling on ungauged areas. There was a wide range of application efficiencies (49% to 88%) in comparison to the perceived efficiency of 75%. The average application efficiency of 66% was well below the design value of 75%, confirming findings by Simpson and Reinders (1999), who reported a mean application efficiency for dragline sprinklers over a period of eighteen months of 69.2%. Wind distortions, wide sprinkler spacings, low pressures and unequal stand-times all contribute to the poor performance of dragline systems.

Table 2. Performance parameters for 19 dragline irrigation events

Event	**1**	**2**	**3**	**4**	**5**	**6**	**7**
CU	75	77	73	77	76	71	76
E_a	75	60	59	80	53	65	74

Event	**8**	**9**	**10**	**11**	**12**	**13**	**14**
CU	70	81	85	80	77	88	81
E_a	87	57	70	63	56	72	64

Event	**15**	**16**	**17**	**18**	**19**
CU	79	88	83	65	74
E_a	58	80	49	63	64

CU= Coefficient of uniformity
Ea = Application efficiency

Figure 1 shows a cumulative frequency distribution for a dragline sprinkler field in which measured amounts were ranked in descending order and the percentage of the field receiving at least a given amount was determined. Given a target amount of 32mm, 55% of the field was adequately irrigated whilst 45% was under-irrigated by varying amounts.

The application efficiency was 64% with an average application of 43mm and coefficient of uniformity of 74%. Actual application efficiency for each irrigation is therefore directly related to the uniformity, target amount, wind drift, evaporation losses and average amount of water applied. The distribution pattern of water under sprinkler irrigation can vary for the same coefficient of uniformity. This variation will affect water application efficiency and the percentage of the field adequately irrigated. Under-irrigation of significant portions of the field was observed on all fields with a CU less than 80%. For the lowest measured coefficient of uniformity of 65% the entire area was under-irrigated. These results indicate that most dragline systems do not meet the evapotranspiration needs of the crop in the under-irrigated areas during the designed irrigation interval because of poor uniformity, particularly on shallow soils. On deep soils, the effect of non-uniform application of water and under-irrigation is minimized by soil moisture stored during early stages of sugarcane growth when water requirements are low. In terms of meeting water requirements throughout the sugarcane growth cycle, the design of dragline systems limits the achievement of optimum yields and high water use efficiency.

Centre pivot systems

Table 3 shows irrigation performance parameters for eight centre pivots. The results consistently show the ability of centre

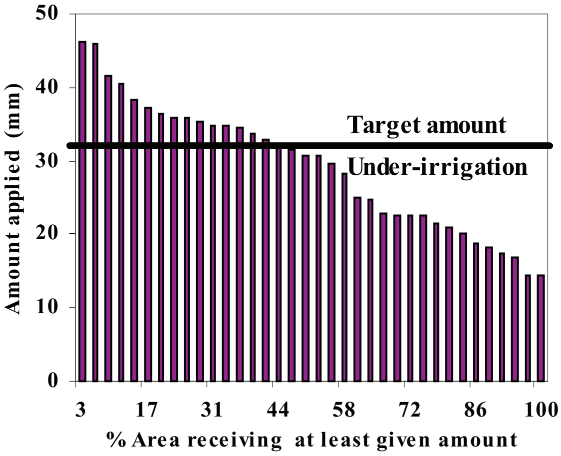

Figure 1. Cumulative water distribution for an 18 x 18m dragline system. Target application = 32mm, CU = 74% and application efficiency = 64%.

pivot systems to achieve high uniformity of application with CU's ranging from 76 to 91%. The composite CU of well-designed centre pivot systems should range from 90% to 94% (Keller and Bliesner, 1990). Of the eight centre pivots only one performed well below its potential with a CU of 76% and application efficiency of 72% because of low operating pressure. Calculated evaporation and wind drift losses ranged from 4 to 8% over wind speeds experienced during the evaluations (< 4m/s).

The cumulative distribution of applied amounts in a centre pivot field show that 90% of the field received at least the required amount of water and only a small area was under-irrigated (Figure 2). This under-irrigated area received at least 75% of the target amount and for practical purposes could be considered adequately irrigated. Run-off losses were not measured and application efficiencies (Table 3) were estimated using the coefficient of uniformity and a wind loss factor calculated from wind speed and evaporation data (Keller and Bliesner, 1990). The application efficiencies in Table 3 represent the maximum attainable efficiency assuming at least 80% of the field received the required amount of water or more without any run-off.

