A MODEL FOR THE EVALUATION OF IRRIGATION AND WATER MANAGEMENT SYSTEMS IN THE LOWVELD OF ZIMBABWE: MODEL DEVELOPMENT AND VERIFICATION

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Abstract

In order to assess the performance of water management procedures and irrigation systems used in the sugar industry in the Lowveld of Zimbabwe, a sugarcane yield and irrigation systems simulation model was developed. The model was used to predict how field derived 'Irrigation Engineering Performance Indices' (IEPIs) of irrigation systems performance, such as the coefficient of uniformity, CU, impacted crop yields and water budgets. This enabled the impacts of the IEPIs on irrigation efficiency and water productivity to be determined in relation to soils, climate, irrigation system type and irrigation scheduling strategy. In this paper the development of the systems simulation model is described. Results of a verification study of the model showed an index of agreement, 'd', of 0.96 between observed and simulated relative Estimated Recoverable Crystal (ERC) yields. This is very close to a value of 1.0, which would indicate perfect agreement between observed and simulated relative ERC yields. The root mean squared error was 0.056, indicating that on average the predicted relative yields were within 6% of the observed relative yields. The model was prone to slight overestimation of yield declines caused by mild soil water stressing and slight underestimation of the yield declines caused by more severe soil water stressing. The correlation coefficient (Pearson's r) of 0.94, nevertheless indicated a very high degree of correspondence between the observed and simulated relative yields. Application of the model is presented in a companion paper.

Keywords: sugarcane, modelling, ZIMsched, ZIMsched 2.0, irrigation, efficiency, yield

Introduction

Many questions were being asked about the performance of the various irrigation and water management systems being used by sugarcane growers in the Lowveld of Zimbabwe. Each type of irrigation system has different characteristics which make it more or less suitable under different circumstances. The water management approaches that were in place were also not necessarily well suited to all the different types of irrigation hardware or circumstances. The sugar industry has already nearly collapsed as a result of crippling water shortages following the 1991/2 drought (Binnie and Partners,1993; Kaseke, 1998). Therefore, to help ensure the long term viability of the industry, increased insight into the performance of the various water management and irrigation systems was needed, together with the development and adoption of strategies to improve performance.

The approach adopted to evaluate the performance of irrigation systems in the Lowveld was as follows.

- Tools and methods to record infield irrigation systems performance data were developed and applied.
- The infield performance data /information recorded or measured in (i) were used to calculate ‘Irrigation Engineering Performance Indices’ (IEPIs) of irrigation systems performance. An example of an IEPI is the coefficient of uniformity, CU, which gives an indication of the distribution uniformity of applied water.
- A sugarcane yield and irrigation systems simulation model was developed and used to predict how the field-derived IEPIs impacted potential crop yields and water budgets, taking into consideration the characteristics of different irrigation systems and water management strategies prevailing in the Lowveld.

The approach hinged on the development and verification of a systems simulation model. In this paper a description of the model and the results of a verification study are presented. Application of the model is presented in a companion paper (Lecler, 2003).

Methodology

The spreadsheet-based irrigation scheduling and crop yield forecasting tool *ZIMsched* (Lecler, 2000), was refined to a deterministic crop and irrigation systems simulation model, *ZIMsched 2.0*. The refinements to the *ZIMsched 2.0* model were developed in order to estimate how water management, different irrigation system characteristics and the infield measures of irrigation systems performance indices derived by the Mobile Irrigation Performance Unit (MIPU) impacted on potential crop yields, irrigation water requirements and water losses. The evaluation procedures used by the MIPU are summarised in Griffiths and Lecler (2001). The main refinements to the original *ZIMsched* model developed by Lecler (2000) and their validity is described here.

Evaporation from the soil and plant (transpiration)

In *ZIMsched 2.0*, evaporation from the soil and the crop were determined separately, based largely on the algorithms described in the Food and Agriculture Organisation of the United Nations (FAO) Irrigation and Drainage Paper No. 56, by Allen *et al.* (1998). It was very important to separate these processes because prior to the development of significant canopy cover, water losses are dominated by evaporation from the soil surface. This evaporative loss can be very variable because different types of irrigation systems wet different fractions of the soil and there are also variations in wetting frequencies. Effective early season water losses and associated crop coefficients can thus vary significantly, depending on the type of irrigation system and its operation.

The main modification to the algorithms given in FAO 56 (Allen *et al*., 1998) involved the incorporation of a relationship between the rate of canopy development and thermal time (cf. Lecler, 2000), and small refinements to the procedures used to calculate the soil surface water evaporation coefficient (K_e). The rate of canopy development is mainly dependent on temperature and therefore the concept of relating canopy development to thermal time is superior to relating it to calendar days. This is because variations in the rate of canopy development that are associated with different planting/ratooning times (early, mid, late season), and seasonal temperature variations can be automatically accounted for.

The FAO 56 coefficient, $K_{e,}$ describes the potential evaporation of water from the soil surface, which can be assumed to take place in two stages. In the first stage, when the topsoil is wet following irrigation or rainfall, K_e is maximal.

In the second stage, after a certain amount of water has evaporated, the soil surface is drier and K_e reduces, eventually reaching zero when there is minimal water near the soil surface for evaporation (Allen *et al*., 1998).

In FAO 56 the effects of shading are accounted for through the fraction of the soil surface covered by vegetation, f_c. In *ZIMsched 2.0,* f_c is determined using thermal time (TT), as given in Equation 1:

$$f_c = Grd_{ini} \qquad \text{for} \qquad TT_A < 340 \qquad (1)$$

$$f_c = \max(Grd_{ini}, \min(0.99,((TT-340)/(1000-340))0.99) \qquad \text{for} \qquad TT_A > 340$$

where

Grd_{ini} = initial ground cover, e.g. due to surface mulching (1)

TT_A = accumulated thermal time (degree days)

= $(T_{max} + T_{min})/2 - 12$ºC

T_{max} = daily maximum temperature (ºC)

T_{min} = daily minimum temperature (ºC)

where 'max' and 'min' select the maximum or minimum of the terms in brackets which are separated by commas. The numerical values '340' and '1000' were based on analysis of leaf area index (LAI) versus thermal time ([1]unpublished data).

Determination of K_e requires a daily water balance computation in order to calculate the cumulative depletion, D_e, for the surface layer from a wet condition. In *ZIMsched 2.0* the depth of the surface layer was taken as 0.1 m. The daily soil water balance equation for the exposed and wetted soil fraction, $f_{ew,}$ of the surface layer (Allen *et al*., 1998) is:

$$D_{e,i} = D_{e,i-1} - (P_i - RO_i) - I_i/f_w + E_i/f_{ew} + T_{ew,i} + DP_{e,i} \qquad (2)$$

where

$D_{e,i-1}$ = cumulative depth of evaporation following complete wetting from the exposed and wetted fraction of the topsoil at the end of day i-1 (mm)

$D_{e\,i}$ = cumulative depth of evaporation following complete wetting from the exposed and wetted fraction of the topsoil at the end of day i (mm)

P_i = rainfall on day i (mm)

RO_i = stormflow/runoff from the soil surface on day i (mm)

I_i = irrigation depth on day i that infiltrates the soil (mm)

E_i = evaporation from the soil surface on day i (mm)

$T_{ew,i}$ = depth of transpiration from the exposed and wetted soil surface layer on day i (mm)

$DP_{e,i}$ = deep percolation from the topsoil layer on day i if soil water content exceeds field capacity (mm) (Note: for the determination of K_e, $DP_{e,i}$ is always assumed equal to zero as although the surface layer may be draining, in such a state the surface will likely be wet and evaporation from the surface uninhibited)

f_w = fraction of the soil surface wetted by irrigation (0.01 - 1)

f_{ew} = exposed and wetted soil fraction (0.01 - 1)

with limits $0.\ D_{e,i}.\ TEW$

$TEW = 1000(2_{dul} - 0.52_{pwp})\ Z_e$

where

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[1] Data collected by Haslem at the Zimbabwe Sugar Association Experiment Station, P/Bag 7006, Chiredzi, Zimbabwe.

TEW = total evaporable water from the top soil (mm)
2_{dul} = soil water content at the drained upper limit (field capacity) (m^3/m^3)
2_{pwp} = soil water content at permanent wilting point (m^3/m^3)
Z_e = depth of the surface soil layer that is subject to drying by way of evaporation, taken as 0.1 m in *ZIMsched 2.0.*

Use of Equation 2 is simplified in FAO 56 where it is assumed that all water infiltrates, i.e. zero runoff (RO) and that transpiration from the surface layer that contributes to E_i is negligible.

In *ZIMsched 2.0*, however:

- stormflow/RO is not assumed to be zero, but is calculated using the modified SCS stormflow equation (Schulze, 1995).
- transpiration, (T_{ew}), from the soil layer contributing to E_i is also not assumed to be zero. The proportion of the actual transpiration for a day that is extracted from the topsoil layer is given in Equation 3:

$$F_{T,\,i} = \max(0,\ 0.1/(R_{fac}.S_{dep}).(TAM_{10} - D_{e,\,i-1})/TAM_{10}) \qquad (3)$$

where
$F_{T,\,i}$ = fraction of actual transpiration on day i that is extracted from the topsoil layer
R_{fac} = proportion of total soil depth that is penetrated by roots
= 0.4 for $TT_A < 340$
= min(1, 0.6(TT_A-340)/(980-340) + 0.4) for $TT_{A,}$ 340
Note: it is assumed that maximum rooting depth coincides with the development of full canopy cover (Jensen *et al.*, 1990)
TT_A = accumulated thermal time (degree days)
S_{dep} = total soil depth (m)
TAM_{10} = Total available water in the topsoil layer of 0.1 m, viz. ($□_{dul}$ - $□_{pwp}$)0.1
2_{dul} = soil water content at the drained upper limit (field capacity) (m^3/m^3)
2_{pwp} = soil water content at permanent wilting point (m^3/m^3)
$D_{e,\,i-1}$ = cumulative depth of evaporation following complete wetting from the exposed and wetted fraction of the topsoil at the end of day i-1 (mm)

Thus, based mainly on the algorithms given in FAO 56, the evaporation losses associated with different types of irrigation systems, the effects of planting/ratooning in different months and the effects of hot or cold intra-seasonal conditions on the rate of canopy development and associated water use were accounted for in *ZIMsched 2.0*.

Atmospheric Evaporative Demand (AED)

ZIMsched 2.0 uses the evaporation measured using a class A-pan to represent AED. In Zimbabwe, most of the research involving sugarcane crop water use has been undertaken using the evaporation from A-pans as the reference evaporation (Nyati, 1996). Nevertheless, the correlation between the evaporation from an A-pan and the evaporation from a cropped surface can be markedly different in summer and winter, and also under advective conditions or when there are wide variations in wind and humidity (Allen *et al.*, 1998).

For this reason, relationships between:

- the FAO Penman-Monteith reference evaporation,
- evaporation from a class A-pan, and

- evaporation from a relatively simple atmometer device (Asbell, 1999) that may better represent a plant,

were investigated for possible incorporation into *ZIMsched 2.0*. However, Lecler (2001a) showed that there was very little difference between using A-pan data with appropriate pan factors and the Penman-Monteith equation with data from an automatic weather station (AWS), especially when the data is averaged over a five day period, which is equivalent to a typical irrigation cycle. As the data from the AWS were only collected beginning in 1998, A-pan data were used as the default option in *ZIMsched 2.0.*

Rooting characteristics

In *ZIMsched 2.0*, the root zone which delimits the volume of soil from which water is available to the crop is dynamic in order to account for root growth. The depth of the zone from which water uptake can occur, R_z, is calculated by assuming that maximum rooting depth coincides with the development of full canopy (cf. Jensen *et al*., 1990), which in *ZIMsched 2.0* is predicted from a relationship with TT:

$$R_z = R_{fac} \,.\, TAM \qquad (4)$$

where

R_{fac} = proportion of total soil depth that is penetrated by roots

= 0.4 for $TT_A < 340$

= min(1, 0.6(TT-340)/(980-340) + 0.4) for $TT_{A.}340$

TT_A = accumulated thermal time

Transpiration under conditions of soil water stress, runoff, drainage and effective rainfall

The procedures used in *ZIMsched 2.0* for the calculation of:

- transpiration if the soils are too wet or too dry,
- surface runoff (or stormflow),
- drainage or deep percolation, and
- effective rainfall,

were unchanged from the algorithms used in the original crop yield and irrigation scheduling tool, *ZIMsched.* These procedures are described by Lecler (2000).

Crop yield estimate

The estimated recoverable crystal (ERC) estimate in *ZIMsched 2.0* is based on a robust relationship between actual evapotranspiration (ET) and tons sucrose as derived by Thompson (1976) using data from Hawaii, Australia, Mauritius, Mount Edgecombe, Shakaskraal and Pongola. *ZIMsched 2.0*'s estimate of potential transpiration is used in a modified form of Thompson's (1976) sucrose versus ET relationship to derive an estimate of potential ERC for a given season. This potential ERC is then further modified according to the timing and magnitude of water stress according to procedures based on research reported on by Doorenbos and Kassam (1979).

In order to quantify the effects of soil water stress on crop yields, Doorenbos and Kassam (1979) used a function relating the relative yield decrease to the relative deficit of total evaporation (i.e. actual evapotranspiration). This relationship is given below as Equation 5:

$$(1-Y_a/Y_p) = K_y(1-E/E_m) \qquad (5)$$

where:

Y_a = actual harvested yield of a given crop (t)

Y_p = potential non-water-stressed harvested yield of a given crop (t)
E = actual total evaporation (i.e. $E_t + E_s$, mm)
E_m = maximum evaporation (i.e. $E_{tm} + E_s$, mm)
E_t = actual evaporation from the plant tissue, i.e. actual transpiration (mm)
E_{tm} = maximum evaporation from the plant tissue, i.e. maximum transpiration (mm)
E_s = evaporation from the soil surface (mm)
K_y = growth stage specific yield response factor

The response of yield to water supply is quantified through the yield response factor, K_y, which relates the relative decrease in yield, $(1-Y_a/Y_p)$, to a relative deficit in total evaporation $(1-E/E_m)$. The K_y values for most crops were derived on the assumption that the relationship between relative yield (Y_a/Y_p) and relative total evaporation (E/E_m) is linear and is valid for water deficits of up to approximately 50%, i.e. $(1-E/E_m) = 0.5$. According to de Jager (1994), concerns about the transferability of the yield function given in Equation 5 can be obviated through the use of transpiration ratios (i.e. E_t/E_{tm}) in the place of total evaporation ratios (i.e. E/E_m). In Equation 6, the influences of atmospheric vapour pressure deficits and climate-crop architecture on E_t/E_{tm} and hence Y_a/Y_p cancel out (de Jager, 1994). Hence the yield response factor, K_y, defined in Equation 6 becomes a purely plant physiological entity and is thus determined by crop genetics and not climate. The K_y factor should thus be neither site nor climate specific (de Jager, 1994).

$$Y_a/Y_b = \prod_{i=1}^{i=G} [\, 1 - K_{yi}(1 - E_t/E_{tm})] \qquad (6)$$

where:
i = i-th growth stage in a growing season with a total of G growth periods
K_{yi} = yield response factor for the i-th growth period

de Jager (1994) tested a range of wheat yield functions, including Equation 6, using the water budgeting algorithms of the PUTU model to calculate E_t and E_{tm}. Results of these tests showed that using a yield function based on Equation 6 with values for K_{yi} for wheat taken from Doorenbos and Kassam (1979), was the most accurate of the various different yield functions tested and that the accuracy was very acceptable for use in decision support applications.