Evaluation procedures assume that the water infiltrates at the point where it lands on the soil surface. This may not be true if the application rate exceeds the soil infiltration rate resulting in run-off and surface redistribution as was observed on some of the pivots. Thus, run-off decreases the uniformity of distribution resulting in the actual uniformity in the soil and application efficiencies being lower than those calculated. Important considerations for optimization of centre pivot performance were identified as design of the system to match field conditions, selection of the correct application amount, proper irrigation scheduling and awareness by operators of the importance of these factors. Centre pivot evaluation results support the present trend towards installing centre pivots to improve water use efficiency.

Table 3. Performance parameters of eight centre pivots.

Pivot No	Uniformity (CU) %	Application Efficiency (E_a) %
1	90	85
2	90	85
3	90	85
4	91	86
5	85	80
6	85	80
7	89	84
8	76	72

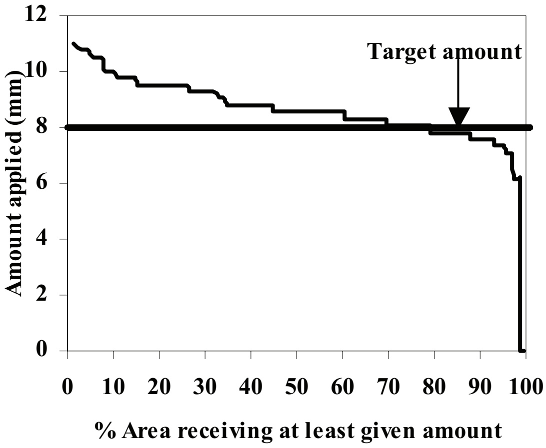

Figure 2. Cumulative water distribution for a 508m centre pivot. Target application = 8mm, CU = 90% and application efficiency = 85%.

Furrow irrigation

Evaluations on seven commercial fields show a wide range of operating and design parameters (length, furrow in-flow, slope, cut-off time) (Table 4). It was necessary, therefore to determine combinations of these variables that maximize application efficiency for a given field. Computer programs such as SIRMOD could be used to carry out this analysis and determine best combinations for each field.

Application efficiencies in inter-row furrow irrigation (water flowing between cane rows) ranged from 70% to 75% (Table 4). SIRMOD simulations of evaluated inter-row irrigation events confirmed that a 70% level of efficiency is readily attainable on duplex soils provided the water supply is reliable (hydraulically constant). For the two in-row furrow irrigation events (water flowing in the cane row), application efficiencies were 48% and 57% respectively showing that this type of furrow irrigation is inefficient. Simulation of in-row irrigation events (Table 4, events 5 and 7) indicated that application efficiencies were limited to 55% to 65% over a wide range of parameter variations on commercial fields. This is mainly attributable to increased resistance to water flow by the crop plants. The overriding effect of soil infiltration rate on furrow irrigation performance was found to be a major limitation.

The results of furrow irrigation trials conducted on duplex soils were analyzed to determine the most appropriate furrow inflow rates ([1]Ndlovu and Gama, provided the data in a personal communication) and efficiencies similar to those obtained during the evaluations were obtained (Table 5). The trials were conducted on furrows 175m long with a slope of 0.4%. The target application amount was 50mm in all the irrigation events and seasonal application efficiencies in second and fourth ratoon sugarcane crops ranged from 61% to 87% for the different furrow inflows (Table5). Measured runoff losses for both the seven evaluations and the seasonal trials ranged from 4 to 16%, which indicates that run-off losses can be minimized with correct design and operation. The unaccounted water losses are attributable to deep percolation below the root zone.

The results in Tables 4 and 5 and SIRMOD simulations show that furrow irrigation can achieve high efficiencies on duplex and other heavy clay soils. This is because these soils have very little deep drainage and run-off losses could be minimized. Efficient furrow irrigation strategies involve monitoring and adjustment of variables such as soil moisture deficit, furrow inflow and application time. Factors limiting the achievement of high application efficiencies were identified as lack of flow measuring devices, the practice of refilling the soil profile at each irrigation, variable tertiary canal flow rates and furrow lengths dictated by field dimensions and harvesting requirements. Most existing systems would have to be re-designed to improve control and reliability of flow rates. There will always

Table 4. Performance parameters of seven furrow irrigation events.

Event No.	Length (m)	Inflow (l/s)	Cut-off time (min)	Application Efficiency (E_a) %	Distribution Uniformity (DU) %	Storage Efficiency (E_s) %
1	258	4.7	33	70	93	100
2	356	5.3	40	70	97	100
3	300	3.7	55	74	89	100
4	175	2.3	132	72	77	100
5	200	3.5	129	57*	81	100
6	240	4.5	90	75	84	100
7	240	4.5	170	48*	67	100

* In-row furrow irrigation events

Table 5. Results of furrow irrigation trials [1].

	4th Ratoon			2nd Ratoon		
Furrow inflow l/s	Application efficiency %	Storage Efficiency %	Runoff %	Application Efficiency %	Storage Efficiency %	Runoff %
2.3	76	100	12	63%	100	9
2.7	86	98	15	87%	100	12
2.3	84	99	16	77%	100	15
6.7	61	100	11	61%	100	11

[1] Furrow irrigation trials to determine the most appropriate furrow inflow rate on duplex soils. 1994-1998. Mhlume (Swaziland) Sugar Company.

be conflict between furrow irrigation practices that maximize application efficiency and those that maximize storage efficiency.

Drip irrigation

Evaluation of 27 drip irrigation laterals in nine fields, revealed that some drip irrigation systems are operating well below their potential (Table 6).

The performance typical of a new, or well-maintained drip irrigation system is shown in Figure 3. It illustrates the water distribution with no emitter clogging and statistical uniformity of application from the emitters of 90%, resulting in an application efficiency of 89%. The area receiving at least the required amount of water was 90%. In contrast, Figure 4 shows the water distribution for a system where 6% of the emitters were clogged and statistical uniformity was 63%. All the water applied was stored in the root zone, resulting in application efficiency of 100% because 90% of the field was under-irrigated. This illustrates the limitation of application efficiency

Table 6. Statistical uniformity (Us) for 27 drip laterals.

Field No	**Statistical Uniformity %**			**Average (%)**
	Lateral No			
	1	**2**	**3**	
1	84	80	73	79
2	60	60	63	62
3	83	83	90	85
4	79	68	85	77
5	70	73	43	62
6	60	74	89	74
7	65	73	73	70
8	40	70	31	49
9	79	71	73	74

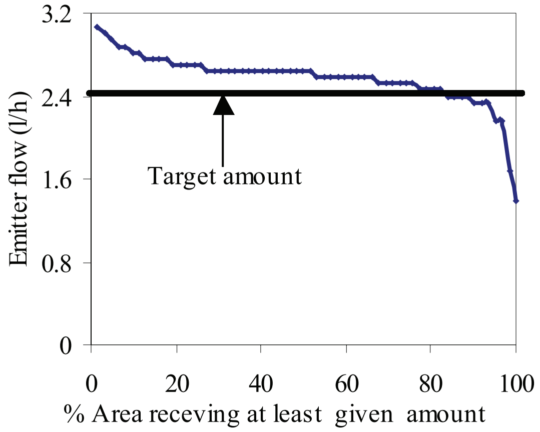

Figure 3. Drip system water distribution with no emitters clogged. Target application = 2.4 l/h, lateral length = 63m, Us = 90% and application efficiency = 89%.