Based on research by, *inter alia*, Doorenbos and Kassam (1979) and de Jager (1994), and a comparison between observed and simulated yields and water use, Equation 6 was adopted as an option for estimating ERC yields in *ZIMsched 2.0*. The overall growing season yield response factor (K_y) of 1.2 proposed by Doorenbos and Kassam (1979) is used in *ZIMsched 2.0* up until the ripening period (taken as 56 days before cutting), after which a K_y value of -0.01 was used. The yield response factor for the final growth period (ripening) was changed to -0.01 from the value of 0.1 proposed by Doorenbos and Kassam (1979) based on analysis of the results from the dry-off trials undertaken in Zimbabwe which showed that stress in this ripening period can have a very mild beneficial effect on ERC (Lecler, 2001b).

Irrigation systems uniformity

To account for the effects of irrigation uniformity on systems performance, the water budget and yield estimate in *ZIMsched 2.0* was based on the average of three equal areas each receiving different amounts of water at each irrigation application. The simulated amount of water on each of the three areas was varied, dependent on the uniformity measure of the irrigation system.

One third of the area was simulated to receive the mean irrigation water application, one third received the mean water application plus a percentage ($D_{\%}$) of the mean and one third received the mean minus a percentage ($D_{\%}$) of the mean.

Assuming normally distributed irrigation water applications, Equations 7, 8 and 9 were derived to relate the percentage deviation ($D_{\%}$) corresponding to a given coefficient of uniformity (CU), statistical uniformity (SU) or distribution uniformity (DU) respectively. For example, if the mean application for a furrow irrigation event is 50 mm, and the DU was equal to 60, one third of the area would receive an average of 50 mm, one third would receive an average of 69 mm and one third would receive an average of 31 mm at each irrigation water application.

$$D_{\%} = 96.48 - 96.50.(DU/100) \quad (7)$$

$$D_{\%} = 122.49 - 122.49.(SU/100) \quad (8)$$

$$D_{\%} = 149.97 - 149.96.(CU/100) \quad (9)$$

where

$D_{\%}$ = percentage of mean application to be added and subtracted from the mean to determine irrigation application amounts

DU = Distribution Uniformity

SU = Statistical Uniformity

CU = Christiansen's Coefficient of Uniformity

With these refinements incorporated into *ZIMsched 2.0* and the facility for estimating ERC yields, it had potential to be used to plan, design and evaluate, *inter alia*, irrigation strategies, taking into account the effects of different water application targets, scheduling practices, irrigation systems and irrigation systems performance measures on crop production, using commonly available data/information. However, the credibility of the model for Lowveld conditions still needed to be established. Verification of *ZIMsched 2.0* for a range of soil, weather and irrigation watering conditions in the Lowveld of Zimbabwe, is the subject of the next section.

Results

Although *ZIMsched 2.0* was based on robust, internationally proven water budgeting and crop yield algorithms, verification of the performance of these algorithms for predicting differences in ERC yields for different types of irrigation systems and watering strategies was needed to demonstrate the model's credibility. A sound model should give accurate predictions of relative sugar yield for different soils, wet and/or dry seasons, and for different watering/irrigation scheduling regimes. Data from two trials stored in the Zimbabwe Sugar Association Experiment Station (ZSAES) trial archives, covering a range of conditions, provided an ideal data set for the verification of *ZIMsched 2.0* and are described here.

Trial 4200/1

Trial 4200/1 was an irrigation trial initiated at ZSAES by Dr J Gosnell. The trial was planted in 1966 and terminated in 1972. Irrigation water was applied using overhead hand-moved sprinkler irrigation and the cane variety was NCo376. One of the main objectives of the trial was to determine the effect of various irrigation watering regimes on the yields of cane and estimated recoverable crystal (ERC).

The irrigation watering regimes (treatments) used were:

- Treatment 1, pan factor 1.0 - 50 mm of water applied at an accumulated A-pan evaporation of 50 mm

- Treatment 2, pan factor 1.0 in summer and 0.5 in winter - 50 mm of water applied at an accumulated A-pan evaporation of 50 mm in summer, and 50 mm of water applied at an accumulated A-pan evaporation of 100 mm in winter
- Treatment 3, pan factor 0.84 - 50 mm of water applied at an accumulated A-pan evaporation of 59 mm
- Treatment 4, pan factor 0.68 - 50 mm of water applied at an accumulated A-pan evaporation of 73 mm
- Treatment 5, pan factor 0.53 - 50 mm of water applied at an accumulated A-pan evaporation of 94 mm
- Treatment 6, pan factor 0.38 - 50 mm of water applied at an accumulated A-pan evaporation of 133 mm

The soils at the trial site were sandy clay loams with an estimated total available moisture (TAM) of 76 mm. Irrigation and weather data for the plant, first, second and third ratoon crops were obtained from ZSAES and used in *ZIMsched 2.0* to simulate the effects of the various treatments on ERC yields. Rainfall for the seasons simulated ranged from 280 to 600 mm and irrigation applications from 660 to 1778 mm. As the main objective of the verification exercise was to assess *ZIMsched 2.0*'s capability to simulate relative differences between irrigation watering regimes and irrigation systems, the observed and simulated yields were compared in relative terms, i.e. yields for the various treatments were calculated relative to the highest yield from the least stressed treatment, Treatment 1.

Trial 4200/12

Trial 4200/12 was an irrigation trial similar to trial 4200/1; however, the treatments were slightly different, the soils were different, the seasons were different and irrigation was applied using flood beds as opposed to overhead sprinklers. The officer in charge was Mr C Nyati, the trial commenced in 1986 and was terminated in 1991 and the cane variety was NCo376. The object of the trial was to apply various irrigation watering regimes and determine their effect on cane and sugar yields.

The irrigation watering regimes (treatments) were also based on A-pan factors to determine the interval between water applications, and were as follows:

- Treatment 1, pan factor 1.0 - 50 mm of water applied at an accumulated A-pan evaporation of 50 mm
- Treatment 2, pan factor 1.0 - 100 mm of water applied at an accumulated A-pan evaporation of 100 mm
- Treatment 3, pan factor 0.85 - 50 mm of water applied at an accumulated A-pan evaporation of 59 mm
- Treatment 4, pan factor 0.70 - 50 mm of water applied at an accumulated A-pan evaporation of 71 mm
- Treatment 5, pan factor 0.55 - 50 mm of water applied at an accumulated A-pan evaporation of 91 mm
- Treatment 6, pan factor 0.40 - 50 mm of water applied at an accumulated A-pan evaporation of 125 mm

The soils at the trial site were sandy clay loams with an estimated TAM of 100 mm. Irrigation and weather data for the first, second and third ratoon crops were obtained from ZSAES and used in *ZIMsched 2.0* to simulate the effects of the various treatments on ERC yields. Seasonal rainfall for the ratoons simulated ranged from 328 to 728 mm and water applications ranged from 550 to 1750 mm.