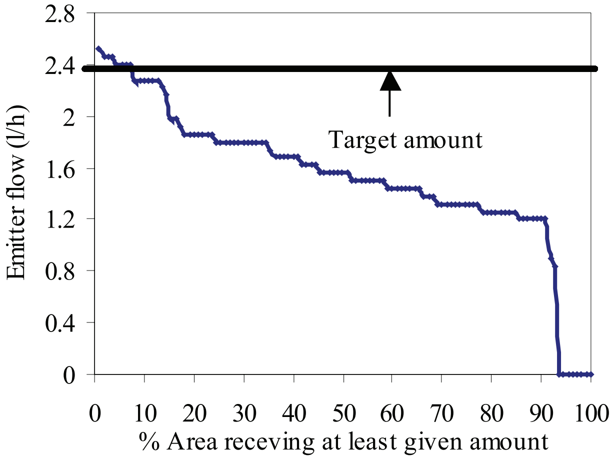

Figure 4. Drip system water distribution with 6% of emitters clogged. Target application = 2.4l/h, lateral length = 110m, Us = 63% and application efficiency = 100%.

as the only measure of irrigation system performance because it does not show the uniformity of distribution or the percentage of the area that was adequately irrigated. Statistical uniformity represents a measure of the potential for improving a drip system. It is also an estimate of the application efficiency and the ability of the system to satisfy crop water requirements throughout the field. These results underline the importance of a structured maintenance programme and performance monitoring to sustain high uniformity in drip systems.

Conclusions

- All the irrigation systems that were studied could be used to apply water efficiently if they were correctly designed and installed. The design should include all structures and other devices necessary for controlling the distribution and application of water and should match the system to the soils and topography of the farm.
- Application efficiency, uniformity and adequacy constitute a complete set of measures for assessing irrigation system performance. Application efficiency can be 100% when an irrigation event does not meet the target application amount, but this can be misleading because under these circumstances, application efficiency does not adequately describe the effectiveness of an irrigation.
- Uniformity of water application is the key to high application efficiency in all irrigation methods. Poor uniformity results in low water application efficiency if the field is adequately irrigated.
- The amount of water applied in each irrigation should not exceed the storage capacity of the soil at the time of irrigation because this will override all other factors affecting irrigation efficiency.
- Great care should be taken with the management of all water application methods. Poor uniformity and water losses arise from operating sprinklers at pressures lower or greater than recommended. Excessive run-off may result from centre pivot systems if application amounts are not matched to soil infiltration rates. Over-irrigation may result from operating furrow systems with inadequate flow rate or drip systems operated for times longer than required.
- Efficient furrow irrigation requires a high level of operating skills, land levelling and reliability in canal flow rates that cannot be achieved without redesign and installation of water measuring devices on existing systems. Soil infiltration rate is a major factor affecting application efficiency and uniformity on more permeable soils. Computer models such as SIRMOD are valuable tools for identifying correct design and operating parameters that maximize application efficiency.
- Inherent disadvantages of dragline systems are wide sprinkler spacing, pressure variations and susceptibility to wind which lead to poor uniformity and under-irrigation of significant portions of the field.
- Drip and centre pivot systems can be more easily operated (although not always) with high efficiency and uniformity. These systems easily achieve water use efficiencies of at least 80% if they are properly designed and managed and accurately match the amount of water applied to crop water requirements throughout the growing season.
- The results of the evaluations reported in this paper confirm that the trend towards installing centre pivot and drip irrigation systems should increase water use efficiency in the sugar industry.

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APPENDIX

Formulae for performance parameters

1. Application efficiency (E_a) $= 100 \times \frac{\text{Amount of water added to rootzone}}{\text{Amount of water applied}}$

2. Storage efficiency (E_s) $= 100 \times \frac{\text{Amount of water added to rootzone}}{\text{Amount required}}$

3. Coefficient of uniformity (CU)

$$CU = 100\left(1 - \frac{\text{Average deviation from the average amount caught}}{\text{Average amount caught}}\right)$$

4. Centre pivot application uniformity CU_H

$$CU_H = 100(1-[\{aS*\text{Absolute}(D-m)\}/aDS])$$

Where

CU_H = coefficient of uniformity for centre pivots
S = the distance from the pivot point
D = the depth of the catch can at S
m = weighted mean = aDS/aS
a indicates that all measured depths are summed

5. Distribution uniformity (DU)

$$DU = 100 \times \frac{\text{Average of low quarter application depth}}{\text{Average application depth}}$$

6. Statistical Uniformity (U_s)

$$U_s = 100(1 - CV)$$

Where

CV = coefficient of variation of emitter flow rates

$$CV = \frac{\text{Standard deviation of emitter flow rates}}{\text{Mean emitter flow rate}}$$