A scatter plot of observed and simulated relative ERC yields obtained using data from both trials is shown in Figure 1 and the associated statistics of model performance are given in Table 1.

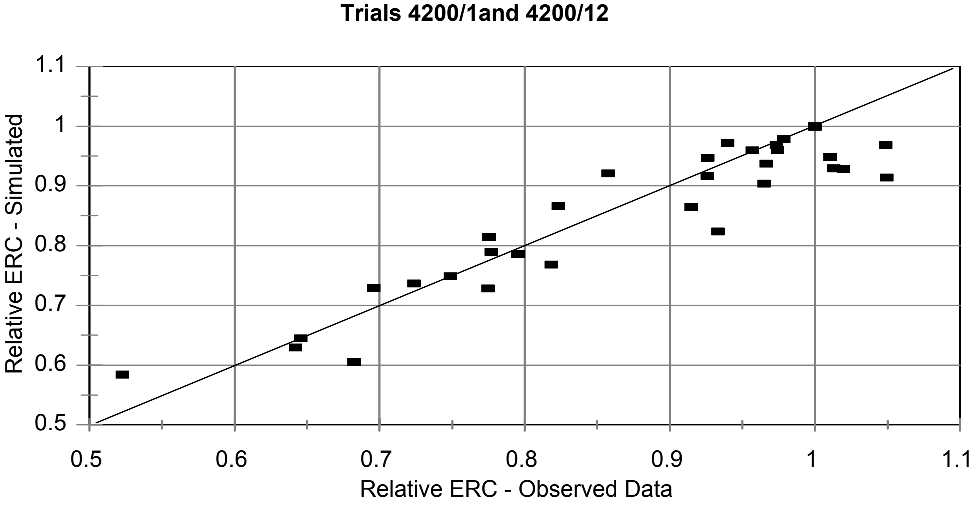

Figure 1. Scatter plot of relative Estimated Recoverable Crystal (ERC) versus simulated ERC showing data obtained from two irrigation trials, Trial 4200/1 (1966-72) and Trial 4200/12 (1986-91) conducted at the Zimbabwe Sugar Association Experiment Station on sugarcane variety NCo376.

Table 1. Quantitative performance measures for comparing simulated relative Estimated Recoverable Crystal (ERC) yields and observed relative ERC yields using data from irrigation trials 4200/1 and 4200/12 combined[1].

O_{mean}	S_{mean}	N	a	b	RMSE	$RMSE_u$	$RMSE_s$	d	r
0.85	0.84	30	0.16	0.80	0.056	0.043	0.036	0.96	0.94

[1] Terms N, b, d and r are dimensionless, while remaining terms represent relative yields in terms of a fraction

O_{mean} = mean of observed relative yields of estimated recoverable crystal (ERC)
S_{mean} = mean of simulated relative yields of ERC
RMSE = root mean squared error
RMSEu and RMSEs = root mean squared errors, unsystematic and systematic, respectively
d = index of agreement, 1.0 indicates perfect agreement, 0.0 indicates no agreement (Wilmott, 1981)
r = correlation coefficient (Pearson's r)
N = number of data points

a (intercept) and b (slope) of a least squares regression between predicted relative yields as the dependent variable and observed relative yields as the independent variable.

The value for the index of agreement, 'd', was 0.96 which is very close to a value of 1.0 which would indicate perfect agreement between observed and simulated relative ERC yields. The root mean squared error (RMSE) is 0.056, indicating that on average the predicted relative yields were within 6% of the observed relative yields.

Most of the error was unsystematic although the intercept, ‘a’, and slope, ‘b’, values showed that the model was prone to slight overestimation of yield declines caused by mild soil water stressing, and slight underestimation of the yield declines caused by more severe soil water stressing.

The correlation coefficient (Pearson’s r) of 0.94, nevertheless indicates a very high degree of correspondence between the observed and simulated relative yields. Overall, the statistics of model performance were indicative of very good model performance, sufficiently accurate for the evaluation of irrigation water management systems, especially the comparison of one system with another in relative terms, which was the primary aim of this study.

Discussion and Conclusions

In order to evaluate the performance of water management and irrigation systems in the Lowveld of Zimbabwe, a strategy was formulated which hinged on the development of an irrigation systems simulation model to interpret results from a MIPU. Based on infield evaluations of irrigation systems, the MIPU provided information on the distribution uniformity of water applications, the magnitude of these water applications relative to soil water holding characteristics, and the watering (or irrigation scheduling) strategy used by the grower. While useful in its own right, significant value was added to the MIPU data and information by translating it into associated impacts on sugar yields, water budgets and associated indices of performance, such as irrigation efficiency and water use productivity. In order to achieve this, robust water budgeting and yield relationships were integrated into a computer simulation modelling tool, *viz*. *ZIMsched 2.0*.

This tool enabled the effects of different water management strategies on water requirements and yields of ERC to be simulated, taking into consideration:

- irrigation system type, for example, sprinkler versus furrow,
- irrigation system performance, *viz*. distribution uniformity of applied water and the characteristic water application depths,
- soil characteristics, and
- weather conditions.

The validity of *ZIMsched 2.0* for simulating ERC and its credibility was established by comparisons between observed and simulated relative ERC yields and water use for a range of soil, weather and irrigation watering conditions.

The development of *ZIMsched 2.0* provided a credible tool for the evaluation of the main water management recommendations and types of irrigation hardware prevailing in the Lowveld of Zimbabwe. The evaluation of these together with comparisons to more optimal recommendations, is the subject of a companion paper (Lecler, 2003). Using *ZIMsched 2.0*, irrigation systems evaluations can be done for different soils and seasons, relatively cheaply, efficiently and objectively. Experiments to do this would not have been practically feasible. *ZIMsched 2.0* is also unique in that, in terms of the simulated ERC yields and water budgets, it differentiates between different types of irrigation systems performing at different levels. In addition, the model can be used to determine how a targeted amount of water can be used in the most effective manner, for example, to determine an effective deficit irrigation strategy. The selected strategy can then be implemented using a simplified version of the same tool.

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A MODEL FOR THE EVALUATION OF IRRIGATION AND WATER MANAGEMENT SYSTEMS IN THE LOWVELD OF ZIMBABWE: MODEL APPLICATION

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Abstract

A computer simulation model was developed to evaluate the performance of irrigation and water management systems. The development of the model is described in a companion paper. In this paper the application of the model to evaluate a selection of the various water management and irrigation systems prevalent in the Lowveld of Zimbabwe is presented. Most of the drip irrigation systems were performing below potential due to excessive infield variations in applied water. The performance of furrow irrigation systems was limited by the large variations in water applied to individual furrows, and water applications that were, on average, excessively high relative to soil water holding characteristics. Simulations showed that sub-surface drip irrigation systems have a slight edge on other irrigation systems in terms of *potential* efficiency, *viz*. average water savings ranged from approximately 2.2 to 1.5 ML/ha relative to floppy irrigation systems, and 3.5 to 2.3 ML/ha relative to typical furrow irrigation systems, depending on how water applications were scheduled. Using existing water management guidelines, large amounts of deep percolation were simulated for all systems, especially furrow irrigation. The danger of increased development of soil salinity problems due to raised water tables, especially under furrow irrigation, was highlighted. A key finding was that there was potential for the Lowveld sugar industry to use up to 30% less water per hectare on an annual basis if *ZIMsched*, a specialist irrigation scheduling tool, was used to derive more appropriate water management guidelines. However, simulations showed that with the more precise irrigation scheduling there could be a slight crop yield penalty when the distribution uniformity of applied water was poor. The potential water savings should be stored, and used to support the industry during the drought years. If water savings are not made nor stored for future use, or a portion of the sugar industry's allocated water or water savings are re-allocated to another user, there is every chance that a similar disaster to that which occurred after the 1991/92 drought, could recur, and again bring the industry to near collapse due to a shortage of water.

Keywords: sugarcane, modelling, irrigation, efficiency, performance, ZIMsched

Introduction

Uncertain water availability and a climate characterised by recurring droughts, provides strong motivation for the sugar industry in the south east Lowveld of Zimbabwe to strive for continuous improvement in water management.

In order to assess the performance of the various water management procedures and irrigation systems used in the sugar industry:

- tools and methods to record infield irrigation systems performance data /information were developed and/or acquired,
- the data and information acquired using the tools and methods in (i) were used to calculate ‘Irrigation Engineering Performance Indices’ (IEPIs), such as the coefficient of uniformity, CU, which gives an indication of how uniformly irrigation water is applied, and
- a sugarcane yield and irrigation systems simulation model was developed to predict how these IEPIs impacted crop yields and water budgets, for different soils, seasonal weather, irrigation systems and water management strategies.

The development of the systems simulation model is described in a companion paper (Lecler, 2003). Results of the application of the model to evaluate a selection of the various water management and irrigation systems are presented in this paper. The performance of the various irrigation systems, if more optimal but achievable IEPIs and water management strategies were used was also assessed and is discussed in this paper.

Methodology

Infield measurement of key irrigation system characteristics undertaken by a Mobile Irrigation Performance Evaluation Unit (MIPU) (Griffiths and Lecler, 2001), combined with a systems modelling approach, was used to evaluate the various water management and irrigation systems. Experiments to compare a representative sample of different irrigation systems, performing at different levels, over many seasons, and for different soils and water management strategies would have been too time consuming, costly and disruptive to be practically feasible. A diagrammatic illustration of the various components of the evaluation methodology and their interrelationships is shown in Figure 1.

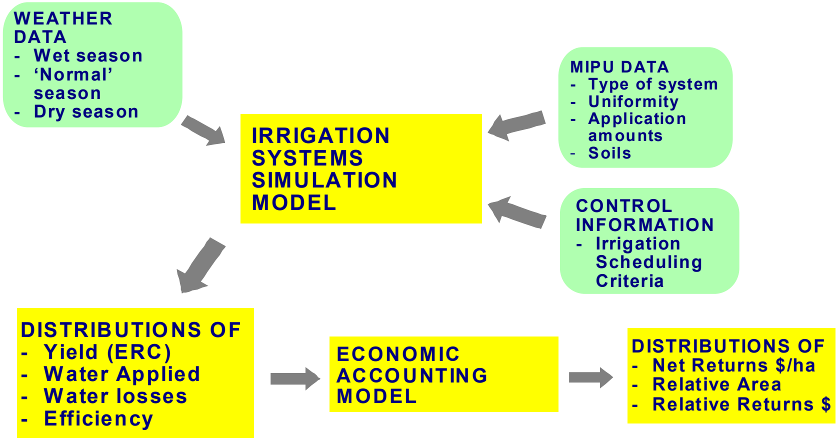

Figure 1. Diagrammatic depiction of the methodology used for the evaluation of irrigation hardware and water management systems. MIPU stands for Mobile Irrigation Performance Evaluation Unit

Irrigation systems performance measures

A multitude of indices have been proposed to quantify irrigation systems performance. There is also some confusion, because many of the indices have been given different definitions and are perceived and interpreted differently by different people. The performance indices used in this study and their definitions are given in Equations 1 and 2.

$$IE = T.100 / (I_g + R_g) \tag{1}$$

Where
IE = Irrigation efficiency (%)
T = Evaporation from the plant canopy or transpiration, representing beneficial water use (mm)
R_g = Total measured rainfall in the growing season (mm)
I_g = Total gross irrigation water applied in the growing season (mm)

$$WUP = ERC.100 / (I_g+R_g) \quad (2)$$

Where
WUP = Water use productivity (t/ha/mm)
Note: WUP has often been referred to as Water Use Efficiency but since the numerator and denominator have different units, the term 'productivity' has been preferred
ERC = Estimated recoverable crystal (t/ha/season)

'Irrigation Efficiency' and 'Water Use Productivity' (cf Equations 1 and 2) and, indeed, other performance indices provide useful standards for comparisons. However, from a business perspective, the selection of one system over another on the basis of say, water use productivity, may not make business sense. To illustrate, consider two irrigation systems with different water use productivities. The system with the highest water use productivity may not necessarily be the most effective system, unless the cost of achieving the very high water use productivity has been taken into consideration. If this cost is too high the system will not be viable from a business perspective, no matter how good its technical performance.

From a business perspective, the return on investment and the overall relative net return are key determinants in the evaluation of different irrigation and water management systems. Systems can thus be compared in terms of Net Return per Hectare and Relative Net Return, as defined in Equations 3 and 4.

Net Return per Hectare (NRH) =(Gross Revenue - Yield Dependent Costs (3)
- Irrigation Variable Costs - Base Production Costs
- Irrigation Fixed Costs) / Hectares in production

Relative Net Return (RNR) = Net Return per Hectare x Relative Production Area (4)

Gross revenue is the product of ERC yield and price. Yield dependent costs are costs that depend on yield; for example, harvesting and hauling, and possibly fertiliser (if fertiliser amount is applied relative to expected yield). Irrigation variable costs include the direct costs of water, energy (electricity or diesel), labour and maintenance. The irrigation variable costs depend on both the amount of irrigation water applied and the rate of application. The rate of application relates to the irrigation system's peak capacity, which impacts on the crop yields that can be obtained with the system and also the energy and fixed irrigation costs. Base production costs include all variable production costs other than yield dependent or irrigation variable costs; for example, herbicides, labour and seed. Irrigation fixed costs include interest on investment and depreciation. The relative net return allows for the opportunity cost of water to be accounted for. This opportunity cost, for example using water savings to increase the production area, or to increase average production over a number of seasons, is a vital consideration, especially when water is limited.

Key inputs needed for the calculation of the NRH and RNR are the predicted crop yield and water use associated with different irrigation systems and operating strategies.

Estimates of these key inputs of crop yield and water use, together with estimates of the IE and WUP were achieved by using *ZIMsched 2.0* (Lecler, 2003) to interpret the results of MIPU evaluations. The crucial crop yield and water use information, together with more routinely available and case specific financial and production cost information, could be used to calculate and compare the NRH and RNR of different irrigation systems for specific cases. Such case specific comparisons whilst facilitated by *ZIMsched 2.0*, are beyond the scope of this paper.

Results

A sample of the type of results obtained through analysis of the MIPU data/information with *ZIMsched 2.0,* is presented here. At the time of analysis, relatively few MIPU evaluations of centre pivots and overhead sprinkler systems had been undertaken; those results have therefore been excluded as they were probably not adequately representative and could lead to biased interpretations.

The majority of the floppy and drip irrigation systems that existed in the Lowveld were evaluated by the MIPU. A frequency analysis was performed on the IEPIs reported on by the MIPU, *viz*. the coefficient of uniformity (CU), and statistical uniformity (SU) values for floppy and drip systems, respectively. The results of this analysis are shown in Table 1. The median CU or SU values associated with the top third, middle third and lower third of system performance measures in combination with the associated %TAM values (cf. Table 1) were then used as inputs in *ZIMsched 2.0* simulations.

Table 1. Ranked 'engineering' performance indices derived from field measurements undertaken by the MIPU for floppy and drip irrigation systems in the Lowveld of Zimbabwe.

System type (performance measure, i.e. CU, DU or SU)	Performance rating	Representative value of CU or SU[a]	Representative irrigation application depth as a percentage of TAM (%TAM)[b]
Floppy (CU)	Top third	81	< 50
	Middle third	73	< 50
	Lower third	69	< 50
	Eng Standard[c]	**> 82 (CU)**	**< 50**
Drip (SU)	Top third	84	< 50
	Middle third	72	< 50
	Lower third	54	< 50
	Eng Standard[c]	**> 88 (SU)**	**< 50**

[a] SU = Statistical Uniformity (drip systems engineering performance index).
CU = Coefficient of Uniformity (floppy sprinkler system engineering performance index).

[b] The application depth could be varied to less than 50% of the soil's TAM. Therefore irrigation applications equivalent to less than 50% of the soils TAM value were used in the *ZIMsched 2.0* simulations, dependent on each estate's water management guidelines, except for drip irrigation where daily irrigation applications were simulated to occur in order to maintain the soil water depletion at approximately 10 % of the soil's TAM.

[c] Refers to the value of the relevant performance measure that should be expected and attainable in practice if the system was designed and installed according to appropriate engineering standards. The spray pattern of individual floppy sprinklers is such that a CU of 82 is close to the optimum that can be expected in the field.

For furrow irrigation all the measured irrigation water applications on individual furrows were converted to a percentage of the field's TAM value (%TAM). All these %TAM values were then used to calculate a global average distribution uniformity (DU) and %TAM value for an estate for either in-row furrow irrigation and/or inter-row furrow irrigation. The results of this analysis are presented in Table 2. *ZIMsched 2.0* was then used to simulate ERC yields, associated irrigation water applications and losses, using the mean DU and %TAM values calculated using all the measured furrow water applications on a particular estate (cf. Table 2).

Table 2. Average distribution uniformity (DU) and irrigation application depths for furrow irrigation derived from field measurements undertaken by MIPU trained evaluation teams on a sugar estate in the Lowveld of Zimbabwe.

System type	Value of DU calculated using all furrows[a]	Mean irrigation application as a percentage of TAM (%TAM)	Number of furrow measurements
In-row furrow	48	73	69
Inter-row furrow	60	62	12
Eng Standard[b]	**> 75**	**< 60**	

[a] DU = Distribution Uniformity, based on measurements of depth of water applied relative to the field's TAM calculated using data from flow measurements into all furrows on all fields evaluated by the MIPU trained evaluation teams on the estate.

[b] Refers to the value of the relevant performance measure that should be expected and attainable in practice if the system was designed and installed according to appropriate engineering standards. It must be noted, however, that these standards may be very difficult and/or expensive to obtain for furrow irrigation on certain topography and with certain soils, especially if the soils have very high infiltration rates, low values of TAM, and the topography is very variable.

Floppy irrigation systems

A number of private farmers and one estate have floppy irrigation systems. A variety of water management approaches are used by the private farmers, and a set irrigation scheduling procedure is followed by the estate.

Performance of water management (scheduling) guidelines used for floppy irrigation systems

The irrigation water management (scheduling) guidelines used by the estate were programmed in *ZIMsched 2.0* so that they could be replicated, and the performance in terms of the water budget and relative ERC yields could be compared with scheduling using *ZIMsched,* a simplified scheduling version of *ZIMsched 2.0.* The results of the comparison between the estate's water management recommendations and scheduling irrigation applications using *ZIMsched,* are shown in Table 3. Evaporation of water sprayed from irrigation emitters and wind-drift losses depend to a large degree on the prevailing weather. However, the contributions that spray evaporation and wind-drift make towards water which is lost from the system were estimated to be only 8%. Spray evaporation is accompanied by a largely compensating reduction in evaporation of water from the soil and plant because, after the evaporation of the irrigation spray, less energy is available to evaporate water from the soil and plant surfaces (Heermann *et al.*, 1990; Thompson *et al.*, 1993). However, the contribution that spray evaporation, wind-drift and wind distorted water distributions have on specific irrigation systems and their performance, needs further research.

Table 3. Comparison of the performance of floppy irrigation systems: 'Estate' water management guidelines versus scheduling with *ZIMsched.* Values shown are representative of systems in the top third of systems in terms of performance (CU = 81) and averaged for April , June and October cut crops.

Season	Gross irrigation applications (ML/ha)		Irrigation efficiency[a]		Relative estimated recoverable crystal (%)		Relative water productivity[b] (%)	
	'Estate'	*ZIMsched*	'Estate'	*ZIMsched*	'Estate'	*ZIMsched*	'Estate'	*ZIMsched*
Wet	14.3	9.9	56	67	102.4	100	100	120
Normal	15.4	11.3	63	76	104.7	100	100	121
Dry	18.0	13.9	67	78	104.8	100	100	117
Mean	15.9	11.7	62	74	104	100	100	119

[a] Irrigation efficiency = Transpiration.100 / (rain + gross irrigation water applied)
[b] Water productivity = Estimated recoverable crystal . 100 / (rain + gross irrigation water applied)

There were significant variations between the amounts of irrigation water applied, depending on the rainfall of the season. On average, gross irrigation water applied from the field edge could be reduced from 15.9 to 11.7 ML/ha if the water management guidelines were changed and *ZIMsched* was used for irrigation scheduling. This represents a saving in water of approximately 36%. However, because floppy irrigation systems are characterised by fairly varied water applications, i.e. CUs not normally more than 82, the over-watering resulting from scheduling according to the estate's recommendations compensated, to an extent, for the variability in water applications. This compensation resulted in a slight benefit in the simulated yield of ERC relative to yields simulated using *ZIMsched* for scheduling. Thus the scheduling guidelines derived using *ZIMsched* may need to be refined depending on the uniformity (evenness) with which water is applied. The water productivity or yield per unit of water applied could be increased by approximately 19% through the implementation of a more optimal irrigation scheduling system.

Impacts of the design, installation and maintenance of floppy systems

The effect of the design and installation of the floppy irrigation system hardware was evaluated by comparing irrigation efficiency and relative ERC yields for systems as they stood, with yields and efficiencies simulated for a hypothetical floppy irrigation system designed and installed according to appropriate engineering standards which could be expected in practise, i.e. a CU of more than 82. These results are shown in Table 4. In general the range of irrigation efficiencies and relative ERC yields for floppy irrigation systems evaluated was small, indicating that it is a fairly robust system. Improvements to the design and installation resulted in simulated gains of 4% in irrigation efficiency and 6 % in ERC yield. These gains should be viewed in the context of *ZIMsched 2.0's* accuracy (cf. Lecler, 2003) and could be masked by other more significant impacts on yields which are likely to occur in practice, for example, due to poor nutrition or pests and diseases.

Table 4. Performance of top, middle and lower third of floppy irrigation systems evaluated in the Lowveld relative to a hypothetical system designed and installed according to appropriate engineering standards, and with irrigation water applications scheduled using *ZIMsched.*

System rating	Irrigation efficiency[a]	Relative estimated recoverable crystal (%)[b]	Average drainage water (mm)
Upper third	74	100	298
Middle third	71	96	337
Lower third	70	94	357
Eng Std	**74**	**100**	**294**

[a] Irrigation efficiency = Transpiration.100 / (rain + gross irrigation water applied) (average for dry, normal and wet seasons)

[b] ERC (%) - assuming other management factors are optimal

Drip irrigation systems

More than 80% of the drip systems in the Lowveld were evaluated by the MIPU and all except two were owned and operated by private growers. The water management systems used for drip were therefore very varied, dependent on the individual grower. Prior to the development of *ZIMsched*, growers had irrigation scheduling guidelines given in the ‘Zimbabwe Sugarcane Production Manual’ (ZSPM), edited by Clowes and Breakwell (1998).

Performance of water management (scheduling) guidelines used for sub-surface drip irrigation systems

To evaluate the ZSPM irrigation scheduling guidelines, they were programmed into *ZIMsched 2.0* for comparison with *ZIMsched*, a more specialist irrigation scheduling programme that can be tailored specifically for drip. The results of this analysis are shown in Table 5.

As with floppy irrigation, there were significant variations between irrigation water applied, depending on the rainfall of the season. On average, gross irrigation water applied from the field edge could be reduced from 13.7 to 10.2 ML/ha if the water management was done according to recommendations provided by *ZIMsched* rather than the SPM. This represents a saving in water of approximately 26%. The reduction in water applied relative to floppy irrigation systems, results from significant reductions in evaporation from the bare soil surface because only a very small fraction is wetted with sub-surface drip irrigation. This reduction in evaporation from the soil surface is not accounted for in the ZSPM scheduling recommendations. Also, with drip irrigation, no spray evaporation and wind drift losses were simulated. The top third of drip systems in terms of uniformity were more uniform than floppy irrigation systems, i.e. SU=84, so the over-watering of the ZSPM approach to irrigation scheduling did not result in significant simulated yield benefits. The water productivity or yield per unit of water applied could be increased by approximately 21% through the implementation of *ZIMsched*, which provides more optimal irrigation scheduling recommendations.

Table 5. Comparison of the performance of drip irrigation systems: 'ZSAES Sugarcane Production Handbook' water management versus scheduling with *ZIMsched.* Values shown are representative of systems in the top third of systems in terms of performance (SU = 84).

Season	Gross irrigation applications (ML/ha)		Irrigation efficiency[a]		Relative estimated recoverable crystal (%)		Relative water productivity[b] (%)	
	H/book[c]	*ZIMsched*	H/book	*ZIMsched*	H/book	*ZIMsched*	H/book	*ZIMsched*
Wet	12.6	8.5	61	74	100.7	100	100	123
Normal	13.6	9.9	70	86	101.3	100	100	124
Dry	15.0	12.3	78	89	101.9	100	100	115
Mean	13.7	10.2	70	83	101.0	100	100	121

[a] Irrigation effficiency = Transpiration.100 / (rain + gross irrigation water applied)

[b] Water productivity = Estimated recoverable crystal . 100 / (rain + gross irrigation water applied)

[c] H/book = Scheduling using pan factors and effective rainfall formulae given in the ZSAES Sugarcane Production Handbook (Clowes and Breakwell, 1998)

Impacts of the design installation and maintenance of sub-surface drip irrigation systems

The effect of the design, installation and maintenance of drip irrigation system hardware was evaluated by comparing irrigation efficiency and relative ERC yields with the performance of a hypothetical drip irrigation system designed and installed according to appropriate engineering standards, i.e. an SU of more than 88. These results are shown in Table 6.

Table 6. Performance of top, middle and lower third of drip irrigation systems relative to a system designed and installed according appropriate engineering standards which can be expected in practice, and with irrigation water applications scheduled using *ZIMsched.*

System rating	Irrigation efficiency[a]	Relative estimated recoverable crystal (%)[b]	Average drainage water (mm)
Upper third	83	99	271
Middle third	80	95	316
Lower third	76	88	387
Eng Std	**84**	**100**	**258**

[a] Irrigation efficiency = Transpiration.100 / (rain + gross irrigation water applied)

[b] ERC (%) - assuming other management factors are optimal

The range of irrigation efficiencies and relative ERC yields for drip irrigation systems evaluated in the Lowveld was relatively large, indicating that drip irrigation was not as a robust a system as floppy. Great care needs to be taken in the design, installation and maintenance of drip systems.

For a third of the systems evaluated in the Lowveld, improvements to the design, installation and/or maintenance could likely result in substantial gains in irrigation efficiency and ERC yields, assuming other management factors are equally optimal.

In-row furrow irrigation systems

Most sugarcane in the Lowveld is grown using in-row furrow irrigation. The three large estates all use different water management recommendations for scheduling irrigation water applications, and one estate has a significant proportion of inter-row furrow irrigation. As relatively few inter-row furrows had been evaluated at the time of analysing the results, only results from one estate's in-row furrow irrigation evaluations are presented here.

Performance of water management guidelines used for in-row furrow irrigation systems

The water management recommendations of the estate were programmed in *ZIMsched 2.0* so that these estate recommendations could be compared with scheduling with *ZIMsched*, given the infield, in-row furrow performance characteristics measured by the MIPU trained evaluation teams. The results of the analysis of the water management system used by the estate are shown in Table 7.

Table 7. Comparison of the performance of in-row furrow irrigation systems: "Estate" water management vs scheduling with *Zimsched* - Values shown are based on average system performance characteristics derived using all the in-row furrow evaluations undertaken by the MIPU trained evaluation teams.

Season	**Gross Irrigation Applications (ML/ha)**		**Irrigation Efficiency[a]**		**Relative Estimated Recoverable Crystal (%)**		**Relative Water Productivity (%)[b]**	
	"Estate"[c]	***ZIMsched***	**"Estate"**	***ZIMsched***	**"Estate"**	***ZIMsched***	**"Estate"**	***ZIMsched***
Wet	15.2	11	52	61	103.5	100	100	117
Normal	17	11.7	57	70	105.4	100	100	125
Dry	19.5	14.7	60	72	105.1	100	100	119
Mean	17.2	12.5	56	68	105	100	100	120

[a] Irrigation Efficiency = Transpiration.100 / (Rain + Gross Irrigation Water Applied)
[b] Water Productivity = Estimated Recoverable Crystal.100/ (Rain + Gross Irrigation Water Applied)
[c] "Estate" = Scheduling using pan factors and effective rainfall formulae given in the Estate's irrigation scheduling recommendations

There were significant variations between seasonal irrigation water applications, depending on the rainfall of the season. On average, gross irrigation water applied from the furrow edge could be reduced from 17.2 to 12.5 ML/ha if the water management was done according to recommendations provided by *ZIMsched* rather than the existing estate recommendations. This represents a saving in water of approximately 27%. However, because of the relatively large inter-row variations in applied water, reflected in the low DU value of 48, the relative over-watering of the estate scheduling system compensated for the poor uniformity and resulted in slight simulated ERC yield benefits of approximately 5% relative to scheduling with *ZIMsched*. Again these simulated crop yield gains should be viewed in the context of *ZIMsched 2.0's* accuracy (cf. Lecler, 2003) but they point to a need for irrigation scheduling guidelines to be refined according to the uniformity with which irrigation water is applied.

The water productivity or yield per unit of water applied could be increased by approximately 20% through the use of *ZIMsched* for irrigation scheduling, which is a significant benefit. The increase in applied water relative to floppy irrigation systems, *viz.* 0.8 to 1.3 ML/ha, was small and resulted from the irrigation applications of furrow being poorly matched to the soil water holding characteristics. This mismatch outweighed potential advantages of furrow, including reductions in spray evaporation and wind drift, and reduced evaporation from the soil surface which is only partially wetted under furrow irrigation. It must also be noted that losses in unlined conveyancing canals were not added to the water requirements shown here as they constitute a separate and variable water loss, potentially but not always pertinent to furrow irrigation. Conveyance losses of 30% have been measured in an unlined conveyance canal on an estate in the Lowveld.

Impacts of in-row furrow irrigation system designs and layouts

The effect of the design and layout of typical in-row furrow irrigation systems at the estate was evaluated by comparing irrigation efficiency and relative ERC yields with the performance of a hypothetical furrow irrigation system designed and installed according to appropriate engineering standards. These standards, *viz*. a DU of more than 75 and water applications of less than 60% of the soil's TAM may, however, be very difficult and/or costly to expect, depending on a particular field's topography and soil characteristics. The results are shown in Table 8. The potential to increase the irrigation efficiency of furrow irrigation systems through improved designs was relatively high, the results of this analysis showing simulated irrigation efficiencies increasing from 56 to 77%. *Assuming adequate drainage*, the over-watering of the estate resulted in little crop water stress, even though variations in water applied were large. The potential to increase ERC through improved design, assuming the estate's existing water management recommendations appeared, therefore, to be relatively small. However, without extensive drainage, salinity problems resulting from raised water tables will increase further and overall sustainability will be threatened. If *ZIMsched* was used for more accurate irrigation scheduling, the ERC yield benefit and reduction in drainage water resulting from an improved system design and installation was simulated to be substantial.

Table 8. Performance of in-row furrow irrigation systems an estate compared to a furrow systems designed and installed according appropriate engineering standards which could be expected in practise, depending on topographic and soil infiltration characteristics.

System	Irrigation efficiency[a]	Relative estimated recoverable crystal (%)[b]	Average drainage water (mm)
HVE $_{\text{estate}}$	56	105	958
HVE $_{\text{ZIMsched}}$	68	100	550
Eng Std	**77**	**108**	**350**

[a] Irrigation efficiency = Transpiration.100 / (rain + gross irrigation water applied)

[b] ERC (%) - Assuming other management factors are optimal

HVE$_{\text{estate}}$ = Furrow systems performance as measured but scheduling using the estate's scheduling recommendations

HVE $_{\text{ZIMsched}}$ = Furrow systems performance as measured but scheduling using *ZIMsched*

Eng Std = Furrow systems performance if designed according to appropriate engineering standards, *viz*. DU >75 and application as % of TAM <60, and irrigation scheduling using *ZIMsched*

Discussion and Conclusions

One of the key findings of this study was that, if the sugar industry in Zimbabwe were to use the irrigation scheduling tool, *ZIMsched,* on a wide scale, it is likely that more than 20% of the water presently used on an annual basis when there are no water restrictions, could be saved. However, unless irrigation application uniformities are improved, there was evidence that slight yield losses may occur with the more precise irrigation scheduling on well drained fields. It should also be stressed, however, that because the sugar industry is located in an area prone to recurring droughts, the simulated seasonal water savings do not necessarily equate to less water being used over an extended, say, 10 year period. The potential water savings in good rainfall years should be stored, and used to support the industry through the drought years. If water savings are not made, or a portion of the sugar industry's allocated water is re-allocated to another user, or a significant portion of the water savings cannot be stored, there is every chance that another disaster, such as that which occurred after the 1991/92 drought, when the industry nearly collapsed due to severe water shortages, could recur. Appropriate institutional arrangements to facilitate 'water banking' should also, therefore, be developed.

Most of the floppy irrigation systems were performing at levels close to those expected if they had been designed and installed to appropriate engineering standards. However, most of the drip irrigation systems were performing below potential. Simulations showed that potential crop yields were limited by an average of approximately 12% on one third of the drip systems evaluated. This was largely due to in-field variations in applied water, caused by substandard system design, installation and/or maintenance. Provided it is designed, installed and commissioned to an appropriate standard, and then operated correctly, simulations showed that sub-surface drip irrigation systems have a slight edge on the other irrigation systems which were evaluated, in terms of *potential* efficiency, *viz*. average water savings ranged from approximately 2.2 to 1.5 ML/ha relative to floppy irrigation systems, and 3.5 to 2.3 ML/ha relative to typical furrow irrigation systems, depending on how water applications were scheduled. With sub-surface drip, water savings occur due to reduced evaporation from the bare soil surface, no spray evaporation or wind drift losses, and the inherent flexibility in applying water which makes it possible to control runoff and deep percolation relatively easily, compared with, say, with furrow irrigation. However, this study revealed that, in practise, most drip systems in the Lowveld were not performing at potential optimum levels. There needs to be a greater level of professionalism in the design and installation of drip systems and growers need to have appropriate drip irrigation management training.

The crop yield potentials and irrigation efficiencies of the furrow irrigation systems were limited by large variations in water applied to individual furrows, and water applications which were, on average, excessively high. Although the large water applications did compensate, to a degree, for the variations in applied water between and down the furrows, they also compromised efficiencies and could lead to further development of other problems, including raised water tables and increased soil salinity levels. Most furrow designs and layouts were not operator friendly. It was difficult for operators to control water applications and application variability using syphons. This is an area that could be improved through better, but more complicated and expensive, designs and installations. For example, well designed supply furrows discharging through pipe spiles could be used to control flows into the furrows more evenly and would be much more operator friendly. On deep soils with high TAMs and on fairly level topography, furrow irrigation could, theoretically, be almost as efficient as sub-surface drip. Under furrow irrigation, evaporation from the bare soil surface is limited because only a portion of the soil surface is wetted, there are no spray evaporation or wind drift losses and with proper design and layout, applications can be applied uniformly.

However, this study has shown that with furrow irrigation, there is a big gap between potential theoretical performance and what is generally achieved in practise in the Lowveld conditions, particularly on the soils with low TAM values. With many furrow irrigation systems, feeder water losses constitute an additional but very variable loss. Water losses in unlined feeders of up to 30% have been measured on an estate in the Lowveld.

On many fields the tail ends of furrows were blocked. This often led to severe over-irrigation at the tail end of a field, with excessive deep percolation (leaching) in that area, and the associated development of high water tables that could cause serious salinity problems. It is far better to rather plan for the collection and re-use of relatively good quality tail water runoff and leave the furrow ends open.

Simulations showed that deep percolation (drainage) losses under all systems, but particularly under furrow irrigation, were excessive. It is fortunate that the irrigation water quality in the Lowveld is generally very good with very low salts; however, unless further remedial actions are initiated, for example, improved irrigation scheduling and better control of water applications, the development of high water tables and associated salinity problems are likely to become increasingly worse. In many cases, particularly on the low TAM soils, changing to another type of irrigation system would be likely to add significant value in the long term.

Together with case specific financial and production cost information, the tools and methods described in this paper, make possible the calculation of comparative Net Returns per Hectare and the Relative Net Returns for different irrigation and water management systems. Thus sound business decisions regarding the upgrading or replacement of existing systems or the selection of an appropriate irrigation and water management system for a given environment, could be facilitated.

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